MPMM 2013

Maintenance Performance
Measurement and Management

12th –13th
September 2013
Lappeenranta, FINLAND

Proceedings

Proceedings of the Maintenance Performance Measurement and Management Conference

12th - 13th September 2013

Lappeenranta, FINLAND

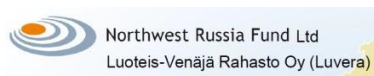Sari Monto, Miia Pirttilä, Timo Kärri (editors)

Table of Contents

Design of the Logistics Support of Complex Engineering Systems

Abdallah Alalawin, Gianpaolo Ghiani, Emanuele Manni* and Chefi Triki

Department of Engineering for Innovation
University of Salento, Lecce, Italy
*Corresponding author: Emanuele Manni
e-mail: abdallah.alalawin@unisalento.it
e-mail: gianpaolo.ghiani@ unisalento.it
e-mail: emanuele.manni@ unisalento.it
e-mail: chefi.triki@ unisalento.it

Abstract

This paper deals with the problem of designing the logistics support of complex multi-indenture and multi-echelon engineering systems, with the aim of determining the spare parts stock and the maintenance resources capacity, as well as the level of repair. The problem is modeled as an integer program with a nonlinear probabilistic constraint on the expected availability, whose satisfaction can only be evaluated by means of very time-consuming simulation experiments. Thus, we use an optimization via simulation approach, in which the search space is efficiently explored through an approximated neighborhood evaluation mechanism, which makes use of several parameters estimated by means of simulation. Experimental results on a number of instances show the effectiveness of the proposed approach.

Key words: Maintenance; level of repair analysis; logistics support design; approximated neighborhood evaluation.

1 Introduction

Complex engineering systems are expensive and long-lived capital equipments (e.g., commercial and military aircrafts and ships, power plants, radars, manufacturing plants, etc.) that, once failed, are not simply replaced, but should be repaired by using a variety of complex maintenance resources and highly skilled personnel. During their long life cycle they may fail several times and their repairing and downtime costs may be extremely high. While discarding is the normal decision in case of failure of cheap and highly demanded products, for complex systems discarding or repairing decisions are taken at the component or part level (rather than at the equipment level) and are driven by both economic and non-economic criteria. In this paper, our focus is on designing the *Logistics Support System* (LSS) of a given complex engineering system (equipment) with the aim of minimizing its *Life Cycle Cost* (LCC), subject to minimum expected availability constraint (the availability is defined by Department of Defence, USA (1981) as "a measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at an unknown (random) time"). More precisely, in this paper we consider equipment availability

as a measure of effectiveness, and the minimization of the LCC as a measure of efficiency in order to take:

1. Level Of Repair Analysis (LORA) decisions: upon a failure of a component, determine whether it has to be discarded and replaced by a functioning component, or repaired. In the latter case, it has to be decided at which facility of the maintenance network it has to be repaired.
2. Spare parts decisions: the number of spare parts that should be stocked for each component at each facility.
3. Maintenance resources location and sizing decisions: the number and capacity of the maintenance resources of various types to locate at each facility.

These three decisions are tightly related because whether repair or discard a component is influenced by the spare parts inventory as well as by the maintenance resources capacity. From one side, high spare stocks should result in reduced queues caused by scarce maintenance resources. From the other side, increasing the maintenance resources capacity should shorten the repairing processes, allowing to potentially reduce the spare parts at stock. Thus, simultaneously facing the aforementioned three types of decisions is crucial in ensuring a given target equipment availability while minimizing the overall expected cost. Complex systems are usually represented as tree structures. Indeed, each equipment is usually composed of several components linked each other through father-son relationships. Each level of the structure, called *indenture*, includes several components that once failed may be either discarded or repaired. In the first case, a disposal action is performed and the failed component is simply replaced with a functioning one taken from the stock. In the latter case, the component is removed and sent to be repaired, and a functioning component is put back into the equipment where the failure occurred. If such a component is not immediately available, then the equipment is down, until the failed component is repaired, or a functioning one becomes available from the maintenance network, which is made up by a number of facilities connected to each other at different levels, called *echelons*. For this reason, we refer to this problem as multi-echelon. Facilities could be bases (sites where equipments operate), depots, or workshops. Each facility can have maintenance resources (both machines and personnel) to repair the defective components, and can send/receive components to/from other facilities.

In this paper, we deal with the integrated problem (LORA, spare parts, and maintenance resources location and sizing decisions) that is solved by means of an optimization via simulation approach. In particular, we propose a heuristic procedure that efficiently explores the search space through an *Approximated Neighborhood Evaluation* (ANE) model, relying on the estimation (via simulation) of a number of parameters, in the spirit of the algorithm proposed by Ghiani et al. (2010) for scheduling same-day couriers' shifts under probabilistic quality-of-service constraints. In contexts like this, the presence of probabilistic constraints does not allow to straightforwardly assess the feasibility of a solution, which can only be evaluated through time-consuming simulation runs. Thus, an approach that explicitly evaluates each neighbor of a given solution results to be very time-inefficient. On the other hand, a procedure picking up a solution at random in the neighborhood of the current solution typically performs poorly in practice. Thus, trading off between these two extremes, we develop a neighborhood-search-based procedure that, when simulating a solution at a given iteration, collects some statistics. Such statistics are then used within an ANE framework in

which the probabilistic constraints are approximated with deterministic linear functions of the problem variables.

The remainder of the paper is organized as follows. Section 2 summarizes relevant literature, whereas Section 3 provides a mathematical formulation of the problem with nonlinear probabilistic constraints on the expected availability. Section 4 describes our ANE model, whereas Section 5 presents a multi-start local search heuristic embedding it. Section 6 reports our computational experiments. Finally, conclusions follow in Section 7.

2 Relevant literature

In the literature, two main streams may be identified. The first stream includes approaches that aim at determining only the slow-moving spare inventories required to achieve the target availability with minimum LCC (Sherbrooke, 1968, 2004). The second stream focuses on tackling the typical LORA decisions to manage the maintenance network (Barros and Riley, 2001). Some other scholars tried to combine both strategies into an integrated framework (Alfredsson, 1997; Basten et al., 2012). Sherbrooke (1968) presents an approach called METRIC (Multi-Echelon Technique for Recoverable Item Control) that is able to determine the inventories for a two-echelon model with the aim of minimizing the number of Expected Back Orders (EBO) over all the recoverable items. The METRIC model is discussed more thoroughly in Sherbrooke (2004), including the extensions MOD-METRIC and VARI-METRIC, which relate the EBO to a measure of the operational availability of the equipments. Alfredsson (1997) improves the way of determining the EBO by using queuing theory. In this work, he considers an equipment with a single indenture level, and a two-echelon maintenance network. He combines the LORA problem with the optimization of the spare parts under the METRIC model. The queuing approach used in Alfredsson's model defines the number of resources as variables of the problem affecting equipment's availability. His model results in a non-linear integer program solved by means of convexification techniques combined with a decomposition approach. His outcomes are based on some practical assumptions that, as also acknowledged by the author, may be restrictive, leading to a maintenance system that may be cost-inefficient. Barros and Riley (2001), Saranga and Dinesh Kumar (2006), and Basten et al. (2009) propose integer linear models to solve the multi-indenture multi-echelon problem. However, they all assume an infinite capacity of the maintenance resources and aggregate the data per echelon in order to simplify the maintenance decisional process. Only few works take into account a limited capacity for the maintenance resources. Diaz and Fu (1997) deal with limited repair facilities, and propose an approximation scheme that works well in the case of high facility utilization rates. Sleptchenko et al. (2002, 2003) study the effect of maintenance resources capacity on the multi-echelon multi-indenture problem, and the trade-off between spare parts inventory and maintenance capacity. They also present a procedure for the simultaneous optimization of spare parts and maintenance resources. Zijma and Avşar (2003) analyze a two-indenture repairable item system, and propose an approximation model as well as a greedy optimization approach to meet a given target service level at minimal cost. Basten et al. (2011a, 2011b) further extend Basten et al. (2009) by limiting the resources capacity, and ensuring that the components to be repaired at each location are less than the installed capacity of the resources. They develop mixed-integer models for the multi-indenture multi-echelon case, and propose an approach based on a minimum cost flow model. Basten et al. (2012) then consider the combination of the LORA model with the spare parts inventory.

In addition to the research community, many software companies are working on the previous issues. A non-exhaustive list includes COMPASS, which is based on a mixed-integer linear programming formulation (Compass, 2008), and OPUS10 that implements the model proposed by Alfredsson (1997) in order to optimize the spare parts supply within the design of a logistic support system (Systecon, 2007).

With respect to the literature, this paper takes into account many of the aspects discussed above, such as LORA maintenance decisions, defining the spare parts inventory and the resources capacity, and integrates them in order to achieve a target operational availability at minimum expected LCC. In addition, our approach explicitly considers the scheduling policy of the maintenance processes, the stochastic nature of the failures and maintenance times, and the transportation resources.

3 General formulation

We consider a set of identical equipments with a multi-indenture structure, which are located at several operating sites (bases) and are subject to different types of failures that occur according to given stochastic processes. For each component of the highest indenture level, we assume that there can be a single failure mechanism. When a failure occurs, the first decision is related to repairing or discarding the failed component. We assume that the action of discarding can take place only if there is at least a spare part available, which replaces the defective part. On the other hand, in case of a repair action, a second level decision involves at which facility of the maintenance network, organized according to a multi-echelon structure, the repair process will take place, according to a predetermined policy (for instance, the decision could be driven by factors like the number of spare parts available at the different facilities, or the expected time needed to repair the component). In particular, our assumption is that the defective component can be repaired at the same facility where the failure occurred (if there is enough capacity), or can be sent to any other facility of the maintenance network. We assume that the repair process, which is composed of a number of repair tasks, takes place at a single facility, which is the same facility where the spare part is available. Moreover, for each part type, there is a unique sequence of repair tasks, independently of the facility where the repair is performed, and a repair task involves using a unique maintenance resource, that can be shared among different repair processes. If no spare part is available for the failed component, then the equipment is down, until a component of the same type exits from a repair process. Downtime comprises the time needed to perform the repair process, the time components are waiting for spare parts or maintenance resources, and the time needed to transport parts among the different facilities.   A general mathematical formulation of the problem, aiming at minimizing the LCC subject to availability restrictions on the operating equipments, is:

$$\text{Minimize } \text{LCC}(\mathbf{x})$$
$$\text{s.t.} \qquad a(\mathbf{x}) \geq a_{\min} \tag{1}$$

where $a(\mathbf{x}) = E[A(\mathbf{x}; \xi)]$. Here, ξ is a vector including the random parameters of our model (i.e., failures occurrences and repair processes durations), $A(\cdot, \cdot)$ represents equipments availability over the planning horizon, and $a(\cdot)$ is its expected value. Moreover, $a_{\min}$ is the target availability, and $\mathbf{x}$ is a vector representing all the decision variables of the problem (the number of spare parts and discarded components, and the number of required maintenance resources, such as machines, persons, etc.). The availability function $a(\mathbf{x})$ is not known

explicitly and may be only estimated through simulation. Since pure simulation approaches may be very computationally burdensome even for small systems, our attention is devoted to the use of an optimization via simulation approach that incorporates an ANE procedure for exploring the solution space, as recently proposed by Ghiani et al. (2010).

4 Approximated neighborhood evaluation

The peculiarity of the availability function $a(\cdot)$ makes it hard to use standard neighborhood search procedures. To clarify this aspect, let $\mathbf{x}^{(k)}$ be the current solution at iteration k of a generic neighborhood search procedure, and let $N(\mathbf{x}^{(k)})$ be its neighborhood, defined according to some criteria. In principle, the new solution $\mathbf{x}^{(k+1)}$ could be selected in $N(\mathbf{x}^{(k)})$ as the least cost feasible solution. This approach could be implemented by checking the feasibility (i.e., the satisfaction of the availability constraint through simulation) of such a solution. If this check does not succeed, we should check the second least cost solution, and so on. Unfortunately, the least cost solutions in the neighborhood are likely to be infeasible, because they typically utilize a lower number of resources than $\mathbf{x}^{(k)}$. As a consequence, this approach might result in the examination of a huge number of solutions, thus requiring many time-consuming simulation experiments. On the other hand, procedures picking up $\mathbf{x}^{(k+1)}$ at random in $N(\mathbf{x}^{(k)})$ perform poorly in practice. Thus, trading off between these two extremes, we propose a procedure that collects some statistics when simulating $\mathbf{x}^{(k)}$ at iteration $(k\text{-}1)$, and uses these statistics into an ANE procedure. More precisely, the basic idea (Figure 1) consists in starting with an initial solution (details about how we determine it are reported in Section 5) that must be simulated to assess its feasibility from the availability point of view. Then, in order to find a new solution in the neighborhood of the current one, all the statistics about the expected values (detailed in Section 4.1) collected at no additional computational cost during the simulation phase are fed into an optimization model, which is based on model (1). In particular, in such a model, the availability function $a(\cdot)$ is locally approximated by means of deterministic linear functions of the $\mathbf{x}$ variables. Then, the simulation phase is run again, and this procedure is iterated, until a satisfactory solution is obtained, or a time limit is reached. It is worth underlying that, since some of the parameters used by the optimization model are estimated when simulating the current solution, the approximation of the availability function is valid only locally (i.e., for neighbors "close" to the current simulated solution). Thus, while moving from one iteration to another for updating the current solution, the optimization phase may involve only small variations of the variables, namely the number of resources, the spare parts and/or the discarded components.
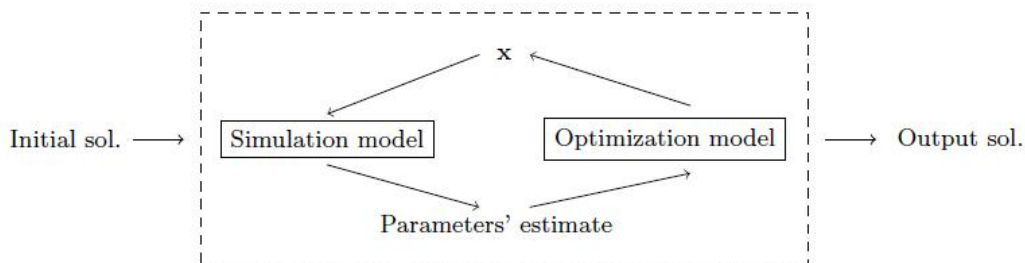

Figure 1. The solution approach

The availability constraint local approximation is based on the interaction between a component and its father and son components from one side, and with components of the

same type in other facilities from the other side. In particular, these relationships will be expressed as flow balance constraints at both the indenture and echelon levels. In addition to such constraints, additional constraints related to the capacity of maintenance and transportation resources are needed. In what follows, we first introduce some additional notation, and then present our mathematical model used within our ANE procedure.

4.1 Notation

In order to describe our mathematical model, we introduce the following additional notation. We note that all average values are obtained when assessing (via simulation) the feasibility of the current solution.

Sets and functions:

I: set of component types (type 0 represents equipments); L: set of maintenance resource types; O: set of facilities; U: set of transportation resource types; H: set of repair tasks (a repair task serves a unique component type and utilizes a unique resource type); E: set of transportation processes; $\alpha: H \rightarrow L$: function defining a mapping between a repair task and the maintenance resource used to perform it; $\gamma: H \rightarrow I$: function defining a mapping between a repair task and the component type repaired by means of it; $H_{io} = \{h \in H$: h is a repair task serving a component of type $i \in I$ at facility $o \in O\}$; $H_{lo} = \{h \in H$: h is a repair task using a maintenance resource of type $l \in L$ at facility $o \in O\}$; $E_u = \{e \in E$: e is a transportation process using transportation equipment of type $u \in U\}$; $E^{sd}_{io} = \{e \in E$: e is a transportation process for sending a defective component of type $i \in I$ from facility $o \in O$ to any other facility$\}$; $E^{sf}_{io} = \{e \in E$: e is a transportation process for sending a functional component of type $i \in I$ from facility $o \in O$ to any other facility$\}$; $E^{rd}_{io} = \{e \in E$: e is a transportation process by which facility $o \in O$ receives a defective component of type $i \in I$ from any other facility$\}$; $E^{rf}_{io} = \{e \in E$: e is a transportation process by which facility $o \in O$ receives a functional component of type $i \in I$ from any other facility$\}$; $R_{io} = \{o' \in O$: o' is a facility that can send components of type $i \in I$ to be repaired at facility $o \in O\}$; $B_{io} = \{o' \in O$: o' is a facility that can receive components of type $i \in I$ for repairing from facility $o \in O\}$; $F_i = \{i' \in I$: i' is father of component type i $\in$ I$\}$; $S_i = \{i' \in I$: i' is son of component type $i \in I\}$.

Parameters:

N_o: number of equipments at facility $o \in O$; W_{ho}: average workload for repair task $h \in H$ at facility $o \in O$; n_{ho}: average number of components repaired by means of repair task $h \in H$ at facility $o \in O$; n_e: average number of components transported by transportation process $e \in E$; r_{io}: average stock of components of type $i \in I$ at facility $o \in O$; $g_{ii'o}$: average percentage of components of type $i \in I$ at facility $o \in O$ that are not repaired because of a discarding decision involving a father component of type $i' \in I$; $m_{io'o}$: average number of components of type $i \in I$ moved from facility $o' \in O$ to be repaired at facility $o \in O$; $w_{ii'o}$: average number of components of type $i \in I$ waiting for components of type $i' \in I$ at facility $o \in O$; ρ_{lo}: average utilization rate of resources of type $l \in L$ at facility $o \in O$; ρ_u: average utilization rate of transportation equipments of type $u \in U$; t: number of years making up the planning horizon; t_h: processing time for repair task $h \in H$; t_e: transportation time for transportation process $e \in E$; c_i: cost of spare parts of components of type $i \in I$; c_l: cost to purchase

resources of type $l \in L$; c_u: fixed cost of transportation equipments of type $u \in U$; c_e: variable cost of transportation process $e \in E$; c_h: variable cost of repair task $h \in H$.

Decision variables:

x^s_{io}: number of spare parts of components of type $i \in I$ at facility $o \in O$; x^r_{lo}: number of resources of type $l \in L$ at facility $o \in O$; x^d_{io}: number of discarded components of type $i \in I$ at facility $o \in O$; x^t_u: number of transportation resources of type $u \in U$; x_{ie}: number of components of type $i \in I$ to be transported by transportation process $e \in E$.

4.2 Mathematical model

In the following, we present a mathematical model, in which the probabilistic constraint on the expected availability is approximated by using estimates obtained by simulation.

Components balance constraints. When a failure occurs, components at different indenture levels may be involved. At the same time, because components may flow between facilities at different echelons, this flow must be balanced. Thus, the first set of constraints aim at balancing father-son interactions as well as inter-facility flows. It is worth noting that equipments (type $i=0$) are treated by means of a different constraint. The balance equation for a given component type $i \in I \setminus \{0\}$ and a given facility $o \in O$ can be expressed as:

$$\sum_{h \in H_{io}} n_{ho} + \sum_{e \in E^{sd}_{io} \cup E^{sf}_{io}} n_e + r_{io} - x^s_{io} + \sum_{i' \in S_i} w_{ii'o} + \sum_{o' \in B_{io}} m_{ioo'} = \sum_{i' \in F_i} w_{i'io} + \sum_{o' \in R_{io}} m_{io'o}. \tag{2}$$

Equipments balance constraint. As mentioned before, balance constraints should be written differently for the specific case of the equipment (component type $i=0$ according to our notation), since from one side an equipment does not have any father component and, from the other side, target availability refers to equipments and not to components. Thus, the flow balance constraint for the equipments ($i=0$) is:

$$\sum_{o \in O} \left(\sum_{h \in H_{0o}} n_{ho} + \sum_{i' \in S_0} w_{0i'o} \right) \leq \left(1 - a_{\min}\right) \sum_{o \in O} N_o. \tag{3}$$

In the left-hand side we consider the average number of equipments that are down, obtained by summing over all the facilities the average number of equipments that are being repaired and the average number of equipments that are waiting for other components to be repaired. This value must not exceed the overall number of equipments available at all the facilities, multiplied by ($1 - a_{\min}$). For instance, if $a_{\min} = 0.9$ and the overall number of equipments is 20, then the average number of down equipments can be at most 2.

Facilities balance constraints. These constraints are modeled as classical flow balance constraints, and ensure that the number of defective and functional components of each type sent out of each facility matches the number of components of the same type entering the same facility. For every $i \in I$ and $o \in O$:

$$\sum_{e \in E^{sd}_{io} \cup E^{sf}_{io}} x_{ie} = \sum_{e \in E^{rd}_{io} \cup E^{rf}_{io}} x_{ie}. \tag{4}$$

Maintenance resources capacity constraints. These constraints aim at ensuring that the maintenance resources are enough to face all the workload generated during the planning horizon. The whole workload of each resource type at each facility should be less than its capacity expressed in terms of duration of the planning horizon, its utilization rate, and the related sizing decision variable x^r_{lo}. Thus, the maintenance resources capacity constraints, for every $l \in L$ and $o \in O$, are as follows:

$$\sum_{i \in I} \sum_{h \in H_{lo} \cap H_{io}} t_h \left(W_{ho} - \sum_{e \in E^{sd}_{io}} x_{ie} + \sum_{e \in E^{rd}_{io}} x_{ie} \right) \leq t \rho_{lo} x^r_{lo}. \tag{5}$$

Transportation resources capacity constraints. Analogously, the transportation resources should respect the following capacity limitations, for every $u \in U$:

$$\sum_{i \in I} \sum_{e \in E_u} t_e x_{ie} \leq t \rho_u x^t_u. \tag{6}$$

Objective function. Minimizing the LCC without violating the constraint on the target availability is the goal of this model. There are five types of costs to be considered: the costs of spare parts, the fixed costs of the resources, the fixed costs to start a maintenance activity, the variable costs for repairing a component, and the fixed and variable transportation costs. The expression of the LCC to be minimized is:

$$\sum_{i \in I} \sum_{o \in O} c_i \left(x^s_{io} + x^d_{io} \right) + \sum_{l \in L} \sum_{o \in O} c_l x^r_{lo} + \sum_{u \in U} c_u x^t_u + \sum_{i \in I} \sum_{e \in E} c_e x_{ie}$$

$$+ \sum_{i \in I} \sum_{o \in O} \sum_{h \in H_{io}} c_h \left(W_{ho} - x^d_{io} + \sum_{i' \in F_i} g_{i'io} x^d_{io} - \sum_{e \in E^{sd}_{io}} x_{ie} + \sum_{e \in E^{rd}_{io}} x_{ie} \right). \tag{7}$$

Approximated neighborhood evaluation model. The whole ANE model for our multi-echelon multi-indenture problem consists in minimizing the LCC defined by (7), subject to constraints (2)-(6).

5 A multi-start local search heuristic

In this paper our attention is not devoted to the development of complex heuristics, but rather to an efficient exploration of the search space. Thus, we decide to embed our ANE model into a basic multi-start local search framework, whose pseudo-code is depicted in Figure 2. Until a time limit is not exceeded, we first generate an initial solution and, in case it is infeasible, we recover feasibility by means of a MAKEFEASIBLE procedure. Then, given such a solution, we perform a local search phase in which the most promising neighbor of the current solution is obtained by solving the ANE optimization model (APPROXIMATEDNEIGHBORHOOD-EVALUATION procedure), until we reach a non-improving solution. An initial solution may be obtained in a number of ways. For instance, we could assign to each variable a value that is high enough to be sure that the target availability value is achieved, even if the cost will not be the least possible. Another way is to initialize all decision variables to zero (which obviously will result in an infeasible solution) and then gradually increase their values (by means of the MAKEFEASIBLE procedure). Alternatively, a METRIC-based approach may be used. In this paper, we use two different approaches, as reported in Section 6.

```
 1: procedure MULTISTARTLOCALSEARCH($t_{max}$)
 2:     $\mathbf{x}^\star \leftarrow$ null
 3:     LCC($\mathbf{x}^\star$) $\leftarrow +\infty$
 4:     while time $< t_{max}$ do
 5:         $k = 0$
 6:         $\mathbf{x}^{(k)} \leftarrow$ INITIALSOLUTION()
 7:         if $\mathbf{x}^{(k)}$ is infeasible then
 8:             $\mathbf{x}^{(k)} \leftarrow$ MAKEFEASIBLE($\mathbf{x}^{(k)}$)
 9:         end if
10:         repeat
11:             $k \leftarrow k + 1$
12:             $\mathbf{x}^{(k)} \leftarrow$ APPROXIMATEDNEIGHBORHOODEVALUATION($\mathbf{x}^{(k-1)}$)
13:             if $\mathbf{x}^{(k)}$ is infeasible then
14:                 $\mathbf{x}^{(k)} \leftarrow$ MAKEFEASIBLE($\mathbf{x}^{(k)}$)
15:             end if
16:         until LCC($\mathbf{x}^{(k)}$) $>$ LCC($\mathbf{x}^{(k-1)}$)
17:         if LCC($\mathbf{x}^{(k-1)}$) $<$ LCC($\mathbf{x}^\star$) then
18:             $\mathbf{x}^\star \leftarrow \mathbf{x}^{(k-1)}$
19:             LCC($\mathbf{x}^\star$) $\leftarrow$ LCC($\mathbf{x}^{(k-1)}$)
20:         end if
21:     end while
22:     return $\mathbf{x}^\star$
23: end procedure
```

Figure 2. MULTISTARTLOCALSEARCH Pseudocode

```
 1: procedure MAKEFEASIBLE($\mathbf{x}$)
 2:     while $a(\mathbf{x}) < a_{min}$ do
 3:         if ($\exists(l \in L, o \in O) \mid \rho_{lo} > \rho_{max}$) then
 4:             Add 1 maintenance resource of type $l \in L$ at facility $o \in O$
 5:         end if
 6:         if ($\exists(u \in U) \mid \rho_u > \rho_{max}$) then
 7:             Add 1 transportation resource of type $u \in U$
 8:         end if
 9:         //$\pi_{io}$ : fraction of times in which unavailability is due to the lack of spare
10:         //parts of type $i \in I$ at facility $o \in O$
11:         if ($\exists(i \in I, o \in O) \mid \pi_{io} > \pi_{max}$) then
12:             Add 1 spare part of type $i \in I$ at facility $o \in O$
13:         end if
14:         Update $a(\mathbf{x})$ through simulation
15:     end while
16:     return $\mathbf{x}$
17: end procedure
```

Figure 3. MAKEFEASIBLE Pseudocode

The MAKEFEASIBLE procedure (Figure 3) generates a feasible solution by iteratively adding resources and/or spare parts to an initial infeasible solution. More precisely, at each iteration

the procedure adds resources, choosing the one with the highest utilization rate, among those whose utilization rate exceeds a given threshold ρ_{max}. Analogously, the procedure adds spare parts of components such that the fraction of times in which unavailability is due to the lack of such components at certain facilities is greater than a maximum percentage π_{max}. Then, the availability function is estimated again through simulation, and this procedure is iterated until $a(\mathbf{x}) \leq a_{min}$. As stated before, the local search phase (Figure 2, line 12) is performed by feeding the current solution into the ANE model and, possibly, applying the MAKEFEASIBLE method to its output, in order to recover feasibility.

6 Computational results

In this section, we describe the computational experiments we have performed to validate our approach and to measure its efficiency. As a benchmark, we consider the widely used VARI-METRIC (VM) method. Algorithms are coded in Java, the optimization models are solved by means of IBM ILOG CPLEX 12.3, and the experiments are run on a computer with an Intel Core i5 processor clocked at 2.53 GHz with 4 GB of RAM. For all the experiments we impose a time limit of 50,000 seconds.

Since no benchmark test problems are available, we consider a test case, resembling the maintenance of complex equipments made up of four indenture levels, namely the equipment at level zero, eight components at level one, 40 sub-components at level two, and 225 parts at the last indenture level. We suppose that each part at the last level can fail according to a Poisson process with failure rate randomly generated in [0.5, 3] failures per year. Moreover, we consider a network with four facilities, consisting of two bases (having N_1=10 and N_2=8 equipments, respectively), one intermediate facility, and one depot. The maintenance resources consist in four types of devices ($L = \{1,…,4\}$). We assume that the cost for purchasing each type of resource (in M€) is 4, 5, 1, and 3, respectively. The cost (in M€) of purchasing one spare part of each component is randomly generated in [0.2, 0.4] for components at level one, in [0.02, 0.04] for sub-components at level two, and in [0.002, 0.004] for parts at the last level. The target availability is chosen to be a_{min}=0.9, and the LCC is estimated over a 10 years planning horizon. The transportation resources between the facilities consist in trucks having a cost of 1 M€each, and having variable transportation costs per component (in M€) and inter-facility transportation times (days) uniformly generated in [0.001, 0.004] and [3, 7], respectively. In each simulation experiment, we compute the 95% confidence interval of the expected equipment availability. The number of samples needed to assess the feasibility of a solution is then determined in such a way that the lower bound of such a confidence interval is greater than or equal to a_{min}. The aim of our computational campaign is twofold: first, we compare the performance of our approach, under different settings, when compared to the VM method; second, we focus on a restricted number of settings, and compare them by varying the values of some input parameters.

6.1 Results

In the first part of our experiments, we compare our approach to VM. As pointed out in the previous sections, VM mainly deals with the determination of the spare parts at stock, assuming that the repair decisions are known a priori. Moreover, it does not allow any flexibility in the maintenance network, does not include the possibility of discarding components, and considers an unlimited capacity for the resources. Thus, to allow a fair

comparison between VM and our approach, the VM solution concerning spare parts has been embedded into our simulator, in order to determine the type and quantity of resources needed to meet the target availability.

Then, we have considered a number of ANE-based variants, in which we vary the way we obtain the initial solution and/or the policy we use for taking maintenance decisions. The details for each of such variants, along with the relative acronym we use, are reported in Table 1, whereas Table 2 shows the results of our comparisons over 100 runs, reporting the LCC and the expected availability (AVAIL) of the best solution, as well as the average number of MAKEFEASIBLE iterations needed to obtain the first feasible solution (MF_ITER), the number of local search restarts (LS), the average number of samples used to declare the feasibility or infeasibility of the solutions generated in the search process (SAMPLES), the overall number of neighborhood search iterations (ITER).

Table 1. Details about initial solutions and maintenance policies for the compared methods

Approach	Initial solution	Policy description
ANE_VM	VM	Discarding is not allowed. 50% of the failed components are repaired where the failure occurs, and the remaining 50% is sent to the upper echelon.
ANE_VM_LT	VM	Discarding is not allowed. The facility where to repair a failed component is chosen to guarantee the minimum lead time to perform the operation.
ANE_VM_SP	VM	Discarding is not allowed. The facility where to repair a failed component is chosen on the basis of the number of spare parts available.
ANE_VM_LT_FULL	VM	Discarding is allowed. The facility where to repair a failed component is chosen to guarantee the minimum lead time to perform the operation.
ANE_0_LT_FULL	0 is assigned to each decision variable	Discarding is allowed. The facility where to repair a failed component is chosen to guarantee the minimum lead time to perform the operation.

Table 2. Experimental results considering different settings (LCC in M€)

Approach	LCC	AVAIL	MF_ITER	LS	SAMPLES	ITER
VM	237,652	0.90				
ANE_VM	181,874	0.91	51.32	9.15	8.31	318.26
ANE_VM_LT	122,124	0.92	118.74	9.02	9.77	274.53
ANE_VM_SP	177,563	0.95	12.12	7.12	9.41	311.82
ANE_VM_LT_FULL	109,965	0.93	31.65	8.15	11.98	267.65
ANE_0_LT_FULL	123,574	0.97	45.74	7.27	10.75	296.87

The data reported in Table 2 show that the best results, in terms of LCC, are obtained for the ANE_VM_LT_FULL variant, where the VM solution is used in order to initialize the procedure, and discarding decisions are allowed. However, it is worth noting that the case in which the initial solution is obtained by assigning zero to all the decision variables, followed

by the MAKEFEASIBLE procedure, has generated good quality solutions, ensuring an availability level of 0.97, even better than ANE_VM_LT_FULL. In general, not surprisingly, it can be observed that all ANE-based variants outperform VM. This somehow expected behaviour can be explained as follows: VM decisions are related to spare parts only. Thus, the simulator tends to use a great number of maintenance resources in order to meet the target availability. On the other hand, our approach aims at finding an adequate trade-off between spare parts and maintenance resources, thus generating better quality solutions.

The second part of our experiments concerns the comparison between ANE and VM by using the Taguchi approach (Montgomery, 2009), which utilizes an orthogonal array to optimize the amount of information obtained from a limited number of experiments by varying the levels of some key input parameters. In our case, the input parameters that affect the LCC are grouped into sets involving costs, times, and failure rates. To each set is assigned either a low or a high randomly generated value. Such values are then combined in several ways generating 64 test problems. The details of this experiment, involving VM, ANE_VM, and ANE_VM_LT_FULL are reported in Table 3. More specifically, for each test problem Table 3 shows the LCC achieved by the three approaches, as well as the average percentage relative deviation (DEV) of the best solution provided by ANE_VM on VM, and by ANE_VM_LT_FULL on ANE_VM. The availability values are not reported, because the a_{min} target is always achieved.

The results of Table 3 confirm the superiority of both our ANE variants with respect to VM. Specifically, ANE_VM produces solutions that on average are about 24% better than VM. Moreover, ANE_VM_LT_FULL clearly outperforms both ANE_VM and VM. In particular, ANE_VM_LT_FULL is, on average, approximately 38% better than ANE_VM.

Table 3. Comparison between VM, ANE_VM, and ANE_VM_LT_FULL (LCC in M€)

Instance	VM	ANE_VM		ANE_VM_LT_FULL	
	LCC	LCC	DEV (%)	LCC	DEV (%)
1	449,784	281,063	-37.51	131,521	-53.21
2	231,260	205,499	-11.14	93,243	-54.63
3	648,475	531,519	-18.04	194,445	-63.42
4	274,597	226,268	-17.60	174,878	-22.71
5	397,324	187,932	-52.70	99,988	-46.80
6	333,071	152,629	-54.18	133,477	-12.55
7	590,036	542,844	-8.00	173,164	-68.10
8	464,135	290,288	-37.46	317,472	9.36
9	303,702	157,070	-48.28	55,937	-64.39
10	259,761	245,261	-5.58	158,458	-35.39
11	186,516	148,366	-20.45	68,254	-54.00
12	363,040	258,192	-28.88	121,268	-53.03
13	389,014	237,118	-39.05	128,627	-45.75
14	392,968	372,693	-5.16	214,413	-42.47
15	469,616	428,645	-8.72	312,733	-27.04
16	712,243	690,216	-3.09	651,992	-5.54

Instance	VM	ANE_VM		ANE_VM_LT_FULL	
	LCC	LCC	DEV (%)	LCC	DEV (%)
17	432,986	246,196	-43.14	204,021	-17.13
18	118,693	85,762	-27.74	58,811	-31.43
19	89,453	55,488	-37.97	26,593	-52.07
20	587,566	437,249	-25.58	220,458	-49.58
21	967,510	896,751	-7.31	586,589	-34.59
22	667,598	673,498	0.88	600,189	-10.88
23	211,517	163,366	-22.76	140,058	-14.27
24	251,486	126,345	-49.76	180,404	42.79
25	225,182	179,056	-20.48	83,132	-53.57
26	117,379	78,318	-33.28	27,034	-65.48
27	301,815	212,074	-29.73	113,485	-46.49
28	167,023	138,799	-16.90	90,355	-34.90
29	498,983	302,544	-39.37	155,462	-48.62
30	288,670	275,495	-4.56	113,565	-58.78
31	233,392	224,491	-3.81	148,871	-33.69
32	273,558	230,310	-15.81	130,483	-43.34
33	178,672	163,062	-8.74	73,316	-55.04
34	193,179	170,894	-11.54	67,700	-60.38
35	544,055	428,413	-21.26	336,980	-21.34
36	462,140	251,353	-45.61	147,342	-41.38
37	475,676	424,236	-10.81	183,706	-56.70
38	179,432	149,441	-16.71	44,188	-70.43
39	228,643	151,446	-33.76	59,924	-60.43
40	223,592	132,375	-40.80	154,050	16.37
41	451,425	285,769	-36.70	174,119	-39.07
42	264,109	230,614	-12.68	190,273	-17.49
43	183,089	182,825	-0.14	173,855	-4.91
44	532,038	316,947	-40.43	132,003	-58.35
45	551,448	318,077	-42.32	329,518	3.60
46	64,290	40,452	-37.08	16,942	-58.12
47	272,253	236,883	-12.99	145,228	-38.69
48	432,794	365,716	-15.50	187,339	-48.77
49	794,094	670,813	-15.52	180,581	-73.08
50	653,695	474,524	-27.41	217,406	-54.18
51	639,273	559,690	-12.45	545,508	-2.53
52	211,910	168,726	-20.38	137,538	-18.48
53	605,674	538,706	-11.06	239,266	-55.59

Instance	VM	ANE_VM		ANE_VM_LT_FULL	
	LCC	LCC	DEV (%)	LCC	DEV (%)
54	338,914	289,954	-14.45	221,249	-23.70
55	516,258	352,823	-31.66	100,276	-71.58
56	393,313	348,505	-11.39	213,501	-38.74
57	272,864	145,879	-46.54	152,891	4.81
58	464,523	328,600	-29.26	172,433	-47.52
59	529,424	293,965	-44.47	157,114	-46.55
60	102,787	69,472	-32.41	39,781	-42.74
61	437,707	351,025	-19.80	134,393	-61.71
62	687,002	688,213	0.18	511,603	-25.66
63	231,552	202,533	-12.53	97,452	-51.88
64	240,868	200,210	-16.88	199,166	-0.52
AVERAGE			-23.54		-37.70

7 Conclusions

This paper deals with the problem of designing the logistics support of complex multi-indenture and multi-echelon engineering systems, in order to determine the spare parts stock and the maintenance resources capacity, as well as the level of repair. The goal is to minimize the equipments' expected LCC, while ensuring a target operational availability. The problem has been approached through an optimization via simulation approach employing a heuristic procedure that explores the search space through an ANE method, which is based on the estimation via simulation of a number of parameters. The experimental results reported in the paper have shown the superiority of our approach with respect to the widely used VM method, with average improvements up to 53%, which could result in very consistent LCC savings. Although the proposed approach has not been evaluated in practical contexts, the results achieved are encouraging for further developments along this line of research. For this purpose, future research will be aimed at strengthening the approximations on which the ANE procedure is based and also at making the search process faster for using in real world.

Acknowledgements

References

Alfredsson, P. (1997) 'Optimization of multi-echelon repairable item inventory systems with simultaneous location of repair facilities', *European Journal of Operational Research*, Vol. 99, pp. 584-595.

Barros, L.L. and Riley, M. (2001) 'A combinatorial approach to level of repair analysis', *European Journal of Operational Research*, Vol. 129, No. 2, pp. 242-251.

Basten, R.J., Schutten, J.M.J. and van der Heijden, M.C. (2009) 'An efficient model formulation for level of repair analysis', *Annals of Operations Research*, Vol. 172, No. 1, pp. 119-142.

Basten, R.J., van der Heijden, M.C. and Schutten, J.M.J. (2011a) 'Practical extensions to a minimum cost flow model for level of repair analysis', *European Journal of Operational Research*, Vol. 211, pp. 333-342.

Basten, R.J., van der Heijden, M.C. and Schutten, J.M.J. (2011b) 'A minimum cost flow model for level of repair analysis', *International Journal of Production Economics*, Vol. 133, pp. 233-242.

Basten, R.J., van der Heijden, M.C. and Schutten, J.M.J. (2012) 'Joint optimization of level of repair analysis and spare parts stocks', *European Journal of Operational Research*, Vol. 222, pp. 474-483.

COMPASS (2011) 'COMPASS STAT User's Manual', https://www.logsa.army.mil/lec/downloads/compass/COMPASS%20STAT%20(620)%20User's%20Manual.pdf, Accessed on August 11th, 2013.

Department of Defence, USA (1981) 'Definitions of terms for reliability and maintainability', *Technical Report MIL-STD-721C*.

Diaz, P. and Fu, M.C. (1997) 'Models for multi-echelon repairable item inventory systems with limited repair capacity', *European Journal of Operational Research*, Vol. 97, pp.480-492.

Ghiani, G., Manni, E. and Quaranta, A. (2010) 'Shift scheduling problem in same-day courier industry', *Transportation Science*, Vol. 44, pp. 116-124.

Montgomery, D.C. (2009) *Design and analysis of experiments*, John Wiley & Sons, 7th ed.

Saranga, H. and Dinesh Kumar, U. (2006) 'Optimization of aircraft maintenance/support infrastructure using genetic algorithms - level of repair analysis', *Annals of Operations Research*, Vol. 143, pp. 91-106.

Sherbrooke, C.C. (1968) 'Metric: A multi-echelon technique for recoverable item control', *Operations Research*, Vol. 16, pp. 122-141.

Sherbrooke, C.C. (2004) *Optimal Inventory Modeling of Systems: Multi-Echelon Techniques*, John Wiley& Sons, 2nd ed.

Sleptchenko, A., van der Heijden, M.C. and van Harten, A. (2002) 'Effects of finite repair capacity in multi-echelon, multi-indenture service part supply systems', *International Journal of Production Economics*, Vol. 79, pp. 209-230.

Sleptchenko, A., van der Heijden, M.C. and van Harten, A. (2003) 'Trade-off between inventory and repair capacity in spare part networks', *Journal of the Operational Research Society*, Vol. 54, pp. 263-272.

Systecon AB, (2007) 'Introducing OPUS10', http://www.systecon.se/documents/Introducing_OPUS10.pdf, Accessed on August 11th, 2013.

Zijma ,W.H. and Avşar, Z.M. (2003) 'Capacitated two-indenture models for repairable item systems', *International Journal of Production Economics*, Vol. 81-82, pp. 573-588.

Solving the Value Puzzle of the Customer and Service Provider in Industrial Maintenance Services

Maaren Ali-Marttila*, Leena Tynninen, Salla Marttonen and Timo Kärri

Department of Innovation Management
Lappeenranta University of Technology
P.O.Box 20
FIN-53851 Lappeenranta
Finland
*Corresponding author: Maaren Ali-Marttila
e-mail: maaren.ali-marttila@lut.fi
e-mail: leena.tynninen@lut.fi
e-mail: salla.marttonen@lut.fi
e-mail: timo.karri@lut.fi

Abstract

To maximize the total value in a maintenance business relationship it is important to know what the partner values. The value of maintenance service can be considered to consist of value elements, and the perceived total value for the customer and service provider is the sum of these value elements. The specific objectives of this paper are to identify the most important value elements for the maintenance service customer and provider and also to recognize where the value elements differ. The data has been collected by an online survey sent to 345 maintenance service professionals in Finland. In the survey, four different types of value elements were considered: the customer's high critical and low critical items and the service provider's core and support service. The most valued elements by the respondents were reliability, safety at work, environmental safety, and operator knowledge. Statistically significant differences in value elements between service types were also found.

Key words: value, value element, maintenance, customer, service provider

1 Introduction

Value, adding value and shared value in services have been a major focus in service literature and are often highlighted to the customers and providers. However, the definitions of value are vague. *Customer value* is generally defined as the tradeoff between the give (sacrifices) and get (benefits) components (Zeithaml, 1988). The benefits can include for example quality, whereas price can be seen as a sacrifice (Dumond, 2000). Customer value can also be viewed as customer desired value and customer perceived value, where the desired value is what the customer wants to receive and the perceived value what has happened (Flint et al., 1997). Customer value can also be split into perceived value and exchange value, where the exchange value is the amount the customer is prepared to pay for the service (Ramsay, 2005). *Supplier value* is seen as the benefit the supplier receives from acting with the customer, for example profit (Purchase et al., 2009; Ramsay and Wagner, 2009). The marketing literature

focuses mainly on the customer, and supplier value is hence studied notably less than customer value (e.g. Purchase et al., 2009; Ramsay and Wagner, 2009). In addition, relationship value has been studied because value is created more and more in collaborative relationships (Smals and Smits, 2012; Ulaga, 2003). For a customer and service provider, the creation of value can be considered as essential when engaging in a collaborative relationship (Walter et al., 2001). Payne (2006) explains that the *value creation* process consists of what value the customer receives, what value the service provider receives, and how the value exchange can be successfully managed to maximize the received total value.

Service value can be considered to consist of value elements (e.g. price, flexibility and quality), and value is created with the right combination of these elements. Value can also be considered to be equal to the sum of all future cash flows discounted to today. For example in maintenance this would mean the future cash flow from asset utilization, cost control, resource allocation and the SHE (safety, health and environment) factors (Jonker and Haarman, 2006). From the point of view of industrial maintenance, there is relatively little literature considering its value or value elements, and this strengthens the need to formulate and assess the value of maintenance services based on customer collaboration (Ojanen et al., 2012; Tynninen et al., 2012).

In this paper we aim at solving the value puzzle of the customer and service provider of maintenance services by identifying the most valued elements for each party. Figure 1 presents the idea how value can be created by profiling the value elements and the intended win-win situation. In addition to value creation, the win-win situation is highlighted because it is essential that both parties gain benefits from the provided maintenance service. In order to improve the competiveness of the relationship, the organizations need to understand what elements create value in maintenance service collaboration (Lapierre, 2000).
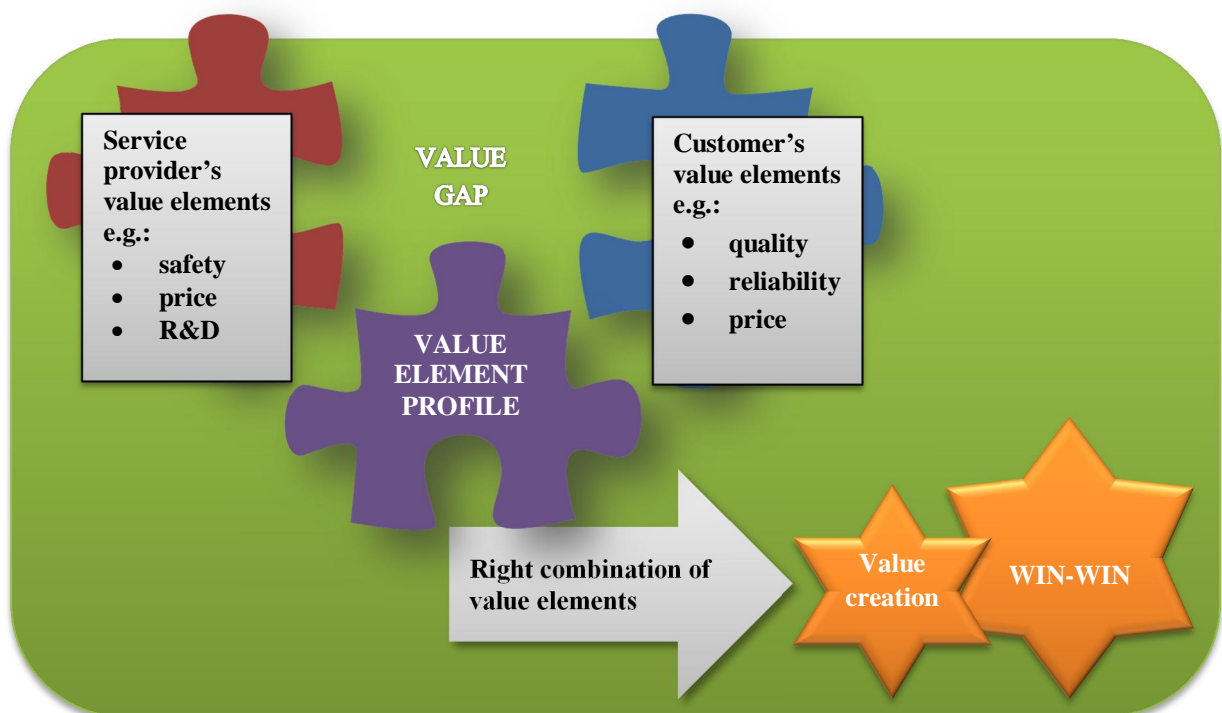

Figure 1. Value creation in maintenance services with the help of value elements

Many companies have outsourced their maintenance services wholly or partially, and this underlines the need to evaluate the value of maintenance services and contracts to avoid disagreement and inadequate performance (Kumar et al., 2006; Tynninen, 2012). The value discussion is important also from the service provider's point, so that the provider is able to price the services correctly and develop trust between the parties based on common understanding of the value creating elements (Ojanen, 2012). With the value element approach we offer one way to find out how the value of industrial maintenance services is modeled and created for each partner. The specific objective of this paper is: *To identify the most important value elements of industrial maintenance from the service customer's and service provider's perspective, and find out the differences between the parties.*

The paper is structured as follows. First the theory and the hypotheses are described. Then the research methodology is described in detail. Next the achieved results are shown and discussed. Finally, a summary of the paper and conclusions with future research objectives are presented.

2 Theory and hypotheses

In this paper we use the term value elements of maintenance services as presented by Ojanen et al. (2012). When defining and discussing value and finding the value-creating areas, the term value element offers a suitable perspective to value. The total value of maintenance service can be considered to be the sum of the value elements.

There is not much literature considering the value and value elements of industrial maintenance services. Value has been considered more in b-to-c businesses, and the focus in the value literature concerning services has been on the customer side (Purchase et al., 2009; Ramsay and Wagner, 2009). When articles related to the value elements of services were reviewed, 14 articles considering the customer view and only 4 articles considering the supplier view were found (Tynninen et al., 2012). None of the reviewed articles considered the value elements of industrial maintenance services. Komonen et al. (2007) have not directly researched value or the total value of a maintenace network but they have researched especially customer and supplier satisfaction in industrial maintenance, and how customer and job satisfaction are related to each other. Their research supports that maintenance service value can be considered as summed elements because they also recognized different dimensions and groups of maintenace operations that concluded in customer and job satsifaction (e.g. quality of operations, professional skills, cost level and orderliness).

To get a starting point for the possible value elements of industrial maintenance, Tynninen et al. (2012) gathered the value elements suitable for industrial maintenance services from the reviewed service literature. Then the recognized elements were discussed and modified in a workshop of company representatives as Sinkkonen et al. (2013) describe. The idea was to test if the value elements of the literature research were even close to the ones the operators consider as value elements of industrial maintenance service.

2.1 Indusutrial maintenance service customer's value elements

Price, technical quality, dependability, contracts, relationship, reliability, flexibility, reputation of the service provider, accessibility, asset management factors, total solutions, and sustainability were chosen as the industrial maintenance service customer's value elements.

After the workshop Sinkkonen et al. (2013) presented safety at work and environmental safety as new elements in addition to the preliminary list Tynninen et al. (2012) had made. Adding safety to the list makes sense, because the impact of maintenance work on safety issues comes up repeatedly in maintenance literature (e.g. Gulati, 2009; Järviö et al., 2007; Márquez, 2007). Also the increased amount of outcourcing emphasizes the safety at work -element in procurement situations (EU-OSHA, 2012; Lind et al., 2008).

The value elements of the customer can be reviewed also from a more specific view at the item level, comparing the value elements from the point of a high critical and a low critical item. At the operational level in maintenance planning, item criticality has to be categorized to make sure how the maintained items have to be prioritized and that the right maintenance method is identifyed (Márquez, 2007). The items can be categorized with a criticality matrix where item criticality is presented as depending on the failure freguency of the item and the severity of failure or fault (SFS-EN 13306, 2010). For example a critical pump can be considered as a critical item, and the maintenance should focus on continous condition-based maintenance. Conversely, the maintenance of the company garden can be considered as a low critical item and the maintenance strategy could be weekly predetermined maintenance. These different maintenance methods will also affect the value elements higlighted in each situation. For example with a high critical item, availability could be the most important value element, while for a low critical item it could be price (Tynninen et al. 2012). Also the workshop results suggested that there would be differences in the most important value elements depending on item criticality and occasion (Sinkkonen et al., 2013). Based on the literature and workshop results it is predicted that the value elements of the customer differ according to the item criticality, and we posit

Hypothesis 1: The customer's value elements differ depending on the item criticality.

2.2 Industrial maintenance service provider's value elements

As the maintenance service provider's value elements Tynninen et al. (2012) suggest price, flexibility, reliability, contracts, relationship, total solutions, operator knowledge, availability, asset management factors, access to market, reputation of customer and R&D. In the workshop also safety at work, service ability and orderliness were presented as elements (Sinkkonen et al., 2013). To be successful in marketing, service providers need to differentiate their service offerings through people and processes that add value, in other words, choose the right value elements. When the customer is correctly assessed, the maintenance service company can offer customized services to each customer and at the same time increase the revenues of the company (Liang, 2010). The theory also suggests that companies that create superior customer value and regularly introduce innovations in service offerings will gain competitive advantage over their competitors (Guenzi and Troilo, 2007; Kotler and Keller, 2012).

Like the value elements of the customer, also the value elements of the service provider can be analyzed from a more specific view when comparing the value elements of core and support services. Grönroos (2000) notes that for managerial reasons, services should be distinguished into three groups: core, facilitating and support services. The core service is the service for which the company is on the market. Facilitating services are the services customers need to use the core service, for example a bank card for an ATM. Support services, on the other hand, are services that are not essential for the company but are used to increase the value of the service or to differentiate the service from competitors' service offerings. However, for this paper we consider core and support services to be a wide enough

separation to see possible differences in the value elements of maintenance service providers. In industrial maintenance services a core service could be for example mechanical maintenance, and a support service would be gardening outdoors. According to Sinkkonen et al. (2013), differences between the core and support service elements of the service provider were recognized, but the differences were not as clear as with the item criticality. Based on the theory we suggest

Hypothesis 2: The service provider's value elements differ between core and support service.

2.3 Differences between industrial maintenance service customer's and service provider's value elements

For example Smith et al. (2012) emphasize that value should always be considered from both sides, how much value can be derived by a company from its customers and also the derived value to the customers from the company. Value also depends upon the participants' perceptions, and even though the companies may work in a network, each of the customers and suppliers have their own motivations, problems and strategies (Ford and McDowell, 1999). This, in addition to the vague definition of value, results in versitile value element listings. In order to create value and improve the competeiveness of the maintenance service relationship, the customer and the service provider need to understand what elements create value for each party (Lapierre, 2000).

As presented above as well as by Sinkkonen et al. (2013), when the item criticality and provided service are discussed, there are some significant differences in the listings when comparing the customer and the service provider. For example the service providers do not list environmental safety or asset management factors as value elements like the customers do. It seems that the value elements are partly similar, partly different between the customer and the service provider, but also depend strongly on the occasion, and therefore we posit as our concluding hypothesis

Hypothesis 3: There are differences (a value gap) between the customer's and the service provider's preferred value elements.

3 Research methodology

Because no previous research was found considering the value elements of industrial maintenance services, the survey method was chosen to test and identify value elements. The final elements used in the survey were chosen on the basis of the preliminary study of Tynninen et al. (2012) and Sinkkonen et al. (2013) (Appendix A). The identification of the most important value elements for the customer and service provider in industrial maintenance services and their differences are the primary objective of this study, and are part of a wider research project MaiSeMa (Industrial Maintenance Services in a Renewing Business Network: Identify, Model and Manage Value).

3.1 Sample

In Finland, outsourcing has increased the demand for industrial maintenance services, and nowadays maintenance is a significant industry (Hatinen et al., 2012). Due to the developed and organized maintenance industry, Finland is a good testing ground for value element research. An online-survey link was sent to 345 Finnish industrial maintenance professionals.

The primary source for the contacts was the Finnish Maintenance Society Promaint, which is an important nationwide actor and has a diverse network of corporations in the maintenance field. The survey was conducted between January-March 2013, and the contact persons received two reminders after the first message. 83 completed questionnaires were received, representing a response rate of 24%. 32 responses were received from maintenance customers and 51 from maintenance suppliers.

The most common position (56%) of the respondent was working in middle management, for example as a maintenance manager, 21% of the respondents represented top management, and the rest (23%) represented mainly consultants and supervisors. In the responder group, 39% represented large companies (over 250 workers), and thus the majority represented small or middle sized companies. The customer side represented mainly the industrial goods and services industry (69%), but also the electricity, gas and heating industry (15%). None of the customers executed the maintenance services wholly by themselves. The service providers represented mainly mechanical maintenance (58%) and electricity (33%), or a combination of different maintenance types.

3.2 Survey instrument

Because value can be interpreted in many ways, in the survey instrument the 16 tested value elements were decided to represent two propositions each (shown in Appendix A). The customer and service provider were thus asked to value 32 propositions on a five-point Likert scale with end points of " strongly disagree" (=1) to "strongly agree" (=5). The customers responded first considering a high critical item to be maintained and after that the same claims were presented for a low critical item to be maintained. To be able to compare the differences of the customer and the service provider it was decided to present the same value elements and claims for both sides in the questionnaire, and so the service provider responded to the same propositions but considering a core service and support service it provided to the customers. It was emphasized to the service provider to respond from their own point of view, not the customer's. The survey instrument was pre-tested by a panel of experts which consisted of company representatives participating in the MaiSeMa-research project.

3.3 Data analysis

The data in the survey sample was not normally distributed, and therefore the non-parametric tests Mann-Whitney U and Wilcoxon were used to examine the statistically significant differences in the value elements (Devore and Berk, 2012). The reliability of the sum variables was tested by computing the Cronbach's alpha. The values were mainly above the recommended 0.700 or close to it, which indicates that the sum variables were reliable and could be used for further analysis with some regard (Cortina, 1993).

4   Results and discussion

4.1 Results regarding the customer's value elements

Descriptive statistics and the results of the Wilcoxon test between the high critical and low critical items can be seen in table 1. For the critical items the customers ranked as the most important value elements *reliability, safety at work, environmental safety, operator knowledge, price, and technical quality,* which all had means above 4.2. The lowest scores

with means below 3.0 were given to R&D, access to markets and asset management factors. When considering the low critical items to be maintained, the customers valued most *environmental safety, safety at work, operator knowledge, reliability, and price.* The value elements with the lowest means were asset management factors, R&D and access to markets.

Table 1. Value elements depending on item criticality (HCI= High critical item, LCI=Low critical item)

Value element	α HCI	Mean HCI	SD HCI	Rank HCI	α LCI	Mean LCI	SD LCI	Rank LCI	Z score/sig.level	Hypothesis 1
Availability	0.798	4.11	1.10	9	0.455	3.76	0.80	11	-2.102/0.036*	Supported
Safety at work	0.407	4.45	0.58	2	0.696	4.41	0,67	2	-0.618/0.537	Not supported
Environmental safety	0.816	4.39	0.76	3	0.819	4.45	0.64	1	-0.479/0.632	Not supported
Technical quality	0.874	4.26	0.85	6	0.821	4.03	0.95	7	-2.385/0.017*	Supported
Flexibility	0.563	4.09	0.67	10	0.384	3.76	0.69	11	-2.226/0.026*	Supported
Reliability	0.656	4.55	0.49	1	0.737	4.21	0.80	4	-2.644/0.008**	Supported
Operator knowledge	0.830	4.31	0.67	4	0.751	4.29	0.66	3	-0.534/0.593	Not supported
Orderliness	0.667	4.13	0.82	8	0.890	3.77	1.17	10	-2.067/0.039*	Supported
Reputation	0.596	4.18	0.54	7	0.881	4.02	0.78	8	-1.907/0.057	Not supported
Relationship	0.923	3.98	0.87	11	0.803	4.05	0.87	6	-0.087/0.931	Not supported
Contracts	0.700	3.87	0.88	12	0.545	3.84	0.80	9	-0.378/0.706	Not supported
Total solutions	0.714	3.72	0.89	13	0.294	3.68	0.77	13	-0.383/0.701	Not supported
R&D	0.813	3.22	1.01	14	0.959	2.50	1.01	15	-3.089/0.002**	Supported
Price	0.327	4.27	0.64	5	0.682	4.20	0.77	5	-0.915/0.360	Not supported
Access to markets	0.907	3.06	1.13	15	0.912	2.45	1.10	16	-3.593/0.000***	Supported
Asset mgmt. factors	0.698	2.53	1.13	16	0.674	2.69	1.11	14	-0.793/0.428	Not supported

2-tailed test *p < 0.05, ** p < 0.01, *** p < 0.001, SD=Standard deviation

As can be seen in the table, when comparing the high and low critical items, the survey results support the idea that there are differences between the value elements. It is interesting to see that with the high critical items, reliability is valued even higher than safety at work. Overall safety is valued very high, though, and it seems that companies value the safety risk assessment methods that also Lind et al. (2008) emphasize. For the high critical items, the value elements have substantially higher means. This is understandable because a high critical item is something that can stop the whole production, so the maintenance strategy is overall valued more for a high critical item than for a low critical item (Järviö et al., 2007; Márquez, 2007).

Statistically significant differences (p<0.05) between the value elements based on the Wilcoxon test can be seen in availability, technical quality, flexibility, reliability, orderliness, R&D, and access to markets. Of all the statistically differentiating value elements, the customers valued higher the element of the high critical maintenance items than of the low critical items. This confirms the assumption that item criticality affects the importance and prioritizing of maintenance strategy (Márquez, 2007). Because Hypothesis 1 is supported in almost half of the value elements and there are recognizable differences in what the customers value within a high critical item versus a low critical item, it can be stated that the value elements differ depending on item criticality, and this should be considered when profiling the value elements. It is also important that the service provider sees the difference to make the right offering for each item to be maintained and be successful, as Liang (2010) suggests.

4.2 Results regarding the service provider's value elements

The descriptive statistics and the results of Hypothesis 2 testing done by Wilcoxon relating the value elements of core and support services are presented in table 2. The service providers rated the highest in core services *operator knowledge, reliability, safety at work, technical quality, environmental safety, and price*, which all had mean values 4.40 or higher. The service providers valued least in core services flexibility, access to markets, R&D, and asset management factors. They all had means above 3.30, so still quite high. When looking at the support services, the providers rated highest *safety at work, reliability, operator knowledge, environmental safety, and technical quality*. The least valued elements were flexibility, access to markets and asset management factors.

Table 2. Value elements depending on provided service (CS=Core service, SS=Support service)

Value element	α CR	Mean CS	SD CS	Rank CS	α SS	Mean SS	SD SS	Rank SS	Z score/sig.level	Hypothesis 2
Availability	0.672	4.26	0.74	9	0.639	4.32	0.62	7	-1.306/0.192	Not supported
Safety at work	0.602	4.60	0.44	3	0.730	4.53	0.53	1	-0.708/0.479	Not supported
Environmental safety	0.682	4.43	0.59	5	0.877	4.48	0.61	4	-0.443/0.658	Not supported
Technical quality	0.793	4.48	0.56	4	0.916	4.47	0.67	5	0.000/1.000	Not supported
Flexibility	0.440	3.98	0.75	13	0.676	3.98	0.75	14	0.000/1.000	Not supported
Reliability	0.502	4.63	0.46	2	0.555	4.52	0.51	2	-1.882/0.060	Not supported
Operator knowledge	0.678	4.65	0.47	1	0.812	4.52	0.61	2	-2.072/0.038*	Supported
Orderliness	0.801	4.26	0.78	9	0.791	4.20	0.72	10	-0.291/0.771	Not supported
Reputation	0.628	4.28	0.57	8	0.674	4.28	0.56	8	-0.759/0.448	Not supported
Relationship	0.758	4.39	0.61	7	0.785	4.33	0.66	6	-0.041/0.967	Not supported
Contracts	0.429	4.19	0.62	11	0.382	4.05	0.71	12	-1.148/0.251	Not supported
Total solutions	0.586	4.08	0.78	12	0.767	4.11	0.85	11	-0.186/0.852	Not supported
R&D	0.799	3.93	0.82	15	0.865	4.00	0.87	13	-0.041/0.967	Not supported
Price	0.580	4.40	0.59	6	0.497	4.27	0.63	9	-0.984/0.325	Not supported
Access to markets	0.812	3.94	0.85	14	0.889	3.87	0.98	15	-1.040/0.298	Not supported
Asset mgmt. factors	0.352	3.35	0.70	16	0.584	3.30	0.98	16	-0.447/0.655	Not supported

2-tailed test *p < 0.05, ** p < 0.01, *** p < 0.001, SD=Standard deviation

Based on the theory, we predicted that the core and support services would differ, and overall there were differences in the ranking of value elements between the core and support services, but they were minor and the most important and least valued elements were almost identical. That there were only minor differences was also supported by the Wilcoxon test. The only statistical significant difference (p<0.05) was in operator knowledge. A potential reason comes up when looking at the survey respondents' open-ended responses. Only a few of the respondents had differentiated the core and support services from each other. It seems that the clear definition in theory had not yet reached the practice.

4.3 Results regarding the differences between the customer's and service provider's value elements

The identification of the differences between the maintenance service customer's and service provider's value elements was executed by comparing how the preferred value elements differed when the service provider would wish to maintain the customer's high and low critical items with its core service. Comparison of the provider's support service and customer's preferred value elements was left out because there were no statistically

significant differences between the service provider's core and support services and also the respondents' separation between the services was questionable. Table 3 shows the Mann-Whitney U test scores and the test results concerning hypothesis 3.

Hypothesis 3 is supported (p<0.05) when comparing the customer's critical items and service provider's core services in operator knowledge, relationship, total solutions, R&D, access to markets, and asset management factors. When the customer's low criticality items and service provider's value elements are compared, there are in addition statistically significant differences (p<0.05) in availability, technical quality and reliability. There are statistically significant differences especially when considering the customer's low criticality items and the service provider's core services. Compared to the customer, the service provider values the different value elements substantially higher. The service providers did not value any elements under 3.30, and for example one of the least valued elements, asset management factors, was still valued notably higher than at the customers' side (3.35 versus 2.54).

Table 3. Value element differences between the customer and the service provider

Value element	Z score/sig.level when comparing the differences between the high critical item and core service	Hypothesis 3	Z score/sig.level When comparing the differences between the low critical item and core service	Hypothesis 3
Availability	-0.295/0.768	Not supported	-3.225/0.001**	Supported
Safety at work	-1.000/0.317	Not supported	-0.972/0.331	Not supported
Environmental safety	-0.166/0.868	Not supported	-0.972/0.331	Not supported
Technical quality	-0.871/0.384	Not supported	-2.118/0.034*	Supported
Flexibility	-0.811/0.418	Not supported	-1.390/0.165	Not supported
Reliability	-0.731/0.465	Not supported	-2.442/0.015*	Supported
Operator knowledge	-2.539/0.011*	Supported	-2.587/0.010*	Supported
Orderliness	-0.752/0.452	Not supported	-1.656/0.098	Not supported
Reputation	-0-756/0.450	Not supported	-1.320/0.187	Not supported
Relationship	-2.082/0.037*	Supported	-1.645/0.100	Not supported
Contracts	-1.435/0.151	Not supported	-1.878/0.060	Not supported
Total solutions	-1.903/0.057	Supported	-2.250/0.024*	Supported
R&D	-3.090/0.002**	Supported	-6.743/0.000***	Supported
Price	-0.804/0.422	Not supported	-1.037/0.300	Not supported
Access to markets	-3.544/0.000***	Supported	-5.251/0.000***	Supported
Asset mgmt. factors	-3.804/0.000***	Supported	-3.336/0.001**	Supported

2-tailed test *p < 0.05, ** p < 0.01, *** p < 0.001

The biggest value gaps seem to be in the least valued elements R&D, access to markets and asset management factors, and the difference is also supported statistically. The low valuation of R&D was expected at least from the customer side, because R&D in industrial services has many contract-related issues and cooperation is considered complicated (Panesar and Markeset, 2008). In the service providers' side this was slightly surprising, because in the workshop it was discussed to be one of the most important value elements in support services (Sinkkonen et al. 2013). To be able to gain competitive advance it would be important for the customer and service provider to work on this value gap and identify innovation activities that would create value for both parties (Guenzi and Troilo, 2007; Kotler and Keller, 2012).

The low score of asset management is also interesting, because asset management has been emphasized in current research and it has been shown that with asset management the customers and service providers can affect the company's operation and capital greatly (Kärri, 2007; Ojanen et al., 2012). The service providers seemed to have recognized this slightly

better than the customers, at least they valued it with a notably higher score. The low level of top manager respondents probably had some influence on the score because normally top managers have a broader view of total asset management within the company than middle managers.

4.4 Value element profile

There were a lot of strong correlations (above 0.700) within the value elements at all levels and no new elements were suggested in the answers to the open-ended questions. This supports the view that the presented value elements can be considered at some levels as industrial maintenance service value elements, and that the value of maintenance services would consist of a value element package. It can also be seen that there are differences between the value elements of the customer and the service provider not only in ranks but also statistically. Especially in b-to-b relations the differences show more clearly because the deviations are not evened out as in this kind of a survey sample. Like Tynninen et al. (2012) suggest, there is a need for a value element profile that the service provider and the customer can use to recognize differences in their value elements while making contracts and measuring the service. With the value element profile, the identification of the right value elements for each situation is made more concrete for the managers. Also the expected benefits and value can be made clear in the total offer for the customer (Payne, 2006). The service provider would work as a co-creator of value, like Grönroos (2008) emphasizes.
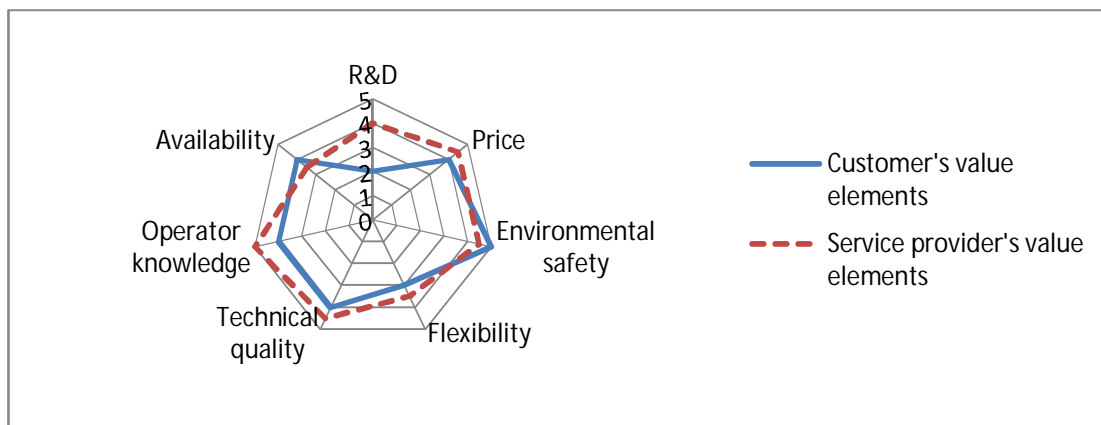
Figure 2. Draft of the value element profile for identifying the right value elements and the "value gap"

In practice the customer and service provider would go through the different value elements in different situations and rank the values according to their importance for them. Then the responses would be reviewed and the most differing elements chosen and put into a radar diagram (figure 2). Then the maintenance service customer and service provider would recognize where the biggest gaps are, and they could negotiate about these key differences more specifically before making the final contract, and also consider this in the overall decision making, for example pricing related to improved safety or possible R&D cooperation in exchange for better technical quality. In the best scenarios this would result in a situation where both parties would gain more value of the contract than originally expected. The organizations would understand what elements create value in the maintenance service collaboration (Lapierre, 2000), and this would result in a win-win situation where the overall value of the relationship would grow and also the competitiveness of the relationship would improve. It should not be forgot, however, that contract-related issues are complicated and require openness and mutual trust (Panesar and Markeset, 2008; Rekola and Haapio, 2009).

5 Conclusions and suggestions for future research

The objective of this paper was to identify the most important value elements from the customer's and service provider's perspective, and to find the differences between the parties of industrial maintenance services as well. Overall, all the suggested value elements got quite high valuations with means between 3.0 and even 4.60 (not agreeing nor disagreeing to strongly agreeing), so they can be considered to be elements that at least somehow affect the experienced value of maintenance services. It also shows that value is constituted of different elements. On the basis of the survey results, there are clearly maintenance service value elements that arise above others in all categories, namely reliability, safety at work, environmental safety, and operator knowledge. Also technical quality and price were rated high. On the other hand, there were also value elements that were constantly rated as less important value elements in all categories. These were access to markets, asset management factors and R&D. Especially the low valuation of asset management factors was surprising, because there has been a lot of discussion and research regarding the importance of asset management factors, but it seems that the customers and service provides have not yet understood their profit potential. Overall, comprehensive value elements like total solutions, asset management factors, access to markets, and R&D were rated lower. The possible win-win potential and development of these elements should be emphasized.

The survey results suggested also that there are differences between the value elements of the customer and the service provider, and also different situations affect the value elements preferred. The statistically significant differences were not as great as expected on the basis of theory, but because there were at least some statistical differences in a big population like this, in business-to-business relations the differences are probably even greater because the means are not evened out. As in negotiation situations the differences play a great role, it is convenient to develop a value element profile to recognize the differences. For example if the service provider rates operator knowledge as the most important value element and the customer places it as the fourth element, there are three elements that the customer values higher than the service provider. When the service provider is aware of this difference, they can pay attention to this and provide the best combination of value elements, and make a better offer.

The paper contributes to the value discussion of industrial maintenance services and provides value elements that can be considered as the value elements of industrial maintenance services. Until now there has been a lack of knowledge about the specific value elements concerning the industrial maintenance service customer and service provider. The paper also points out that there are differences in maintenance service value elements that should be considered in negotiations. The paper also provides a first draft of a value element profile, which could be used in negotiation situations. It provides a method for assessing value and making it more concrete for the customer and the service provider by visualizing a possible gap in the value elements of the customer and the service provider. By closing the gap, the customer and the service provider can reach their maximum value creation potential, and an overall win-win situation in the cooperation can be reached. Of course profiling the value elements would require openness and interest in honest cooperation.

There are also limitations in the study that should be taken into account in future research. The mean values and sum variables had a high weight in this paper to get an overall view of the situations, but for future research also the value elements should be reviewed in closer

detail because in some cases Cronbach's alpha was considerably low. Possible dividing and regrouping of elements should be considered. Also correlations received little attention because the focus was on finding differences. But because there was a great amount of significant correlations, it would be interesting to test the correlations further and also make a factor analysis to see whether some value elements could be merged.

A major future research target is the building and focusing of the maintenance service value framework based on the value element profile. The framework should be studied in different situations, like preventive and corrective maintenance, and also specified for different customers, for example according to size or maintenance service area. Later the framework could be added with weights to the life-cycle model developed by Sinkkonen et al. (2013) and also included in service offering discussions and presented as a comprehensive manager tool.

References

Cortina, J. M. (1993) 'What is coefficient alpha? An examination of theory and applications', *Journal of Applied Psychology,* Vol. 78, No. 1, pp. 98-104.

Devore, J. L. and Berk, K. N. (2012) *Modern Mathematical Statistics with Applications,* 2nd edition, New York, NY: Springer New York.

Dumond, E. (2000) 'Value management: an underlying framework', *International Journal of Operations & Production Management,* Vol. 20, No. 9, pp. 1062-1077.

EU-OHS (2012) 'Procurement of maintenance services and health and safety at work', *E-fact 63,* Available at: https://osha.europa.eu/en/publications/e-facts/e-fact-63-procurement-of-maintenance-services-and-health-and-safety-at-work.

Flint, D., Woodruff, R. and Gardial, S. (1997) 'Customer value change in industrial marketing relationships: A call for new Strategies and research', *Industrial Marketing Management,* Vol. 26, No. 2, pp. 163-175.

Ford, D. and McDowell, R. (1999) 'Managing business relationships by analyzing the effects and value of different actions', *Industrial Marketing Management,* Vol. 28, No. 5, pp. 429-442.

Guenzi, P. and Troilo, G. (2007) 'The joint contribution of marketing and sales to the creation of superior customer value', *Journal of Business Research,* Vol. 60, No. 2, pp. 98-107.

Gulati, R. (2009) *Maintenance and reliability best practices: with contributions by Ricky Smith,* New York: Industrial Press.

Grönroos, C. (2000) *Service management and marketing: a customer relationship management approach,* Chichester: Wiley.

Grönroos, C. (2008) 'Service logic revisited: Who creates value? And who co-creates?'; *European Business Review,* Vol. 20, No. 4, pp. 298-314.

Hatinen, L., Pirttilä, M., Viskari, S. and Kärri, T. (2012) 'The investment logics of Finnish industrial maintenance service providers', *International Journal of Strategic Engineering Asset Management*, Vol. 1, No. 1, pp. 33–48.

Jonker, R. and Haarman, M. (2006) 'Value Driven Maintenance: What is the actual added value of maintenance?', *Uptime Magazine,* Nov. 06, Available at: http://www.reliabilityweb.com/art07/value_driven_maintenance_uptime.pdf.

Järviö, J., Piispa, T., Parantainen, T. and Åström, T. (2007) *Maintenance,* Helsinki: KP-Media. (In Finnish)

Komonen, K., Suominen, S. and Kupi, E. (2007) 'Interaction between customer satisfaction, server satisfaction and effectiveness within industrial maintenance, *Conference proceedings, The 2nd World Congress on Engineering asset Management,* June, 11-14, 2007, Harrogate, UK.

Kotler, P. and Keller, K. L. (2012) *Marketing Management,* 14th edition, Harlow: Pearson Education.

Kumar, R., Markeset, T. and Kumar, U. (2006) 'Implementation and execution of industrial service strategy. A case study from the oil and gas industry', *Journal of Quality in Maintenance Engineering,* Vol. 12, No. 2, pp. 105-117.

Kärri, T. (2007) *Timing of Capacity Change: Models for Capital Intensive Industry,* Acta Universitatis Lappeenrantaensis 287, Dissertation, Lappeenranta University of Technology, Finland.

Lapierre, J. (2000) 'Customer-perceived value in industrial contexts', *Journal of Business & Industrial Marketing,* Vol. 15, No. 2, pp. 122-145.

Levery, M. (1998) 'Outsourcing maintenance – a question of strategy', *Engineering Management Journal*, Vol. 8, No. 1, pp. 34-40.

Liang, Y. (2010) 'Integration of data mining technologies to analyze customer value for the automotive maintenance industry', *Expert Systems with Applications,* Vol. 37, No. 12, pp. 7489-7496.

Lind, S., Nenonen, S. and Kivistö-Rahnasto, J. (2008) 'Safety risk assessment in industrial maintenance' *Journal of Quality in Maintenance Engineering*, Vol. 14, No. 2, pp. 205-217.

Márquez, A. C. (2007) *The maintenance management framework: Models and methods for complex systems maintenance. -* Springer series in reliability engineering*,* London: Springer-Verlag.

Ojanen, V., Hatinen, L., Kärri, T, Kässi, T. and Tuominen, M. (2012), 'Flexible investment planning and collaborative maintenance management' in: van der Lei, T., Herder, P. and Wijnia, Y. (Eds.). *Asset Management: The State of Art in Europe from a Life Cycle Perspective*, Dordrecht, Springer, pp. 65-77.

Panesar, S.S. and Markeset, T. (2008) 'Industrial service innovation through improved contractual relationship', *Journal of Quality in Maintenance Engineering,* Vol. 14, No. 3, pp. 290-305.

Payne, A. (2006) *Handbook of CRM: Achieving excellence in customer management,* Oxford: Elsevier, 438 p.

Purchase, S., Goh, T. and Dooley, K. (2009) 'Supplier perceived value: Differences between business-to-business and business-to-government relationships', *Journal of Purchasing & Supply Management,* Vol. 15, No. 1, pp. 3-11.

Ramsay, J. (2005) 'The real meaning of value in trading relationships', *International Journal of Operations & Production Management,* Vol. 25, No. 5, pp. 549-565.

Ramsay, J. and Wagner, B. (2009) 'Organisational supplying behavior: Understanding supplier needs, wants and preferences', *Journal of Purchasing & Supply Management,* Vol. 15, No. 2, pp. 127-138.

Rekola, K. and Haapio, H. (2009) *Industrial Services and Service Contracts: A Proactive Approach,* Helsinki: The Federation of Finnish Technology Industries.

SFS-EN Std. 13306. (2010) *Maintenance*, *Maintenance terminology*, Finnish Standard Association SFS, 53 p.

Sinkkonen, T., Kivimäki, H., Marttonen, S. and Kärri, T. (2013) 'A value-based life-cycle framework for networks of industrial maintenance services', *The 26th International Congress of Condition Monitoring and Diagnostic Engineering Management*, June 11-13, 2013, Helsinki, Finland.

Smals, R. and Smits, A. (2012) 'Value for value-The dynamics of supplier value in collaborative new product development', *Industrial Marketing Management,* Vol. 41, No. 1, pp. 156-165.

Smith, L., Ng, I. and Maull, R. (2012) 'The three value proposition cycles of equipment-based service', *Production Planning & Control: The Management of Operations,* Vol. 23, No. 7, pp. 553-570.

Tynninen, L., Sinkkonen, T., Marttonen, S. and Ojanen, V. (2012) 'Framework for the value elements of maintenance services', *The 2nd International congress on Maintenance Performance Measurement & Management,* September 12-13, 2012, Sunderland, UK.

Ulaga, W. (2003) 'Capturing value creation in business relationships: A customer perspective', *Industrial Marketing Management*, Vol. 32, No. 8, pp. 677-693.

Walter, A., Ritter, T. and Gemunden, H.G. (2001) 'Value creation in buyer-seller relationships: Theoretical considerations and empirical results from a supplier's perspective', *Industrial Marketing Management,* Vol. 30, No. 4, pp. 365-377.

Zeithaml, V. (1988) 'Consumer perceptions of price, quality, and value: A means-end model and synthesis of evidence', *Journal of Marketing*, Vol. 52, No. 3, pp. 2-22.

Appendix A

Appendix A shows the proposed value elements and defining propositions based on the previous literature research of Tynninen et al. (2012) and the workshop results of Sinkkonen et al. (2013).

Availability: 1. The target of the maintenance work functions as expected, its maintainability and repair is easy. 2. The users look after their part of the in use maintenance operations and enhance the maintainability of the item.
Safety at work: 1. The operational conditions and safety increase along the service. 2. The maintenance is performed according to safety policies.
Environmental safety: 1. The maintenance service performer recognizes the environmental safety hazards. 2. The maintenance is performed according to environmental safety policies.
Technical quality: 1. The maintenance service outcome is as expected. 2. The maintenance service outcome is sustained for the promised time.
Flexibility: 1. The maintenance service partner bends from its claims (e.g. . delivery time) 2. The maintenance services are tailored based on need.
Reliability: 1. The maintenance service cooperation is executed on time and as promised. 2. The maintenance service cooperation is based on confidentiality.
Operator knowledge: 1. The maintenance service provider has the knowledge to solve upcoming problems. 2. The maintenance service operators are professionally skilled and qualified.
Orderliness: 1. The resources and timetable of the maintenance service can be planned well in advance. 2. The maintenance service operations are developed in cooperation.
Reputation: 1. The current reputation of the maintenance service partner is good. 2. The previous experiences with the maintenance service partner have been positive.
Relationship: 1. The maintenance service cooperation works well considering the conditions of all partners. 2. The information exchange works between the maintenance service partners.
Contracts: 1. The maintenance service warranty and terms of payment are kept and executed as promised. 2. The risks and responsibilities considering the maintenance services are shared between the customer and the service provider.
Total solutions: 1. The maintenance service cooperation covers comprehensively the whole maintenance services (from management to execution) 2. The maintenance service covers the whole life span of the item.
R&D: 1. Own research and development can be developed with the maintenance service partner. 2. The maintenance service partner can provide information and knowledge related to the development of R&D activities.
Price: 1. The price paid for the maintenance service corresponds with the received service. 2. The price is negotiated in cooperation with the maintenance service partner.
Access to markets: 1. The maintenance service cooperation enables contact with new customers. 2. The maintenance service cooperation enables starting a new type of business.
Asset management factors: 1. The maintenance service partner is responsible for the spare part storage so that it does not tie your own resources and capital. 2. The maintenance service partner owns the fixed assets, for example the maintained items so that they do not stress your own balance sheet.

A Holistic System Approach for Turnaround Performance Management

Umar Al-Turki*, Salih Duffuaa and Mohammed Bendaya

Department of Systems Engineering
King Fahd University of Petroleum & Minerals
Dhahran, 31261
Saudi Arabia
*Corresponding author: Umar Al-Turki
e-mail: alturki@kfupm.edu.sa
e-mail: duffuaa@kfupm.edu.sa
e-mail: bendaya@kfupm.edu.sa

Abstract

Turn-around maintenance (TAM) is a major event that impacts a whole supply chain as well as other external stakeholders. In the current practice turn-around is planned and executed at the individual plant level in isolation from the other members in the supply chain. The purpose of this paper is to develop a framework for planning, scheduling and executing TAM taking into consideration the needs of all stakeholders network (system) including the supply chain in which the concerned plant is part. The members in the supply chain include; end user customer, upstream plants, downstream plants, and raw material suppliers. The proposed framework integrates the planning and scheduling among stakeholders in the supply chain in terms of objectives, goals and performance measures. The proposed framework helps in developing a holistic approach for planning and scheduling that takes the needs of all stakeholders in the supply chain into consideration.

Key words: Turnaround Maintenance, Performance Management, Systems Approach, Turnaround Planning.

1 Introduction

Turnaround Maintenance (TAM) is a crucial activity in process industry where a periodic plant shutdown is done to allow for inspections, repairs, replacement and overhauls. Many industries, such as chemicals processing or power generation, may have a continuous demand to produce products that cover a wide range of customers. Hence, TAM is needed to sustain a reliable process for the whole supply chain.

TAM projects are, in general, divided into several sequential phases that include validating work scope, pre-shutdown work, planning and organization, execution, and termination. These phases are cascaded to more detailed steps at each phase to achieve an effective TAM. Lenahan (1999; 2006) addressed fewer TAM phases: initiation, preparation, execution and termination. For more details, readers may refer to the following books [Duffuaa et al. (1999); Levitt (2004); Lenahan (1999; 2006); Brown (2004)].

TAM projects are huge projects in terms of manpower and financial expenditure. The industrial processes that undergo TAM projects are often of high value and their maintenance operations are intensive, complex and costly. A recent example by Shell shows that TAM in Athabasca Canada required thousands of workers in its peak, extended beyond planned duration by eight weeks and averaged to the tune of hundred million dollars (Pokharel and Jiao, 2008). It is therefore vital that TAM is planned and executed effectively.

In the arena of globalization and mass economy, business is getting more competitive and interconnected giving rise to giant corporate dominating small businesses. In that kind of business environment, managing assets becomes highly critical in surviving and maximizing profit. In that environment, the traditional project management view of TAM needs to be replaced a more global business view that takes into consideration the whole network of interconnected organizations including the production supply chain and other supporting services. The literature on TAM planning and scheduling is mostly concerned about TAM at the plant level, and recently at a strategic level, but falls short in addressing this issue.

The purpose of this paper is to develop a new planning approach for TAM that takes into consideration the whole production supply chain as well as other stakeholders. The methodology used to formulate the interconnection and the interrelation between different organizational levels and their objectives and measures in relation to maintenance is as follows:
   a. Reviewing the literture on maintenance planning and classifying their impact on different organizational and planning levels
   b. Reviewing the literture on supply chain management and best practices on improving the global performance of the supply chain and identifying practices for global maintenance system
   c. Survey of experts and practicing personnel about their focus and best practices at a high level of maintenance planning
   d. Drafting a global maintenance system view that includes all maintenance related decisions at all levels
   e. Verify the developed system by managers and experts in maintenance planning
   f. Finalizing the global maintenance planning framework

The remaining of the paper is organized as follows. Section 2 provides a brief survey of the literature on TAM planning. Section 3 develops the system view of the TAM activities which identifies the supply chain as well as the stakeholders. Section 4 defines the objectives and performance measures at the global level in relation to individual unit objectives and measures. Section 5 discusses some supply chain principles and best practices that would have an impact on the global system efficiency and effectiveness of TAM. Section 6 concludes the paper.

2. Literature survey

TAM planning at a global level as explained in the introduction is, as far as we know, nonexistent in the literature. In the other hand, the literature on production and inventory planning and management at the supply chain level is quite mature. The literature on TAM is mainly focused on strategic, long and short term planning and scheduling. In this section a brief preview of the literature on TAM planning will be reported for setting the stage for global holistic planning approach.

It is essential to link maintenance strategy to the organization mission and objectives. Dyke (2004) suggested various steps that need to be taken to improve turnaround performances covering the strategic objectives, reliability and availability, management of risk, and time and cost management. He also used, to improve TAM, benchmarking that involves data gathering, workshops, interviews, informal discussions, review of procedures and systems, and site inspections. Nath and klingler (2009) presented, in the case of chemical cleaning, a strategic discussion on turnarounds covering the timeframe to clean equipment; safe environments for maintenance personnel; team strategy; best practices to shutdowns; best practices related to cleaning technology and vendor personnel; defining key planning deliverables; dedicating manpower resources; executing and archiving the plan; and documenting lessons learned for future turnarounds. Mayo (2009) discussed turnaround strategy and how to achieve both predictable and competitive turnaround cost and schedule.

Long term planning for TAM program should coincides with the organization' strategic plan. A recent trend in the literature spots the importance to look to the maintenance function at strategic level. Tsang (2002) identified four strategic dimensions of maintenance: service delivery options, organization and work structuring, maintenance methodology and support systems. These dimensions should be linked with plant strategic plan in order to have the best suitable selected maintenance alternative. Murthy et al. (2002) addressed the need for data collection in strategy selection. Al-Turki (2011) developed a framework that puts elements of strategic planning together. The framework studies the involvement of major stakeholders as well as top management in the strategic maintenance plan. It also urges commitment of senior management for the successful development of a maintenance strategic plan. Principles for strategic maintenance planning can be considered in TAM planning.

Contractors for TAM plays major role in planning. Ghazali et al. (2011) proposed a multi-criteria decision model as a mean of facilitating contractors' selection for a petrochemical company in Malaysia. They should have technical know how about the scope of work set up for contracting. They need to guarantee availability of skilled and specialized man power to deliver the work to be contracted. They should also satisfy: quality of work, reliability in delivery, availability to meet safety requirements, flexibility to respond to unforeseen circumstances, compatibility of contractor system with company system. High performance contracting was suggested by Singh et al (2012) to improve TAM program in addition to active involvement of all plant departments; team building alignment, mechanical work window, performance evaluation.

TAM budget should cover manpower cost, equipment and material, contingency plan. To control TAM work budget, Motylenski (2003) presented methods with an overview of the practices successfully applied in planning and executing turnarounds that resulted in reduced turnaround cost and shorter downtimes. Key to an effective and efficient turnaround is proper and early planning. An effective work plan is achieved by early development of an overall milestone plan called "planning the plan". Roup (2004) reported a discussion covering important plant manager responsibilities to control TAM budget. He reported nine key strategies of pacesetter turnarounds, i.e., single-unit turnarounds, limited scope of work, risk-based inspection, short schedule, small and experienced workforce, operations' ownership and costs, cohesive team, schedule focused on critical path, and well planned with key milestones. Reiland and Busick (2011) presented a methodology to effectively monitor basic project parameters to improve turnaround predictability and performance. This study is applicable for any type of facility (onshore, offshore, etc.) that undergoes periodic outages for maintenance

and capital improvement for long term performance of the facility (asset). Schroeder and Vichich (2009) studied fundamental relationships illustrating the impact of specific trade-off decisions upon overall economic viability of the turnaround. The relationships include the major cost-contributing factors in TAM such as shift-patterns, labor productivity, and turnaround duration, fixed costs, quality and lost opportunity costs, and generic turnaround trade-off model.

Short term TAM planning covers all needed resources for successful TAM implementation. Oliver (2002) stressed the need of TAM planning to address the specific challenges that are parts of repairing process equipment In addition, it is necessary to design a number of criteria to provide balanced indication of performance. It includes: TAM budget, spare parts suppliers, contractors, and site logistics.

In conclusion, the literature on maintenance planning is highly focused on short term low level of objectives and performance measures. Research is mostly focused on optimizing resources and improving performance of single plants in isolation of other plants in the supply chain and other stakeholders within the same organization or multiple organizations. Other related, upstream and downstream, plants as well as other external stakeholders such as contractors and technology providers are mostly not within the scope of the planning process. Some researchers studied the maintenance system at a strategic level addressing issues having long term impact on the organization and also addressing strategic planning and management approaches. However, the literature still lacks the link between the different levels of planning, operational and strategic. The global maintenance system developed in this paper puts all stakeholders in a framework that integrates their needs and plans and objectives for the benefit of all parties.

3. System development

The objective of this section is to develop a global view of TAM in terms of its stakeholders and their relation to its planning and execution. The core of TAM where plans are developed and executed is the unit within the plant in charge of the project. Figure 1 shows a system view for TAM for any given plant (unit).
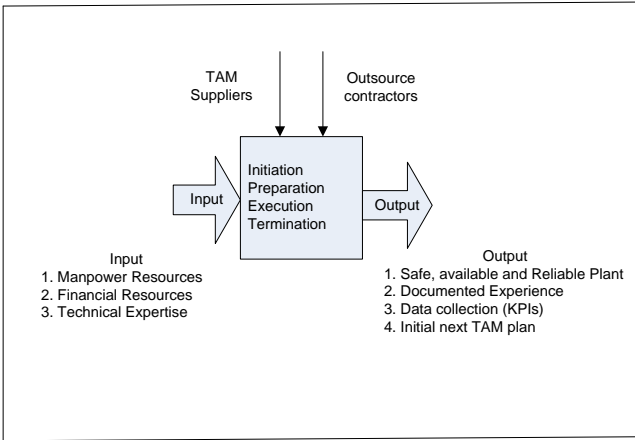

Figure1: TAM System view

Within the plant, TAM plans are prepared with enough lead time for all preparation, coordination and arrangements to be done before the actual start of execution. All necessary arrangements with external suppliers and contractors are to be done to secure on time delivery of equipment, spare parts, etc., and assuring the availability of the human resources with the right combinations of qualifications and skills. Similarly, financial resources, technical, managerial and IT expertise has to be secured internally for controlling and monitoring all TAM operations. Execution should then start at the pre set time and continues based on a schedule controlled and monitored by a group of project managers to ensure timing and quality and to be ready for any correction actions and emerging situations. Success is measured in terms of achieving the predefined objectives in terms of outcomes as well as in terms of execution. Success of execution is mostly measured in terms of meeting the schedule within the preset budget in the right predetermined quality. Success of outcomes is usually measured in terms of having a safe and reliable plant in addition to compounded experience build up for future TAM operations and continuous plant performance improvement.

In a larger context (corporate level) the system consists of several plants connected in series, where the output of a plant is fed to the next plant or in parallel where each plant is independent of the other. These plants can be producing raw material or finished products in the petrochemical industry. The plants can also be refineries in the oil industry for any oil producing and processing company. In case of series of plants feeding each other with raw material (sub-products), a buffer or a stock of the material is maintained for continuous uninterrupted production. Final products are passed to external customers without shortage or delay. TAM planning for each plant draws upon a set of resources from different sources, internal and external, such as subcontractors, spare parts suppliers, and technology providers. TAMs are highly labor intensive with various types of skills and capabilities and usually secured through external subcontracting. Spare parts of different technologies are needed to be available at the right time and need to be ordered from different sources taking into consideration lead times and financial commitments. The support and consultation is usually needed to be available from technology providers before, during and after TAM. Figure 2 shows all stakeholders of the TAM at the corporate level. The supply chain in the lower part of the figure starting from raw material suppliers to end product customer with buffers (stocks) inbetween plants can be within a single corporate organization and hence share the same resources within the organization. External stakeholders such as contractors, sparepart and tecknology providers may may be shared by all plants within the supply chain. Hence a shoutdown in one of the palnts may affect all other plants as well as external stakeholders.

Integrated TAM planning and coordination secures a maximum utilization of resources at the global system level as well as maximizing the global objective of the entire system that includes internal and external stakeholders.
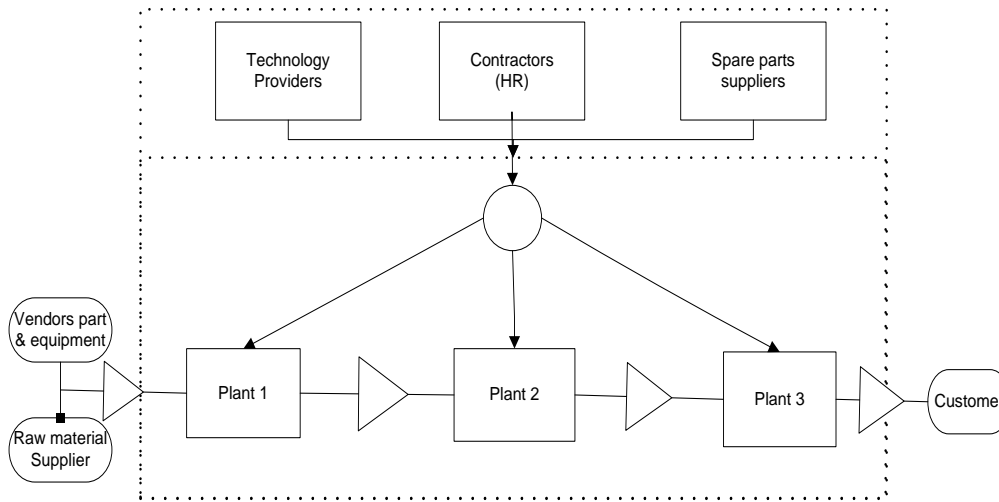
Figure 2: TAM multi plant system view

For the global system to be integrated for serving the global objective of the supply chain, several issues has be addressed and built within the system. These issues are as follows:

1. Coordination with supply chain partners
2. Shutdown effectiveness
3. Learning process and sharing of best practices with similar industries

Each of these issues is discussed below for better understanding and integration.

3.1 Coordination with supply chain partners

A plant undergoing TAM has an impact on, and impacted by, all other supply chain partners including:

- Upstream plants providing raw materials;
- Downstream plants using the plant products as raw materials;
- Vendors providing spares and long lead time items;
- Contractors providing manpower; and
- Final customers buying the plants products.

High level coordination within the supply chain at all TAM stages helps in maximizing benefit within the whole supply chain. Coordination within the supply chain can go to a level of deciding on the timing of the TAM for each plant, upstream and downstream, as well as sharing information during the stages of TAM and afterwards. This coordination can be through common committees or task forces at the planning level. Mathematical models and other scientific tools may be utilized for optimizing time TAM windows and costs. Such committees might get in contact with vendors and contractors for building strong long term relationship. Establishing such relationship with suppliers and contractors secures benefits to all parties and resolves conflicts effectively ahead of time. At the end of the supply chain comes the end customer that sets the requirement for the whole supply chain. Obviously that requirements is largely a major driving force for the whole supply chain. To enhance the communication process within the supply chain, an integrated information system that links all these partners together should be developed and forms the backbone for timely effective

coordination. This coordination and information sharing is highly needed during TAM execution to secure fast response to unexpected events by other partners.

3.2 Shutdown effectiveness

The overall objective of TAM is to ensure high plant safety, reliability and availability. Therefore, conducting a TAM within schedule and budget may not be enough. In addition to operational measure of budget and schedule, there is need to also emphasize and implement plant effectiveness measures. At the plant level, measures of TAM success has to be set, monitored and utilized for future plans. Such measures should be in line with high level objectives of the organization and agreed upon at the plant level. Having similar measures across the plants within the organization helps in coordination and sharing information across different plants. Including some high level measures that impact the organization helps in optimizing TAM at the global (system) level. Measures should be effectively utilized for improving the TAM process at the plant level and a global level in future plans and executions.

3.3 Learning process and sharing of best practices

A formal process for documenting positive and negative experiences during TAM planning and execution should be established. The result should be shared as a best practice document that will enhance the learning process across the organization. Failing to feed back this accumulated experience to the system for future improvements is a major shortage in current TAM practices in the industry. A plat form or a mechanism for sharing best practices across the supply chain should be established and systemized to ensure gaining the expected benefits. This learning process can be extended to other partners (suppliers, contractors and vendors) in terms of the technical know-how for design and technical specifications of equipment and spare parts.

4. Objectives and performance measures

A Supply Chain is a network of organizations that cooperate to maximize the value generated by improving material and information flows among suppliers and customers at the lowest cost and the highest speed. This effort can be measured by sustainable profitability generated. Although profitability of the supply chain is important, however within the chain may exist some organizations that compete to maximize their return on investment (ROI). This overall objective of the chain may be supported with tactical objectives that include:

- Improving customer satisfaction.
- Improving product quality.
- Minimizing the time required for converting orders into cash.
- Minimizing the total Work-In-Process (WIP) in the Supply Chain.
- Improving visibility of demand by each one of the partners.
- Reducing costs.
- Enhancing services.

In order to assess the strategies for achievig the above objectives many supply chain performance measures are proposed and used. Gunasekaran et al.(2004) proposed a framework for promoting better understanding of supply chain performance measures. Gunasekaran et al.(2001) developed performance measures with empasis on supplies but he attempted to relate them to customer service. Kleijnen and Smits (2003) provides a survey and a critical review of supply chain management metrics.

In this paper it is proposed to align the objectives of TAM with the overall supply chain objectives. The following objectives are suggested for TAM:

- Maximize productive capacity.
- Improve product quality.
- Enhance equipment reliability.
- Minimizing operation cost, and reducing downtime.
- Cope with legal and safety requirements.
- Enhance cooperation among partners, access and usability of past TAM maintenance knowledge base.
- Improving accessability and usability of best practices.

The current state of TAM measures is mostly operational to assess conformance to the planned activities. The current utilized measures do not focus on plant performance measures let alone the supply chain measures. Our purpose in this section is to tie the TAM maintenance performance measures to the supply chain overall goal and objectives. The following TAM measures are proposed and can be mapped to the supply chain performance measures:

- Information availability, accessibility and usability.
- SM duration
- Reliability with six month TAM.
- Quality rates.
- Process rate.
- Availability of major machines.
- Spare parts lead time
- Overall equipment effectiveness
- Utilization of resources.

Table 1. shows the alignment between supply chain measures and TAM measures. The circle indicates a strong alignment or influence of the TAM measure on the supply chain measure while the triangle indicates moderate alignment. The selection of the overall TAM measure must be based on the alignment with supply chain measures.

5 Principles for global TAM effectiveness

Turnaround maintenance events have impact not only on the plant undergoing the TAM but also on other supply chain partners. In this section, we briefly discuss some best practices that would have a positive impact on TAM global effectiveness on the whole supply chain and relevant stakeholders rather on only the concerned plant.

Table 1: Alignment of TAM and Supply Chain Performance Measures

Measures	Improving customer satisfaction	Improving product quality.	Minimizing the time required for converting orders into cash.	Minimizing the total Work-In-Process (WIP)	Improving visibility of demand	Reducing costs.	Enhancing services
Information availability, accessibility and usability	O	Δ	O	O	O	Δ	O
TAM duration			O	O		O	Δ
Reliability within six month TAM		Δ	O	O		O	
Quality rates.	O	O				O	Δ
Process rate.			O	O		O	
Availability of major machines.			O	O		Δ	Δ
Overall plant effectiveness		O	O	O		Δ	Δ
Utilization of resources.						O	Δ

O: Strong relationship,   Δ: Moderate relationship

5.1 Upstream plants providing raw materials

Collaboraion with suppliers involves at a lower level informing suppliers ahead of time of the timing of TAM so they can plan better their production activities. At a higher level of coordination, both parties jointly deciding on the timing of TAM so that it is more convenient for both parties. In this case a clear famework for this type of collaboration is jointly developed specifying timing, roles and responsibilities and channels of communications. If the plants share similar processes, the collaboration can be extended to sharing TAM experiences and best practices. If they are heavily dependent on each other, e.g. the TAM plant is a major customer of the supplier and their plants have the same TAM frequency, they may decide to have their TAM event overlap to minimize the negative effect of the inturruption on both plants.

5.2 Downstream plants using the plant products as raw materials

This is similar to the previous case and collaboration can benefit both parties as discussed earlier. In addition, TAM plant arrangements to satisfy downstream plant needs during TAM period should be in place and communicated to downstream partners to ensure their smooth operation.

5.3 Vendors providing spares and long lead time items

Good practices with spare parts and equipment vendors takes different forms. Proper selection of these partners based on long term relationships can benefit both parties:

- TAM plants recives appropriate service from vendors in terms of high quality parts and equipment and training on new equipment ahead of installation.
- TAM plants share maintenance and equipment experience with vendors. This is crucial for vendors to develop better and more reliable equipment in the future.

5.4 Contractors providing manpower

Many plants are usually competing for few qualified contractors having the appropriately trained manpower. A close collaboration between plants and manpower contractors can have positive impact on the operation of all parties involved.

5.5 Final customers buying the plants products.

Having arrangement for an unterrupted supply of product to customers during plant shutdown is part of good service and building lasting relationships with these customers. Plants usually build the appropriate inventory levels ahead of TAM to ensure that their key customers and unaffected by the interruption.

6 Conclusion

The paper presents a holistic view of TAM at a global level that includes all plants in the supply chain as well as supporting and service providing organizations. These parties form a network of stakeholders and supply chains with interconnected resources and benefits. In this paper the traditional TAM objectives and performance measures are taken to higher level for more integrated TAM planning and scheduling for the benefit of the whole network (supply chain). This view of TAM is not studied in the literature but is becoming more crucial for large size corporate originations. Possible objectives, performance measures and best practices are suggested for TAMs at the global level for more integrated planning and scheduling. Future work in this area will include further investigation on current practices and issues related to holistic view of TAM. An alternative future research area is on developing integrated planning scheduling models for TAM.

5 Acknowledgements

References

Al-Turki, U. M. (2011) 'A framework for strategic planning in maintenance', *Journal of Quality in Maintenance Engineering*, Vol. 17, No. 2, pp. 150-162.

Brown, M.V. (2004) 'Chapter 6. Shutdowns, Turnarounds, or Outages', *Audel managing shutdowns, Turnarounds, and Outages.* France: Lavoisier.

Duffuaa, S.O., Rouf, A. and Campbell, J. (1999) *Maintenance planning and control: Modeling and analysis*, New York: Wiley.

Dyke, S. (2004) 'Optimizing plant turnarounds', *Petroleum Technology Quarterly*, Vol. 9 No. 5, pp. 145-151.

Ghazali, Z., Abd Majid, M.A., and Mustafa, M.N. (2011) 'Contractors selection based on Multi-Criteria decision analysis', *In Humanities, Science and Engineering, (CHUSER), 2011 IEEE Colloquium*, pp. 957-962.

Gunasekaran, A., Patel, C. and McGaughey, R.E. (2004) 'A framework for supply chain performance measurement, *International Journal of Production Economics*, Vol. 87, No. 3, pp. 333–347.

Kleijnen, J.P.C. and Smits, M.T. (2003) 'Performance metrics in supply chain management', *Journal of the Operational Research Society*, Vol. 54, pp. 507–514.

Lenahan, T. (1999) *Turnaround Management*, Butterworth-Heinemann.

Lenahan, T. (2006) 'Effective planning and step-by-step execution of planned maintenance operations', *Turnaround Shutdown and Outage Management*, Elsevier, Oxford, UK.

Levitt, J. (2004) *Managing Maintenance Shutdowns and Outages*, Industrial Press Inc.

Mayo, H. (2009) 'Achieving accurate and competitive turnaround outcomes', 2009 NPRA Reliability and Maintenance Conference and Exhibition, pp. 38-85

Motylenski, R.J. (2003) 'Proven turnaround practices: Maintenance and reliability', *Hydrocarbon Processing*, Vol. 82, No. 4, pp. 37-42.

Murthy, D.N.P., Atrens, A. and Eccleston, J.A., (2002) 'Strategic maintenance management', *Journal of Quality in Maintenance Engineering*, Vol. 8, No. 4, pp. 287-305.

Nath, C., and Klingler, U. (2009) 'Beyond decon: Strategic chemistry for turnarounds', 2009 NPRA Reliability and Maintenance Conference and Exhibition, pp. 391-402

Patel, G. and E. Tirtiroglu, E. (2001), 'Performance measure and metrics in a supply chain environment', International Journal of Operations & Production Management, Vol. 21, No. 1/2, pp. 71–87.

Pinto, F.W., and Valenta, A. (2006) 'Turnaround scope optimization process', NPRA 2006 Reliability and Maintenance Conference and Exhibition.

Pokharel, S. and Jiao, J, (2008) 'Turn-around maintenance management in a processing industry: A case study', *Journal of Quality in Maintenance Engineering*, Vol. 14, No. 2, pp. 109-122.

Reiland, M.T., and Busick, S.A. (2011) 'Cost and schedule analysis of refinery turnarounds', AACE International Transactions, pp. 286-301.

Roup, J. (2004), 'Strategy maximizes turnaround performance', *Oil and Gas Journal*, Vol. 102, No. 20, pp. 46-54.

Schroeder, B., and Vichich, R. (2009) 'Trade-off economics in plant turnarounds', 2009 NPRA Reliability and Maintenance Conference and Exhibition, pp. 94-103.

Singh, B. (2012) 'Executive leadership-essential to ensure world-class turnarounds', *Hydrocarbon Processing,* Vol. 91, No. 3, pp. 69-72.

Tsang, A.H.C. (2002) 'Strategic dimensions of maintenance management', *Journal of Quality in Maintenance Engineering*, Vol. 8, No. 1, pp.7-39.

Supply Network and Operations Analysis in the UK Food Industry

D. Baglee, A. Melvin and M.J. Knowles

Institute for Automotive and Manufacturing Advanced Practice (AMAP)
University of Sunderland
Corresponding Author: D. Baglee
Email: david.baglee@sunderland.ac.uk
Email: michael.knowles@sunderland.ac.uk

Abstract

The food and drink processing industry is the fourth highest industrial energy user in the UK, largely due to its extensive use of refrigeration systems, meaning energy is one of the major costs in this industry. This paper is based on a project whose objective was to identify, develop and stimulate the development and application of more energy efficient refrigeration technologies and business practices for use throughout the food chain.

The focus of this paper was the investigations carried out into the operations and supply network configuration and design in order to identify areas where energy savings can be made through the reduction of refrigeration usage whilst not compromising food safety and quality. The investigation identified that maintenance is a key activity for refrigeration systems since poorly maintained systems are known to exhibit increased running costs and reduced reliability.

Key words: Food and Drink Industry, Refrigeration, Supply Chain

1 Introduction

The food and drink processing industry is the fourth highest industrial energy user in the UK (Carbon Trust 2012), it is also one of the largest users of refrigeration technology with many businesses within the sector finding that refrigeration costs make up a significant proportion of their energy bill. This paper is based on a project titled 'Fostering the developments of technologies and practices to reduce the energy inputs into the refrigeration of food' funded by the Department for Environment, Food and Rural Affairs (DEFRA). The overall objective of the project was to identify, develop and stimulate the development and application of more energy efficient refrigeration technologies and business practices for use throughout the food chain.

Refrigeration systems are major users of energy in the food and drink industry and as such they are a major source of cost to companies working in this sector. The literature contains many examples of the development of new and refined technologies (c.f. Tani et al 2012) or new refrigerant formulations (c.f. Bayrakci 2011, Rasti et al 2012). What is missing from the

literature, however, is any discussion of how the efficiency of refrigeration can be improved by optimising its operation and use. A great deal of attention has been placed on improving the operational efficiency of manufacturing operations by reconfiguring maintenance practice, process flow, supply chain, operational procedures and factory layout. The hypothesis which will be examined here is that such techniques can be applied to industrial refrigeration to improve the efficiency and reduce the cost of operation.

The aim of this work was to analyse food manufacturing supply chains to identify areas where energy savings can be made through the reduction of refrigeration usage as a result of operations/supply network improvements whilst not compromising food safety and quality. The focus of this paper was the investigations carried out into the operations and supply network configuration and design and the effect they have on the use of refrigeration and to identify any operations which were not seen as important by the case study companies yet after detailed analysis has shown as a major contributor to system failure and high energy usage.

Maintenance is a key activity for refrigeration systems since poorly maintained systems are known to exhibit increased running costs and reduced reliability. By optimising the use of refrigeration systems it is envisaged that the requirements for maintenance, and indeed the impact of suboptimal maintenance can be improved.

The paper will discuss the impact of maintenance on energy use in industrial refrigeration before describing the development of instruments and tools used for data collection. Four supply chains are presented as particular case studied and key areas of wastage in the food supply chains studied will be identified, and their contribution to unnecessary refrigeration usage and the implications for system maintenance are then be assessed.

2 Impact of Maintenance on Energy Use in Industrial Refrigeration

It is widely accepted that the demand for refrigeration will rise in the future, as will the corresponding energy requirements (Sivak 2009, Hermes et al 2009). While the topic of energy efficiency in refrigeration has been well documented, very little work has been done on the role of maintenance. Due to the lack of available data it has been necessary to investigate the link between maintenance activity and energy efficiency in the literature. Litt et al (1993) concluded that maintenance provides no significant improvement in energy consumption but several significant flaws existed in their study. The refrigerators tested had an average age of 16 years and many had received no maintenance during their life. The tasks carried out were not significant, consisting mainly of cleaning and gasket replacement. Furthermore some of the refrigerators where in an extremely poor overall condition, for example the doors of some models were being held together by the seals suggesting poor structural condition. These faults were not rectified as part of the maintenance performed. Full lifecycle assessment (LCA) is crucial in determining the true benefit of a course of action such as widespread replacement (Techato et al 2009).

A study in the USA by Miller and Pratt (1998) carried out as part of the Energy Star program analysed the energy savings obtained by replacing old refrigeration equipment in New York and found a strong correlation between the age of refrigerators and their baseline energy

usage. The authors concluded that 'degradation' plays a major part in energy consumption and can be regarded as a separate factor to labelled energy rating and age.

From these studies it is possible to conclude that the condition of refrigeration equipment has a substantial effect on energy consumption. In determining the effects of maintenance on the efficiency of refrigeration equipment it is necessary to study both maintenance policies/procedures and energy consumption. Initial investigations involving a variety of refrigeration users have highlighted various shortcomings in maintenance policy. Most maintenance is reactive, occurring only in response to a failure in the refrigeration plant. Any planned maintenance which does occur is generally related to service agreements or compliance requirements. Furthermore it was found that very little monitoring and recording of either maintenance activity or energy consumption is undertaken. This lack of monitoring means the relationship between running costs, maintenance and usage patterns is generally neglected.

The work carried out by the University of Sunderland has shown that a large number of companies do not collect and analyse maintenance data and therefore are unable to develop a new maintenance strategy based historical trends. In addition, companies rarely collected data regarding the cause and effect of a failure and what corrective action had been implemented. The research has also shown that cost to maintain (including energy consumption) and utilisation costs (running cold rooms on maximum with less that 20% full) were rarely recorded. In addition, the majority of companies studied did not employ condition monitoring techniques to detect, at an early stage, the onset of poor performance and eventually equipment failure. Further studies have shown that the food and drink industry, which are not part of large and dedicated supply chains, and therefore are not subject to the financial pressure often found within supply chain to ensure production and delivery times, often suffer from the lack of maintenance strategy developments and technical advancements to ensure just in time methods.

Research and case studies in other areas of engineering have demonstrated the energy efficiency benefits of maintenance. The Carbon Trust performed a case study at RAF Kinloss (Select Committee on Defence, 2007) where they used monitoring techniques and auditing to identify areas where the most substantial savings were possible. In a similar study for Westbury Dairies, a computer monitoring system was installed which it is estimated could lead to policies which could save the diary £400,000 of its £2 million energy bills (Carbon Trust 2007).

3 Supply Chain Case Studies

In order to assess the use of refrigeration in food and drink supply chains, four different supply chains were studied to identify areas of waste and in particular, implications for maintenance.

3.1 Dairy

The dairy industry involves a wide range of processes being carried out at a range of different temperatures to ensure that a) the product is safe to consume and b) is maintained in a safe condition. The production of yoghurt is presented as a case study in this area.

Two dairies producing yoghurt were studied. Raw milk is collected from farms in and around the areas of the sites. On arrival, the raw milk is tested for temperature, taste, added water, acidity and antibiotics. Once the load passes these receiving tests it is pumped into large storage silos. All raw milk within these silos is processed within 72 hours of receipt at the plants.

Upon receipt raw milk is standardized this involves reducing the fat content and increasing the total solids, the fat content is then reduced by using centrifugation to separate the fat from the milk. The solid content of the milk can then be increased further by evaporating off some of the water or by adding milk powder. After the solid composition has been modified to the required consistency the milk is pasteurized. This involves heating the milk to 50°c for 15 seconds to destroy the microorganisms in the milk that may interfere with the controlled fermentation. The pasteurised milk is then homogenised at 180°c to break up the fat globules in the milk. This process produces a smoother and creamier end product.

The processed milk is transferred to an incubation tank where the temperature is reduced to 41°c. Here two different methods are used to reduce the temperature. First is a cooling jacket which takes approximately 8 hours to cool the yoghurt to the required temperature and the second is central agitation which takes approximately 4 hours. Once the yoghurt has been cooled to the acquired temperature of 41°c culture is added accordingly. This whole process takes around 8-10 hours depending on the yoghurt type.

The mixture is then transferred to smaller holding tanks and fruit and flavourings are added as required. The holding tanks are connected to the filling machines and the mixture is pumped into pots, sealed and date stamped. At this stage the yoghurt is still around 20¬30°c however in order for the product to be despatched the required temperature is <5°c. This proves problematic since the yoghurts are packed into cardboard trays and placed onto a pallet with restricted access for air movement. Chiller boxes are used to reduce the temperature however; they are not energy efficient and require large amounts of energy and time to cool the yoghurt. The sites also use rapid blast systems which hold around 10 pallets, these are set between -3°c to -6°c. However, the pallets of yoghurts still take 2 hours to meet the required temperature of <5°c.

Table 1 shows a summary of the approximate temperatures of the yoghurt mixture throughout processing.

Table 1. Summary of yoghurt temperatures

Initial	After Processing	After incubation	Filling	Dispatch
6°c	180°c	41°c	20-30°c	<5°c

The above process is particularly demanding in its use of electricity. This is due to the thermal requirements of its many processes such as pasteurization, homogenization and rapid chilling. The main problems in the dairy industry are:

- Achieving and maintaining low temperatures for despatch

- Storage

All of the sites visited find it difficult to achieve the required temperature for despatch in a short period of time. Many dairy sites have little space for further developments however; the layout of the processing lines could be improved dramatically with little investment. The process was repeated within 3 hours, allowing for cleaning and a visual inspection of seals and pipes as Health and safety regulations dictated. Maintenance tasks were carried out if time permitted, or, in several instances, the equipment would be allowed to run-to-fail in the hope the process was complete.

3.2 Meat

The meat companies studied all manufactured pork products, as products such as bacon or sausages require large amounts of electricity for a 12-15 process production line. The factories varied greatly in size and can slaughter from 1000 to 1700 pigs a day each. Livestock is received at various times throughout the day and they are normally unloaded within 30 minutes or arrival. The slaughtering process takes approximately 45 minutes however the chilling of the meat, de boning, cutting/slicing and packing takes much longer.

Following slaughtering, carcasses are placed into a steam tunnel/scald tank which has a temperature of around 80°c to soften the skin. They are transferred into a de-hair unit, a singer for 5-10 sec at a temperature of around 700°c and they are then scraped and polished to remove any final hairs. This process required large amounts of energy which is often lost in the atmosphere after use, the equipment was often old, suffered from damaged caused by excessive heat and maintained only after a problem had occurred.

After the de-hair process the carcasses are weighed, stamped to acknowledge they have passed inspection and placed into the deep chill where they are stored between 0-5°c for up to 16 hours overnight depending on the sites specifications. This length of time is needed so that the meat is at an ideal temperature to be able to be cut and de boned, any warmer and the meat would be too tough. The process is again, energy intensive, often the meat is stored in large chillers capable of storing 100+ units however, the chillers usually have between 10 and 30 units stored at any one time. The fan blowers work constantly to ensure the optimum temperature is maintained.

Processed meats, for example, are cooked at a temperature of 80°c and are then placed into the blast chiller at 5°c for 16 hours. They are sliced, packed and date stamped and moved to the cold storage area for approximately 2-3 days at a temperature of <5° until they are ready for despatch. Depending on the site, deliveries are made either directly to the customer or to a logistics company who receive customer's orders and pick goods accordingly.

One of the sites studied has a major problem with refrigeration due to the amount of machinery used in each of the individual processes. They try to keep rooms chilled to 5°c or below however in reality the temperature is approximately 9-10°c. Also due to the design of the site some chilled rooms are used as a thoroughfare therefore doors are left open. The lack of thermal sensors is widespread, thus when a door is left open or a fan blowing cold air is inoperative, it could be several hours before the fault is detected. Meat or dairy products are often discarded (waste), maintenance is carried out to repair the problem but rarely is data collected and analysed to identify the cause of the fault and plan future maintenance. In

addition, the large blast chiller rooms are often located outside the main building and therefore open to the effects of extreme external temperatures on fan motors, coolant pipes and water pumps. None of the external chillers were fitted with condition monitoring systems to detect early signs of degradation.

Table 2 shows a summary of the approximate temperatures of pork throughout the processes within the factory.

Table 2. Summary of meat temperatures

Initial	After cleaning	Chill	Cutting.& de boning	Dispatch
37°c	67-80°c	-4 to 5°c	5-10°c	<5°c

The main energy usage in the pork factories visited are chilling of carcasses and maintaining temperatures throughout the factory. Temperatures throughout the factories varied greatly due to the design and layout. In some sites, although rooms are chilled to 5°c the actual temperature is much higher due to machinery used in the production processes and rooms being used as a thoroughfare. Transportation is also another main energy user with goods being transported to and from logistics and between sister sites locally, nationally and internationally.

3.3 Fresh Produce

The fresh produce company studied produces salad produce for supermarkets, caterers, food chains and retailers. They use mostly home grown UK leaf from May to October however come October the majority of supplies and more exotic leaves are imported from Spain, France and Italy except from the more common fresh produce which can still be grown locally. Deliveries from Spain take around 3-7 days therefore the site hold a 3-day buffer stock incase problems arise with suppliers. This may impact storage, the need for chilled and or frozen rooms (often at other parts of the plant) and maintenance to ensure rooms are availble and 'running' to support storage at a moments notice.

Various temperatures are in operation throughout the factory and these range from <5 °c to ambient. The intake and chilled area is kept below 5°c whereas the preparation area is kept from 5°c to ambient temperature to allow workers to be able to work comfortably.

Once the salad cut surface is exposed to air, the cut surfaces will brown or pink by enzyme action therefore it is important that the factory temperature, wash processes and packaging methods are designed to reduce the effect of the enzyme action. This process is unertaken in a 'sealed' room in which hygeine is important, It is necdssry to reduce the risk of cross contamination from wash and clean fluids and to ensure the oils, grease and equipment is maintained and cleaned on a regular basis. In this process maintenance has been recognised as important to ensure pipes, pumps and motors are clean, to reduce contamination, and the equipment is running at the required speed to ensure food is packaged within the specifiied time limit.

Temperatures are monitored every 20 minutes and the site tries to maintain these at <5°c however the temperatures vary throughout the day. The peaks in temperature can be correlated to when the system goes into defrost and the other variations in temperature are when the sites receive and despatch goods.

Table 3 shows a summary of the approximate temperatures of fresh produce throughout the processes within the factory.

Table 3. Summary of fresh produce temperatures

Initial	Preparation	Pack	Dispatch
<5°c	<8°c	<5°c	<3°c

Maintaining low temperatures throughout the factory is a major problem for fresh produce manufacturers since the temperatures can have a great affect on the produce. This site monitors temperatures and tries to maintain them however they are built on an existing factory layout and therefore they have to try and utilize the space they have as best as they can.

3.4 Convenience Food

The small factory which was studied is relatively new and on the visiting date, it had only been situated in a new premise for 5 months. The products produced are a variety of pies, peas and mash. The company receives meat and vegetable deliveries daily and dairy twice a week.

The companies chilling areas are situated at the back of the factory next to the delivery and despatch areas. Here there is a raw materials freezer, raw materials fridge, finished goods freezer and works in progress fridge. This area leads into the preparation room where all ingredients which do not need refrigerating are stored, for example tinned produce, herbs etc.

The mixture is prepared according to the recipe and taken to the boiling pans situated in the main part of the factory. These large pans are used to cook the mixture to the required temperature. Once the mixture has be cooked it is cooled from around 75-80°c to below 10°c and kept in the works in progress fridge below 5°c overnight ready for use for the next day. All pastry for the pies is made by hand and stored in the works in progress fridge overnight. Pastry is rolled out by hand, cut to the required size and placed into pie tins. A machine compresses the pastry down and flour paste is applied to the top of the pastry. The pies are hand filled; a lid is placed on top and sealed. The remains of the lid are trimmed from the pie, the edges pressed down and an egg wash applied. Pies are then placed into an oven which holds around 730 pies for 30 minutes at 207°c here they are placed onto a rotating pallet for even heat distribution.

In the high care end of the factory pies are taken from the oven and placed in front of two ambient temperature fans which run on 1.7kw for around 20 minutes to lower the temperature which at this stage is normally 75-80°c. Pies are then placed into the rapid blast chillers to a temperature of -6°c. The blast chillers have openings at either end so that products can be placed in one end and removed from the other.

Once cooled, pies are placed into the pie holding fridge where they are date coded and packed into one of the three types of packaging. Once packed the pies go through a metal detector and then into the despatch area which is kept at <5°c. These temperatures are summarised in table 4.

Table 4. Summary of pie temperatures

Initial	After Cooking (filling)	Overnight Storage	Cooking (Pie)	Dispatch
<5°c	75-80°c	<5°c	207°c	<5°c

The main energy used at this site is in the cooling of the pies since this takes around 4-5 hours. The site is also built on an existing layout and although space has been utilized, many problems occur. For example, the ovens are situated next to the chilled area and ambient temperature fans therefore when the oven doors open heat escapes causing the temperature to fluctuate. The site however does have plans to build a divide with curtains between the two rooms to try to control the temperature.

4 Summary Analysis

The following areas of wastage have been identified:

Inappropriate plant layout. New machinery added where space is available. For example, the milk processing plant had a shrink wrapper in the cold storage area and the pie processing plant had an oven next to the chilled area.

Poor information flow. Customers orders are often unpredictable and unreliable therefore many of the sites hold a buffer stock.

Badly utilised equipment Inappropriate quantities of storage were found in chilling rooms. Furthermore various technical errors with machinery were discovered along with inappropriate maintenance practices

Repetitive handling and moving. Goods moved between various rooms / sites. Rooms used as thoroughfares.

Inconsistent product quality. Customers specifications are not met therefore products are rejected. For example damaged stock due to poor processing lines.

Inconsistency of processes. Due to staff/product changeovers.

Transportation. To and from logistics, customers, sister sites and suppliers.

Based on the identified areas of waste a number of recommendations are formulated for the producers in question and for other organisations in the food and drink industry:

- Fit sub metering equipment to improve energy monitoring
- Examine maintenance practices to improve machine errors
- Redevelop/redesign the processing lines to avoid unnecessary movement of goods
- Address space utilisation to improve plant layout and processing lines

- Streamline Supply chains to improve information flow Utilise the opportunity for heat recovery
- Improve product handling to reduce defective stock and wastage
- Fit door strip curtains or automatic doors to minimise changes in temperature

5 Maintenance

With regard to maintenance practices to support production, it was evident that many problems were seen as inherent and difficult to remove or mitigate against.   The majority of senior management and maintenance technicians within the case study companies were interviewed to obtain an 'accurate' and clear description of maintenance practices and what were seen as 'barriers' to improvement.   The results, which follow, are seen as the main problems which need addressing in order to start developing a maintenance management strategy to help reduce unnecessary waste in energy consumption.

- Predominantly reactive maintenance
- Little or no planned maintenance activities
- Costs of maintenance (planned or unplanned) not recorded
- OEE data not recorded
- 25% of maintenance outsourced
- Operators lack basic skills in maintenance activities
- No clear route to maintenance development
- Energy consumption not recorded
- Space utilisation is poor (increased running costs including maintenance costs)

Research has shown that Maintenance activities within the food and drink industry can account for as much as 30% of an operator's direct operating costs and have remained at this level for many years.   There is, however, scope for increasing the efficiency of the maintenance process. The maintenance technicians' interviews stated that they spend 30% - 40% of their time trying to access information to diagnose and rectify failures. This had an effect on the occurrence of the need for unscheduled maintenance which introduces costly delays through complete equipment failure. The aim is to examine new technologies, current working practices and new approaches to maintenance management in order to reduce unscheduled maintenance by increasing the effectiveness of scheduled maintenance and provide the means to make the maintenance task more efficient and effective. The use of diagnostic methods to identify and locate failures and malfunctions and so reduce the number of breakdowns could be introduced coupled with decision support techniques to provide the maintenance technicians with process-oriented information and guidance.

Training programmes were recognised as a necessity for the majority of companies, however, most training programmes were either inadequate for the equipment, based solely on Health and Safety regulations with little regard to actual maintenance problems or nonexistent due to the perceived barrier that such programmes would require funding and reduced production times.   It is important to address this problem when developing a new approach to maintenance.

6 Conclusions

The work described herein aimed to investigate the potential to improve the efficiency of industrial refrigeration operations in the food and drink industry through non-technological measures. This project has highlighted the complexity of the supply chains studied and has uncovered a number of opportunities to improve efficiencies. The major findings are:

- Effective Maintenance strategies are limited and at best 30% efficient
- Throughout all of the sites, multiple heating and cooling processes throughout production are present thus resulting in an increase in energy consumption.
- Many of the sites are built on existing factory layouts where space is limited and in some cases not utilized effectively.
- Repetitive handling and movement of goods is present due to disorganized processing lines and supply chains resulting in inconsistent product quality.
- Transportation is another main energy user with some companies obtaining goods from overseas where although the labour and the cost to make the produce is much less the effect on the environment/carbon footprint is vast.
- Little knowledge of the power consumption of individual components and refrigeration systems.

Based on these conclusions, a need to re-develop and streamline the processing lines and supply chains to improve product handling, reduce stock and streamline frequency of collections and deliveries has been identified. The following recommendations are proposed based on these outcomes:

- Develop and implement a range of asset management programmes
- Introduce specific condition monitoring tools and techniques to ensure key pieces of equipment are monitored
- Develop a range of training and skill enhancement programmes
- Apply the value stream mapping process to investigate the changes in temperature throughout the process stream for each product to identify inefficiencies in the form of either unnecessarily rapid chilling or the unnecessary addition of heat.
- Redesign plant layout to optimise the efficiency of production processes.
- Consider the need for transportation of goods and assess the impact on overall process efficiency
- Apply energy sub-metering technology to support the ongoing value stream based analysis of process efficiency and to monitor the condition of equipment.
- Develop a culture of change to embrace new production support initiatives

As illustrated by the literature, maintenance has a critical role to play in optimising the efficiency of food and drink production systems by ensuring they operate effectively. Cost is often cited as a barrier to enhancing maintenance provision. As a final observation it is worth noting that by optimising production systems the demands placed on equipment can be reduced which will potentially lead to improved reliability and reduced maintenance costs potentially leading to an overall saving.

7 Acknowledgements

References

Bayrakci, H. C. (2011). Effect of new generation refrigerant selection to the low temperature circuit efficiency in cascade systems. *Energy Education Science And Technology Part A-Energy Science And Research*, Vol 27(1), 15-24.

Carbon Trust (2007) 'Westbury Dairies' http://www.carbontrust.com/our-clients/w/westbury-dairies

Carbon Trust (2012) 'Food and Drink Processing'.
http://www.carbontrust.com/media/39212/ctv004_food_and_drink_processing.pdf

Hermes C.J.L., Melo C., Knabben F.T. and Gonçalves J.M. (2009) 'Prediction of the energy consumption of household refrigerators and freezers via steady-state simulation'. *Applied Energy,* Vol. 86, pp 1311 – 1319.

Litt B., Megowen A. and Meier A. (1993) 'Maintenance doesn't necessarily lower energy use'. *Home Energy Magazine*
http://homeenergy.org/archive/hem.dis.anl.gov/eehem/93/930108.html.

Miller J.D. and Pratt R.G. (1998) 'Estimates of refrigerator loads in public housing based on metered consumption data'. Report PNNL-11991. *Energy Star Partnerships Program*, October 1998

Rasti M. , Hatamipour M.S., Aghamiri M. And Tavakoli M. (2012) 'Enhancement of domestic refrigerator's energy efficiency index using a hydrocarbon mixture refrigerant'. *Measurement*. Vol 45, no 7, pp1807 – 1813.

Select Committee on Defence (2007) 'Select Committee on Defence Fifteenth Report, Section 7, Environmental Issues.'
http://www.publications.parliament.uk/pa/cm200607/cmselect/cmdfence/535/53510.htm#n104

Sivak M. (2009) 'Potential energy demand for cooling in the 50 largest metropolitan areas of the world: Implications for developing countries'. *Energy Policy*, Vol. 37, pp 1382 – 1384.

Tani M., Arai T. and Kato T. (2012) "Development of High Efficiency Rotary Compressor by Adopting a New Manufacturing Method." International Compressor Engineering Conference. http://docs.lib.purdue.edu/icec/2117

Techato K-A, Watts D.J. and Chaiprapat S. (2009) 'Life cycle analysis of retrofitting with high energy efficiency air-conditioner and fluorescent lamp in existing buildings'. *Energy Policy*, Vol. 37, pp 318 – 325.

Asset maintenance maturity model as a structured guide to maintenance process maturity

Peter Chemweno*, Liliane Pintelon, Adriaan Van Horenbeek

Department of Mechanical Engineering,
Centre for Industrial Management/Traffic and Infrastructure, KU Leuven,
Celestijnenlaan 300A, BE-3001 Heverlee, Belgium.

*Corresponding author: Peter Chemweno
e-mail: PeterKipruto.Chemweno@cib.kuleuven.be
e-mail: liliane.pintelon@cib.kuleuven.be
e-mail: adriaan.vanhorenbeek@cib.kuleuven.be

Abstract

The rising cost of doing business coupled with a fast changing competitive business environment is forcing organizations to consider adapting asset management strategies, not just as a cost saving measure, but also to remain competitive. Implementing an efficient and effective maintenance program is one way of achieving this desired competitiveness. However implementing such maintenance program is often not straightforward due to the lack of a structured decision support approach. Capability maturity models present such structured approach. This paper proposes a generic asset maintenance maturity model (AMMM) as a structured guide for implementing new maintenance programs, evaluating existing programs and finally directing continuous improvement activities likely to lead to high levels of asset maintenance efficiency and effectiveness. Central to the proposed model is the use of risk assessment methodologies at different phases during the evolution process of asset maintenance maturity in the organization.

Keywords: Asset management, Maturity models, Risk assessment

1 Introduction

Organizations operating in today's competitive business environment continuously face competing and often conflicting requirements. On the one hand is the requirement for high product quality, but also on the other hand ensuring affordability. Achieving these conflicting requirements is often not straightforward and requires novel management techniques. One such strategy is asset management (AM) (Schneider et al., 2006). The attractiveness with AM is that it considers all important aspects that need to be managed in the life cycle of an asset, right from inception to disposal. One important phase within an asset's life-cycle is the operational and maintenance (O&M) phase with recent studies indicating that depending on the business context, it constitutes between 15 and 70 % of the total cost of ownership (Koronios et al., 2007; Bevilacqua, 2000). Passing this cost burden to the consumer undermines the competitiveness of the organization. As such, the maintenance function is receiving considerable attention and is no longer perceived as "necessary evil" but of strategic importance to the organization (Van Horenbeek, 2014).

In many organizations, the maintenance function is the core responsibility of the maintenance department whose main roles entail making decisions regarding selection of most appropriate maintenance strategy(s). Often, such decisions are implemented through a set of detailed asset maintenance programs specifying the overall goal, objectives and requisite maintenance activities. However implementing such programs is often not straightforward, largely due to lack of a structured decision making framework. Capability maturity models (CMM) presents an appropriate structure through which maintenance programs may be designed, on-going programs audited, continuous improvement activities proposed, and finally as an internal and external benchmarking tool (Fraser, 2002; Tiku, 2007). Moreover, CMM proposes a structured guide allowing the evolution of maintenance decision making capabilities through progressively increasing maturity levels. Central to the CMM framework are different well-known techniques and tools addressing the following decision making aspects (Pintelon, 2006):

- Decision support (e.g. maintenance concepts, risk assessment, maintenance planning).
- Resource management (e.g. materials, personnel and outsourcing).
- Assessment (e.g. performance measurement, audit and bench marking).
- Excellence in maintenance (evolution to world class maintenance).

Whilst several CMM have been developed in the past few decades, applicability of such models in asset maintenance is rather limited (Wendler, 2012). To address this gap, we therefore propose a generic asset maintenance maturity model (AMMM) aimed at assessing maintenance decision making processes within organizations. Here, we extend a recent study by Van Horenbeek (2014) by linking maintenance performance indicators to different risk assessment methodologies.

The remainder of this paper is organized as follows. In Section 2, we introduce the notion of asset management (AM) and briefly discuss CMM in the context of AM. This is followed by a review of existing CMM developed for various domains. The aim of the review is to understand the development, architecture and possible applicability of the CMM's in asset maintenance. Furthermore suitability of CMM as a tool for maintenance performance measurement, benchmarking studies, and guide to "world-class maintenance" status is discussed. In Section 3, we discuss the proposed methodology for AMMM and finally conclude by stating the major conclusions and proposals for future research.

2   Asset management, maintenance decision making and maturity models

2.1 Situating maturity models in asset management

Several definitions for AM are reported in literature. Schuman (2005) defines AM as "operating a group of assets over the entire technical life-cycle, guaranteeing a suitable return while ensuring defined service and security standards". The British standards institutes' BSI PAS-55:2008 defines AM as "the systematic and coordinated *practices* through which the organization optimally and sustainably *manages* its assets and *asset systems*, their *associated performance*, *risks* and *expenditures* over the *life-cycle* for the purpose of achieving its *organizational strategic plan*" (BSI, 2008).

From the latter definition (i.e. BSI PAS-55:2008), we deduce several important aspects regarding situating CMM in asset maintenance. The first aspect relates to the application of

systematic and *coordinated* practices for managing assets. Here, practices may imply design and selection of appropriate maintenance policy(s). Well-known maintenance policies applied in asset maintenance include the failure based maintenance (FBM), use/time based maintenance (UBM/TBM), condition based maintenance (CBM), opportunity based maintenance (OBM), and design-out maintenance (DOM) (Pintelon, 2006). Secondly, selection of appropriate maintenance policy(s) are often planned and implemented through a *structured* and *systematic* decision-making framework defined by the maintenance concept. Well-known maintenance concepts discussed in literature include reliability centered maintenance (RCM) (Moubray, 2001; Pintelon, 2006), risk based inspection and maintenance (RBIM) (Khan, 2003), life-cycle costing (LCC) and total productive maintenance (TPM) (Nakajima, 1988).

Several of the maintenance concepts, for example RCM and RBIM, base the decision making approach on *asset failure risk*, where risk is defined qualitatively (e.g. high, medium or low risk) or quantitatively (e.g. cost of repair). Thus, to evaluate asset failure risk, several risk assessment methodologies are incorporated in these maintenance concepts. For instance, in RCM, asset failure risk is evaluated using failure mode and effect analysis (FMEA). On the other hand, RBIM, evaluates and prioritizes asset failure risk using several reliability and dependability analysis tools that include fault tree analysis (FTA), Bayesian networks (BN), or stochastic Petri-nets (SPN). The third aspect considered in the BSI PAS-55:2008 definition relates to the *organizations' strategic plan*. The strategic plan often defines the roles of each function in the organization. Maintenance is one such function and as such requires a set of strategic maintenance goals, often defined as maintenance objectives. Ideally, the maintenance performance objectives together with respective performance indicators should cascade from the defined strategic plan as depicted in Fig. 1, (Kumar et al., 2011).

```
┌─────────────────────────────────┐
│  Organizational strategic plan(s) │
└─────────────────────────────────┘
                 ▼
┌─────────────────────────────────┐
│   Maintenance strategic goal(s)   │
└─────────────────────────────────┘
                 ▼
┌─────────────────────────────────┐
│     Maintenance objective(s)      │
└─────────────────────────────────┘
                 ▼
┌─────────────────────────────────┐
│     Maintenance performance       │
│          Indicator(s)             │
└─────────────────────────────────┘
```

Figure 1. Hierarchical cascade of maintenance performance indicators

However, in many organizations, the methodological approach depicted in Fig. 1 is often not observed. Rather a generic listing derived from different literature sources is adopted (Van Horenbeek, 2014; Muchiri et al., 2011). Moreover, existing frameworks seldom link maintenance performance indicators to the overall organizational strategy (Van Horenbeek, 2014). To address the aforementioned gap several maintenance performance measurement (MPM) frameworks are proposed in literature. For instance, Van Horenbeek (2014) developed a MPM framework for selecting business specific MPI's. The proposed framework explicitly links the MPI's, to the different organizational levels, i.e. strategic, tactical and operational. Moreover, each maintenance objective and respective performance indicator(s) are assigned importance weighting factor derived from the analytical network process (ANP) methodology. In this paper, we extend the MPM framework developed by Van Horenbeek

(2014) through proposing the incorporation of the asset maintenance maturity model (AMMM). A detailed discussion is presented in Section 3.

2.2 Capability maturity models in asset management

The development of CMM traces its origin to the early research work of Crosby (1980) who proposed the quality management maturity grid (QMMG) for use in the spectrum of quality management. The grid defines five distinct capability maturity levels contrasted against several dimensions. Here, maturity implies "*the evolutionary progress in demonstrating the specific ability or accomplishment of a target from an initial stage to a final desired stage*" (Mettler, 2009). On the other hand, dimensions refer to important process areas the organization places emphasis on, e.g. asset performance. Typically, a maturity model consists of the following components (Fraser, 2002):

(i)   number of levels,
(ii)   descriptor for each level, (e.g. uncertainty,….., certainty),
(iii)   description of characteristics expected of an organization at each level,
(iv)   number of dimensions,
(v)   description of elements/activities at each dimension, and
(vi)   description of each activity as performed at each maturity level.

Over the past few decades, maturity models have been developed and applied in diverse application areas encompassing product development, software management, patient safety culture, information management and risk management (Maier et al., 2009; Becker, 2009; Mettler, 2009). However, not much published literature is reported on the development and application of maturity models in asset maintenance. Indeed a literature search on Google Scholar©, Science Direct© did yield few results discussed in the next section. On the other hand, a large number of CMM developed for asset maintenance are instead reported in unpublished literature sources, developed largely by consultants or individual companies as in-house maturity assessment tools. However, these models are largely proprietary and contain rather limited information, especially regarding their development and use. Moreover applying these models to different organizations may not be straightforward due to difference in several aspects that include; organizational structure, or business context.

Development of maturity models

This section presents a brief discussion on existing CMM developed and applied in several domains. The purpose of the review is to highlight important aspects that could act as a potential guide for developing maturity models for the asset maintenance domain. For instance, De Bruin et al. (2005) propose a six-phase framework for developing a generic business process maturity model (BPMM). The phases in the BPMM include: *scope*, *design*, *populate*, *test*, *deploy*, and *maintain*. The BPMM consists of six-dimensions and thirty assessment areas. Strutt (2006) propose an eight-phase framework for developing a generic design safety capability maturity model (DCMM). The DCMM defines an architecture consisting of five maturity levels, and twelve key processes/assessment items evaluated via a 5-point Likert scale. Mettler (2009) proposes a four-phase framework for the design of the hospital supplier relationship management (HSRM) capability maturity model. The HSRM defines three maturity aspects contrasted against three domain specific dimensions. Here, several assessment items are defined in each cell of the defined matrix. In Becker et al. (2009) an eight-phase approach for developing a generic information technology performance measurement maturity model (ITPM) is proposed. Compared to the other three

aforementioned CMM's, here the authors propose a model architecture that is largely influenced by existing models in the information technology and business intelligence domains. In Maier et al. (2009) a four-phase methodology for developing a generic maturity model is proposed. In the study, the authors do not specify an explicit model architecture but rather propose the use of descriptive and prescriptive text in the *populate* phase of the maturity model. Steenbergen et al. (2010) propose a ten-phase methodology for developing a generic maturity model, but no model architecture is proposed. Hauck et al. (2011) propose a five-phase methodology for developing the software process capability maturity model (SPCMM) based on the well-established and internationally accepted ISO/IEC 15504-2 standard.

In the aforementioned review, several generic maturity models propose performance assessment criteria that are rather ambiguous. Moreover, the reviewed CMM's propose the use of numerous subjective assessment criteria and as such may present applicability challenges when used for maintenance performance measurement and benchmarking studies. This is in contrast to suggestions by several authors who propose the use of a limited number of performance assessment criteria/measures (max. 20) (Pintelon, 2006). Here, the author argues that doing so enables the organization focus on the most important improvement areas. Moreover, the CMM's discussed are not specific to the asset maintenance domain. Recently, several authors have proposed CMM's specific to asset maintenance. For instance, Oliveira et al. (2012) propose a conceptual CMM for evaluating the maturity of the maintenance function in the organization. The model consists of three maturity levels and five dimensions. Another example is the IAM's PAS-55 assessment methodology developed by the Institute of Asset Management and derived from the BSI PAS-55:2008. Campbell and Reyes-Picknell (2006) also propose a maintenance maturity grid (MMG) for evaluating capability maturity in asset maintenance. The MMG architecture consists of five maturity levels contrasted against ten dimensions.

However, the asset maintenance specific CMM's discussed in the previous paragraph ignore several important aspects that include: (1) no clear framework for deriving the performance indicators; (2) absence of a clear linkage between the performance indicators and organizational strategy; and (3) no clear linkage between the performance indicators and derived maintenance policies. Moreover, the models largely propose subjective assessment criteria potentially leading to ambiguous performance assessment results. To address the aforementioned deficiency, Galar et al. (2011) propose the use of a performance measurement framework combining both qualitative and quantitative maintenance performance measures. The framework is based on the well-known balanced score card (BSC) and considers the re-location/deployment of performance indicators to the three organizational levels, i.e. strategic, tactical and operational. However, the proposed scorecard assigns the same importance weighting to each performance measure potentially limiting its applicability in benchmarking studies, where organizations in different business context are compared. Finally, these maintenance specific CMM's seldom incorporate maintenance benchmarking. Table 1 depicts an overview of several CMM's discussed in literature.

Maintenance benchmarking

According to Pintelon (2006), benchmarking is defined as "a structured approach for learning from the practice of others, internally and/or externally, who are leaders in a field or with whom a legitimate comparison can be made". The authors here distinguish between four prevalent types of benchmarking which include: (1) internal benchmarking; (2) external benchmarking; (3) functional benchmarking and (4) generic benchmarking.

Table 1. Overview of maturity models specifying development phases, dimensions and performance assessment items

Reference/name	Application Domain	Development phases	Dimensions	Performance assessment items/criteria
(De Bruin et al., 2005) Business Process Maturity Model (BPMM)	Business process management & Knowledge management	Six-phases	Five-dimensions:- *Strategic alignment; Governance; Methods; People; Culture*	30 assessment items
(Strutt, 2006) Design Safety Capability Maturity Model (DCMM)	Off-shore installation's organization management.	Eight-phases	Twelve-dimensions:- *safety requirements;..., managing the approach to research and development.*	12 assessment items
(Mettler, 2009) Hospital Supplier Relationship Management (HSRM)	Supplier relationship management	Four-phases	Nine-dimensions:- *strategy formulation; strategy implementation;..., and settlement*	110 assessment items
(Becker, 2009) IT Performance Measurement Maturity Model (ITPM)	Information technology (IT) support management	Eight-phases	Three-dimensions:- *Contents; organization; and Technology*	15 assessment items
(Maier et al., 2009, Maier et al., 2012) Communication Grid Method (CMG)	Assessing communication management in engineering design	Four-phases	Five-dimensions (deduced from the proposed maturity levels)	Propose the use of 20 assessment items
(Steenbergen et al., 2010) Focus area maturity models	Enterprise architecture and software product management	Ten-phases	Definition of dimensions dependent on the areas of focus where the model is applied	User dependent.
(Hauck et al., 2011) Customizing Software Process Capability Maturity Model (SPCMMs)	Software process capability	Nine-phases	The proposed framework is meant to customize existing SPCMM's and thus the dimensions is dependent on the type of SPCMM undergoing customization	Dependent on the SPCMM being customized.
(Oliveira et al., 2012) Maintenance management based on organization maturity level	Asset maintenance	Survey based	Five-dimensions:- *maintenance strategy; key performance indicators;......; management models*	Propose 15 assessment areas
The Institute of Asset Management: BSI-PAS 55:2008 international reference standard	Asset management	Survey based (consultation with asset managers, consultants,..)	Not clearly specified	28 assessment items
(Campbell and Reyes-Picknell, 2006) Maintenance maturity grid (MMG)	Asset maintenance	Six-phases	Ten-dimensions:- *strategy; people;work-measurement;....;processes.*	Generalized assessment criteria/areas
(Galar et al., 2011) Integrated maintenance scorecard	Asset maintenance	Based on four-perspectives defined from the BSC	Four-perspectives:- *client ; financial; internal process; learning and growth*	Based on four-perspectives defined from the BSC

Performance measurement and recommended improvement actions are central to the benchmarking exercise. In literature, few research works is directed towards developing maintenance benchmarking framework, an important pre-requisite for comparing the maintenance function of different organizations. Notable exceptions include Komonen (2002) who propose a benchmarking tool for analyzing the effects of maintenance costs on the profitability of an organization. The benchmarking tool is incorporated in a three-phase maturity grid, but only considers the economic cost as a performance measure. MacGillivray (2007) propose a maturity model for benchmarking and improving the risk management process of the water utility sector. However, the model largely proposes subjective performance assessment criteria resulting in possible standardization challenges. Several other studies propose application of generic maintenance performance measurement and benchmarking standards such as the EN 15341 (BSI, 2007) which largely propose subjective performance assessment criteria. The importance with maintenance benchmarking is that forms an important transition to "world-class maintenance" discussed in the following paragraph.

Path-way towards world-class maintenance

The notion of world-class maintenance is described in literature using varied terms and definitions. For instance, Pintelon (2006) describes the path to "world-class maintenance" through a maintenance excellence framework having four distinct phases, i.e. starting level, basic level, advanced level and excellence level. Mishra et al. (2006) on the other hand propose a framework for maintenance excellence derived from comparative studies of several frameworks describing best practices in asset maintenance. Tomlingson (2007) propose a six-phase framework for maintenance excellence. From the brief review, it seems that defining what constitutes "world-class maintenance" is often not straightforward and differs depending on several factors that include the business context, strategic importance of the maintenance function and how the performance measures are derived and measured.

3 Asset maintenance maturity model (AMMM)

This section presents the proposed conceptual asset maintenance maturity model (AMMM) and extends the MPM framework developed by Van Horenbeek (2014). The framework enumerates maintenance objectives and respective performance measures derived through literature survey and validated by industrial case studies. Moreover, the framework aims at addressing the following deficiencies associated with existing MPM frameworks that include:

- are generic and in many cases describe a list of possible maintenance objectives together with the corresponding maintenance performance indicators;
- fail to explicitly link the derived MPI's with the maintenance objectives;
- failure in accounting for the varied importance of different maintenance performance measures depending on the operating/business context.

The proposed MPM framework depicted in Fig. 2 explicitly links the different maintenance performance measures to all organizational levels, while at the same time taking into consideration the varying importance of the maintenance objectives and respective indicators. The framework consists of 5 steps (circled in the framework) namely (Van Horenbeek, 2014):
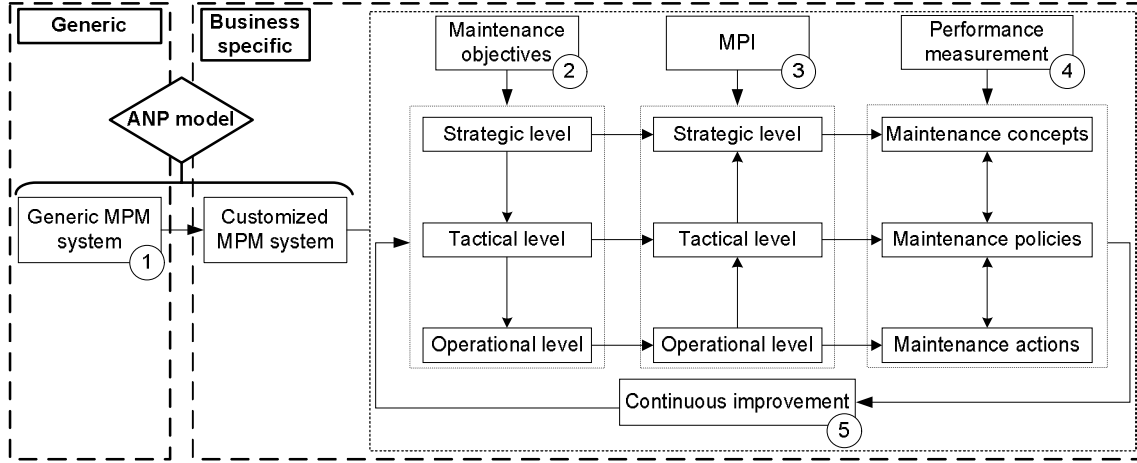
Figure 2. Maintenance performance measurement (MPM) framework (Van Horenbeek, 2014)

1. Translating generic MPM frameworks into a customized MPM system taking into account all organizational levels;
2. Prioritize the maintenance objectives on all the organizational levels based on analytical network process (ANP) methodology;
3. Translating the business specific maintenance performance measures into MPI's;
4. Measure, monitor, and control maintenance performance based on MPI's; and
5. Continuous improvement through re-defining maintenance targets according to evolving business environment (performance measurement and benchmarking)

The study by Van Horenbeek (2014) focuses on the first three steps enumerated above. In this paper we extend the MPM framework by focusing on steps 4 and 5, where we propose inclusion of the AMMM. The AMMM constitutes three phases that include performance assessment, continual improvement, benchmarking and standardization.

3.1   Performance assessment

In this phase, the maintenance objectives and respective MPI's are deployed to the respective organization level according to the relative importance weighting defined in the ANP's limit super matrix. As such, maintenance objectives are deployed at the strategic level, while the MPI's are deployed to the tactical and operational levels. The summation of importance weighting scores sums to a value of 1. Next, each MPI is evaluated independently and assigned a performance score using either of three assessment approaches: (1) objective; (2) subjective; or (3) combination of both objective and subjective. Depending on the availability of historical data, several MPI's such as reliability may be computed objectively (i.e. reliability analysis). Thus, here we apply a modified mathematical formulation first proposed by Hsieh (2009), where we define the weighted global performance assessment score (PAS) computed as follows:

$$wPAS = W_{PE} \sum_{i=1}^{n} PE_i + W_{FT} \sum_{i=1}^{n} FT_i + W_{PDL} \sum_{i=1}^{n} PDL_i + W_S \sum_{i=1}^{n} S_i + W_{MB} \sum_{i=1}^{n} MB_i \qquad (1)$$

Where:

- W_{PE}, W_{FT}, W_{PDL}, W_S, and W_{MB}: the importance weighting factors for each of the five maintenance objectives, i.e. people and environment, functional and technical aspects,…, and maintenance budget;

- n : the total number of maintenance performance indicators in each maintenance objective;
- $PE_i = sc_{PEi} \times w_{PEi}$; weighted score for each maintenance indicator defined as the product of assigned performance assessment score and importance weighting derived from ANP.

To ensure uniformity of the weighted PAS, it is proposed that each performance assessment score should be transformed into ratios ranging from 0 to 1. For instance, the MPI "maintenance costs" is normally described in economic terms e.g. Euros, but can instead be expressed as a ratio of actual maintenance cost incurred versus budgeted maintenance budget. For subjective performance assessment, domain experts assign performance assessment scores to each of the MPI defined at the tactical and operational level. Here, we propose a 5-point Likert scale with a score range of '1' to '5', the latter being the most important. Thus, assigning each MPI a rating based on the Likert scale, a weighted global performance assessment score may be computed by using equation (1) defined above. Thus, the value of sc_{PEi} is based on the Likert scale (i.e. range of 1-5), rather than ratio (e.g. reliability $= 0.85$).

Introducing the weighted PAS allows for a realistic evaluation of the organizations' performance in that the most important maintenance performance indicators (i.e. assigned the highest weights), are assigned a higher weighting compared to less important MPI's. Moreover, the weighted PAS assumes a final value ranging from 0 to 1, easily transformed into a percentage thus presenting an intuitive approach through which the organization is situated on a specified level on the maturity ladder depicted in Fig. 3.

3.2 Continual improvement process

After situating on the maturity ladder, the organization may find the need to improve their maintenance programs, i.e. move to the next step on the maturity ladder. However, achieving such improvements is not always straightforward. Several studies report the implicit link between choice of the maintenance policy (e.g. FBM, TBM and CBM) and MPI's and as such improvement activities are invariably linked to the selection of appropriate maintenance policy(s). In this paper we propose the use of risk assessment methodologies as a central tool for continual improvement of maintenance programs. The reasons are three-fold:

1. allows for a systematic identification of failure risk and as result focuses maintenance effort on the most important failure modes;
2. constitute important tools within the maintenance decision making framework. For instance, the FMEA is an important tool in the RCM concept, while the fault tree is an important reliability analysis tool in RBIM;
3. allows for the incorporation of important externalities often ignored during development of maintenance improvement programs that include economic feasibility, safety factors, or environmental considerations.

Therefore, the proposed structured improvement framework acts as a potential guide for developing improvement programs. A wide variety of risk assessment methodologies are reported in literature (Tixier et al., 2002). The effectiveness of the selected maintenance strategy(s) on the MPI is continuously evaluated (i.e. measure, monitor) via the feed-back loop depicted in Fig 3. For instance, a particular risk assessment methodology (e.g. RCM)
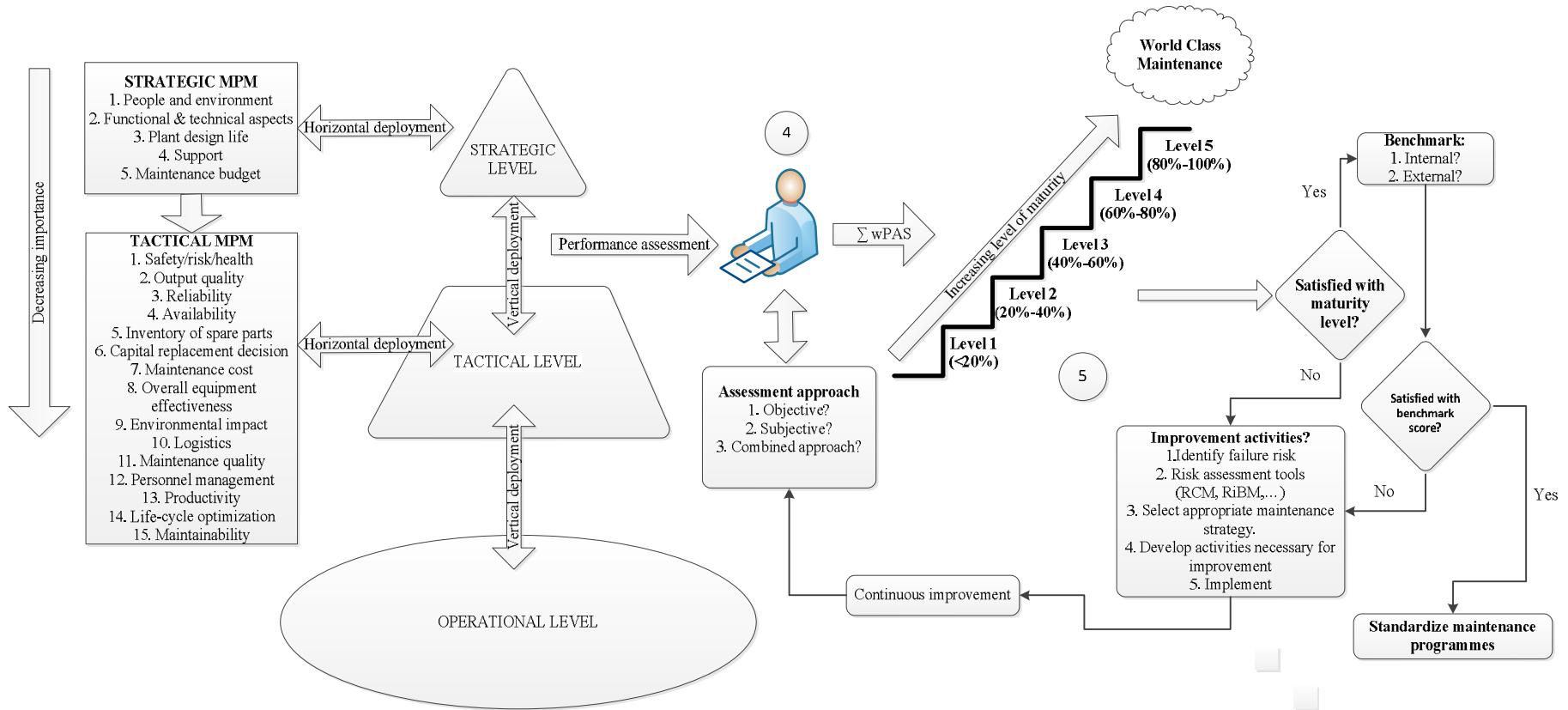
Figure 3. Overview of proposed asset maintenance maturity model (AMMM) framework

may suggest implementing combined FBM and TBM, which upon evaluation does not necessarily lead to improved MPI's scores. As such, a different risk assessment approach, e.g. RBIM may instead propose optimizing preventive maintenance schedules leading to possible improved scores. Thus, the application of risk assessment methodologies marks an important departure from several conventional maturity models often proposed in literature which situates novel maintenance strategies, e.g. CBM at the highest maturity level, while traditional strategy(s) e.g. FBM and TBM are situated at the lowest maturity levels. Rather, the selection of maintenance strategy is specific to the business and operation context of the organization and explicitly linked to maintenance performance measurement.

3.3   Benchmarking and standardization of maintenance programs

Once the organization is satisfied with the current maturity level an internal or external benchmarking study is considered. Since the MPI's are generic but vary in importance depending on the business context, the AMMM presents an intuitive approach for benchmarking maintenance programs across different organizations. Organizations achieving consistently high weighted PAS (i.e. > 80%) scores may be considered as having high maturity. Here, it does not necessarily imply implementing CBM, but rather the organizational specific maintenance strategy(s) that allows attainment of high performance evidenced by the weighted PAS. Thus the AMMM dispels existing asset maintenance maturity frameworks that situate maintenance policy(s) depending on its complexity. Rather, the organization may as well attain high maturity through implementing effective TBM as opposed to CBM. Indeed, implementing CBM may instead make the organization "over-mature" and as such not necessary.

4   Conclusion

This paper reviews research work carried out on the development of capability maturity models. In as much as several CMM's exist, not much research works on models specific to asset maintenance domain are reported in published literature. Moreover, existing CMM's largely propose subjective assessment criteria leading to possible ambiguity when applied for maintenance performance measurement and benchmarking studies. Thus, a novel asset maintenance maturity model (AMMM) is proposed specifically for the asset maintenance domain. The proposed model extends recent research work on maintenance performance measurement (MPM) and introduces the concept of weighted performance assessment score (wPAS) as the basis for maintenance performance measurement and benchmarking studies. Furthermore, the use of risk assessment methodologies is proposed as part of a structured decision making framework for selecting the most appropriate maintenance policy(s) best suited to the organization considering the operational and business context.

The AMMM marks an important departure from existing CMM's in that organizations in different business context are assessed based on the same generic list of maintenance objectives (and respective MPI's), but with varying importance weighting. This presents an intuitive approach allowing for a better comparison for the maintenance performance of different organizations. Moreover, situating the capability maturity for the organization on the basis of the weighted PAS allows for better performance assessment and attempts to de-link the performance assessment exercise from the assessor's subjectivity. Proposed future work will be on validating the proposed AMMM through case studies.

References

Becker, J. (2009) 'Developing maturity models for IT management'. *Business & Information Systems Engineering,* Vol. 1**,** pp. 213.

Becker, J., Knackstedt, R. and Pöppelbuß, J. (2009) 'Developing Maturity Models for IT Management'. *Business & Information Systems Engineering,* Vol. 1**,** pp. 213-222.

Bevilacqua, M. (2000) 'The analytic hierarchy process applied to maintenance strategy selection'. *Reliability engineering & systems safety,* Vol. 70**,** pp. 71.

BSI (2007) 'Maintenance Key Performance Indicators', *British Standards Institution.*

BSI P. (2008) 'PAS 55-2: asset management, Part 2: Guidelines for the application of PAS 55-1', *British Standards Institution.*

Campbell, J. D. and Reyes-Picknell, J. V. (2006) *'Uptime: Strategies for Excellence in Maintenance Management'*, Productivity Press Inc.

Crosby, P. B. (1980) *'Quality is free: the art of making quality certain'*, Penguin.

De Bruin, T., Freeze, R., Kaulkarni, U. and Rosemann, M. (2005) 'Understanding the main phases of developing a maturity assessment model'.

Fraser, P. (2002) 'The use of maturity models/grids as a tool in assessing product development capability', *IEEE International Engineering Management Conference,* Vol. 1**,** pp. 244.

Galar, D., Parida, A., Kumar, U., Stenstrom, C. and Berges, L. (2011) 'Maintenance metrics: A hierarchical model of balanced scorecard', *Quality and Reliability (ICQR), IEEE International Conference*, September, 14-17, 2011.

Hauck, J. C. R., Caivano, D., Oivo, M., Baldassarre, M. T. and Visaggio, G. (2011) *Proposing an ISO/IEC 15504-2 compliant method for process capability/maturity models customization product-focused software process improvement.*

Hsieh, P. J. (2009) 'The construction and application of knowledge navigator model (KNM): An evaluation of knowledge management maturity', *Expert systems with applications,* Vol. 36**,** 4087.

Khan, F. I. (2003) 'Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning', *Journal of loss prevention in the process industries,* Vol. 16**,** pp. 561.

Komonen, K. (2002) 'A cost model of industrial maintenance for profitability analysis and benchmarking', *International journal of production economics,* Vol. 79**,** pp.15.

Koronios, A., Nastasie, D., Chanana, V. and Haider, A. (2007) 'Integration through standards–an overview of international standards for engineering asset management', *Fourth International Conference on Condition Monitoring*, Harrogate, United Kingdom, 2007.

Kumar, U., Galar, D., Parida, A., Stenström, C. and Berges, L. (2011) 'Maintenance Performance Metrics: A State of the Art Review', *1st International Conference on Maintenance Performance Measurement and Management (MPMM)*, 2011.

Macgillivray, B. H. (2007) 'Benchmarking risk management within the international water utility sector. Part II: A survey of eight water utilities', *Journal of risk research,* 10**,** 105.

Maier, A. M., Clarkson, P. J. & Moultrie, J. (2012) 'Assessing organizational capabilities: Reviewing and guiding the development of maturity grids', *IEEE Transactions on Engineering Management,* Vol. 59**,** pp. 138.

Maier, A. M., Moultrie, J. & Clarkson, P. J. (2009) 'Developing maturity grids for assessing organisational capabilities: Practitioner guidance'.

Mettler, T. (2009) 'Situational maturity models as instrumental artifacts for organizational design', *Proceedings of the 4th International Conference on Design Science Research in Information Systems and Technology* - DESRIST '09. 1.

Mishra, R. P., Anand, G. and Kodali, R. (2006) 'Development of a framework for world-class maintenance systems', *Journal of Advanced Manufacturing Systems,* 05**,** 141-165.

Moubray, J. 2001. *Reliability-centered maintenance*, Industrial Press Inc.

Muchiri, P., Pintelon, L., Gelders, L. & Martin, H. (2011) 'Development of maintenance function performance measurement framework and indicators', *International Journal of Production Economics,* 131**,** 295-302.

Nakajima, S. (1988). *Introduction to TPM: total productive maintenance*, Productivity Press.

Oliveira, M. M., Lopes, I. D. S. and Figueiredo, D. (2012) 'Maintenance management based on organization maturity level'.

Pintelon, L., Vanpuyvelde, F.,(2006). *Maintenance decision making,* Leuven, Belgium, Acco.

Schneider, J., Gaul, A. J., Neumann, C., Hogräfer, J., Wellßow, W., Schwan, M. and Schnettler, A. (2006) 'Asset management techniques', *International Journal of Electrical Power & Energy Systems,* Vol. 28**,** pp. 643-654.

Schuman, C. A. (2005) 'Asset life cycle management: towards improving physical asset performance in the process industry', *International journal of operations & production management,* Vol. 25**,** pp. 566.

Steenbergen, M., Bos, R., Brinkkemper, S., Weerd, I. and Bekkers, W. (2010) 'The Design of Focus Area Maturity Models', *Global Perspectives on Design Science Research.* Springer Berlin Heidelberg.

Strutt, J. E. (2006) 'Capability maturity models for offshore organisational management', *Environment international,* Vol. 32**,** pp. 1094.

Tiku, S. (2007) 'Using a reliability capability maturity model to benchmark electronics companies', *The International Journal of Quality & Reliability Management,* 24**,** 547.

Tixier, J., Dusserre, G., Salvi, O. & Gaston, D. (2002) 'Review of 62 risk analysis methodologies of industrial plants', *Journal of Loss Prevention in the Process Industries,* Vol. 15**,** pp. 291-303.

Tomlingson, P. D. (2007) 'Achieving world class maintenance status', *Coal Age,* pp. 112.

Van Horenbeek, A. (2014) 'Development of a maintenance performance measurement framework using the analytic network process (ANP) for maintenance performance indicator selection', *Omega : The International Journal of Management Science,* Vol. 42**,** pp. 33.

Wendler, R. (2012) 'The maturity of maturity model research: A systematic mapping study', *Information and Software Technology,* Vol. 54**,** pp. 1317-1339.

Modelling maintenance and operation strategies for high value water industry assets

Helen Cornwell*, Linda B Newnes, Jon Wright**, Paul Cook**

Department of Mechanical Engineering
University of Bath
Claverton Down
Bath, BA2 7AY, UK
*Corresponding author: Helen Cornwell
e-mail: h.cornwell@bath.ac.uk, e-mail: l.b.newnes@bath.ac.uk

** Wessex Water
Claverton Down
Bath, BA2 7WW, UK
e-mail: jon.wright@wessexwater.co.uk, e-mail: paul.cook@wessexwater.co.uk

Abstract

The overall aim of the research introduced in this paper is to estimate the impact of maintenance and operation strategies on the economic sustainment of in-service long-life high-value assets in the water sector. The focus of the research presented is to understand and model the utilisation and support costs for such assets. First in-service cost, maintenance strategy and maintenance modelling literature is reviewed, and the state of the art in the water sector is compared with other industrial sectors. A modelling methodology is then proposed, and an industrial exemplar is used to illustrate the estimation of in-service costs. This is demonstrated through the evaluation of alternative scenarios, and the potential benefits for industry are discussed. Finally, future research is described aimed at extending the model to include cost and performance perspectives, encompassing maintenance and operational costs, reliability, availability, contractual and regulatory obligations.

Key words: Through life cost for high-value assets, in-service costs, maintenance strategy, maintenance modelling

1 Introduction

Literature states that in-service costs constitute the largest proportion of through life cost (Waghmode and Sahasrabudhe, 2012). In-service costs include all costs incurred from when an asset enters service through to retirement or disposal, such as operation and maintenance cost, technical costs and support costs. In-service costs can account for 75% to 85% of the through life cost of a long life asset (Newnes et al., 2011) therefore the control and management of these costs has a major influence on the effective use of assets within an enterprise. Figure 1 depicts in-service costs as part of through life cost, and illustrates where the user can influence cost (and performance) from the in-service stage to the end of life.
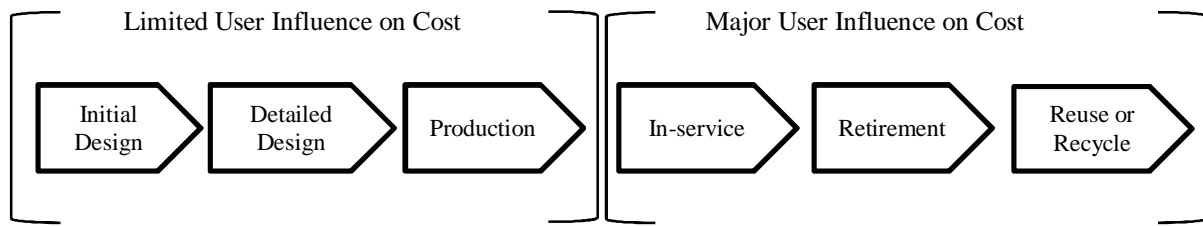
Figure 1. Asset user sphere of influence in though life cost

Water is a major global industry, with the world market for drinking and wastewater having an estimated worth of 400-500 billion USD annually (Deutsche Bank Research, 2010). Water is a key input to industry, the economy and the health and well-being of the population, impacting the environment and sustainable development. However, factors such as increasing population and urbanisation and the effects of a changing climate mean that water resources are under increasing pressure. One such pressure is the operation and support costs for the assets used in the production and treatment of clean and wastewater. The control and management of in-service costs is critical to meeting the unprecedented coincident challenges to in-service costs and asset value (Palmer, 2010). Whilst there is little published evidence which quantifies in-service costs in the water industry, Lim et al. (2008) estimate the costs of operation and maintenance to be around 80% of the total Life Cycle Cost, whilst Bennett (2006) proposes 70-80%. Further, many water industry assets have long life cycles of up to 50 years (Englehardt et al., 2002), and the industrial exemplar discussed in this paper considers assets with a typical life cycle of up to 30 years. Such long life cycles increase the expected magnitude of in-service costs in the water industry.

This research builds on existing work for long life assets in aerospace and defence, where the use of through life cost estimating techniques is well established. Techniques used include quantitative parametric approaches (Niazi et al., 2006), where Cost Estimating Relationships (CERs) estimate costs based on defined asset parameters, for example weight. However, the potential of these techniques in other industries sharing similar product life and value characteristics has not been widely explored. Within the water sector, cost estimating research has been found to be inadequate (Cornwell and Newnes, 2012) to fulfill the aims of the National infrastructure Plan - a resilient and affordable water industry (HM Treasury, 2011). This research seeks to combine through life cost estimating techniques with techniques from established research into maintenance strategy and policy (Sherwin, 2000; Veldman et al., 2011; Wang, 2002) in order to estimate the impact of maintenance and operational strategies on the economic sustainment of water industry assets. Maintenance policies aim to balance asset reliability and cost for maximum benefit (Sharma et al., 2011), and to assess this trade-off it is necessary to understand and model costs, using for example a bottom up approach, breaking costs down into the constituent parts of maintenance activities (Park and Seo, 2004). This research addresses current gaps in knowledge and practice in the following areas; extending quantitative parametric techniques to include performance in addition to cost, developing a robust model to include more than one category of maintenance activity and maintenance policy, and optimising the asset system with regard to both cost and performance. This research aims to answer the following question:

Can through-life cost estimating techniques, performance measurement and maintenance theory be combined to provide a robust estimate of in-service cost and performance?

These estimates can be utilised for informed decision-making such as; operational/scheduling conditions, or determining the appropriate level of maintenance to optimise economic conditions whilst maintaining asset availability. The next section of the paper critiques the current literature on both in-service cost estimating and operational maintenance strategies.

2 Review of in-service cost estimating, maintenance strategies and modelling

This section presents a review of in-service cost estimating, the influence of operation and maintenance strategy on in-service costs, and maintenance modelling approaches.

2.1 In-service cost research

In order to understand and model in-service costs, researchers have defined the cost components within a breakdown structure (Asiedu and Gu, 1998; Fabrycky and Blanchard, 1991, Goh et al., 2010). Table 1 summarises the differing views on the specific components of in-service cost.

Table 1. Definition of in-service costs as part of through-life cost

Reference	Defined in-service cost components	Comments
Goh et al. (2010)	Operation, Maintenance and Repair, Operation/Maintenance Management, Operator and Maintenance Training, Technical Data, Modification and Upgrade, Inventory and Obsolescence	Focussed on Operation and Maintenance
Asiedu and Gu (1998)	Transport, Energy, Storage, Maintenance and Materials, Waste, Breakage, Cost of Warranty, Packaging, Waste, Pollution, Health Damages	Alternative views based on company, user, and society perspective
Fabrycky and Blanchard (1991)	Product Operation, Product Distribution, Product Maintenance, Operation and Maintenance Management, Inventory, Operator and Maintenance Training, Technical Data, Product Modification	Earlier classification focussed on operation and maintenance costs
Gitzel and Herbort (2008)	Corrective Maintenance and Preventive Maintenance (Material, Downtime, Personnel), Change (Material, Downtime, Personnel, Other), Service Contracts (Personnel), Leasing (Other)	Focussed on maintenance and modifications to system, splits out cost of external personnel and equipment
Blanchard (1988)	Operation (equipment, software, personnel), Maintenance (personnel, facilities, software, data), Technical (Training and Data), Consumables, Transportation and Handling, Test and Support Equipment, Supply support	System view, wider scope to include data and support functions

The majority of models focus on operation and maintenance costs (Fabrycky and Blanchard, 1991; Goh et al., 2010), including repairs, modifications and upgrades. Gitzel and Herbort (2008) split out the costs of external personnel (service contracts) and leased equipment. Asiedu and Gu (1998) define the factors that are considered during the user experience of the in-service cost stage, such as transport, maintenance and materials and users' costs, with the exception of any operation costs (other than energy). Blanchard (1988) presents a system view of operating and support elements, in a wider breakdown of in service costs, including software and support functions. Whilst there are differing views of the precise constituents which make up the in-service cost, maintenance costs are normally included. This suggests that the strategy and policies used to direct and effect maintenance activities can be expected to have an influence on the control of in-service costs. Sachdeva et al. (2008) concur that this is a key driver within the in-service costs.

2.2 Assessing and selecting a maintenance policy

Most researchers agree that maintenance can be classified as corrective maintenance and preventive maintenance (Park and Seo, 2004; Wang, 2002). Corrective maintenance (CM) refers to all actions taken following a failure, in order to return an asset to a specified condition. Preventive maintenance (PM) occurs when an asset is operational and includes the activities undertaken with the aim of retaining an asset in a specified condition. A sub-set of PM, Condition based maintenance (CBM), aims to diagnose an asset failure, or predict when a failure will occur (Veldman et al., 2011). Specific PM policies can be further classified based on parameters such as asset age, number of assets, failure history or elapsed time since the last intervention (Wang, 2002). Most policies assume the asset failure rate increases over the lifetime, that failures follow the same distribution, and that salvage value is negligible. Whilst this may not be true for larger complex assets in the water industry, this would hold true for consumables and replacement parts used to repair those assets.

The aim of a maintenance policy is to balance asset reliability and cost for maximum benefit (Sharma et al., 2011). Achieving the required availability of an asset, whilst minimising spend on maintenance activities are often in conflict. Whilst it may be possible to optimise by satisfying a single criteria, such as minimum maintenance cost rate or maximum reliability, an optimal maintenance policy needs to consider both maintenance cost and reliability measures simultaneously (Wang, 2002). Researchers have suggested simple heuristics to assess the effectiveness of a maintenance policy. Ignizio (2010) proposes that the ratio of PM to CM downtime should be of the order of 9 or above (The M-ratio). Others suggest considering the positive impact of maintenance as a critical asset function and contributor to profit, rather than a cost to the business (Sherwin, 2000). Kumar et al. (2007) investigate how changing maintenance parameters such as reliability, maintainability and supportability affect overall operational availability and total cost of ownership.

Table 2 illustrates the effect varying maintenance strategies may have on parameters such as cost and operational availability, based on a proposed 'desirability' ranking of maintenance policies (Sherwin, 2000). Here an improvement in one parameter leads to an expected degradation in another. Whilst the magnitude of the effects cannot be predicted in the general case, a trade-off between parameters is required when selecting an optimal maintenance policy as summarised in Table 3. Tables 2 and 3 depict the challenges of impact on cost, as well as the factors that influence the maintenance strategy. Hence to assess the trade-off it is necessary to ascertain the operating expenditure (OPEX) for assets in the water industry.

Table 2. Effect of varying maintenance strategy

Maintenance strategy employed	Likely effect
Remove maintenance task by improved design	Increase in design cost, increase in availability
Condition based maintenance task performed while asset is operational	Increase in PM cost, increase in availability
Condition based maintenance task requiring asset operation to be paused	Further increase in PM cost, decrease in availability, reduction in CM cost
Periodic preventive maintenance tasks (requiring asset operation to be paused)	Further increase in PM cost, decrease in availability, reduction in CM cost
Reduce MTTR by improved design	Increase in design cost, availability, maintainability
Reduce MTBM by modifying PM schedule	Increase in PM cost, availability, reduction in CM cost
No preventive maintenance, asset operated to failure and corrective maintenance undertaken	Removal of PM cost, increase in CM cost, decrease in availability

Table 3. Factors for consideration when selecting maintenance policy

Maintenance Parameters	System Parameters	Modelling
Policy – repair/failure limit, sequential, age/block replacement	Redundancy – none (series), full (parallel), partial (run x out of y assets)	Tools – quantitative/qualitative analysis, probability theory
Outcome – replace as new (perfect), replace as rotables (imperfect), minimum repair	Criticality – high (regulatory or safety issues), medium (no short term issues), low (no issues)	Data – Availability, reliability
Objective – minimum cost/ down time, maximum availability/reliability		Timescale – strategic decisions, day-to-day decisions

2.3 In-service costs and maintenance strategy in the water industry

From a review of the literature, research into in-service costs and maintenance policies in the water industry was found to be limited when compared to other sectors. Table 4 summarises papers found in this area, classified by industry sub-sector, costing driver, and primary focus.

Table 4. Classification of papers found in water industry through life costing review

Reference	Classification	Primary focus	Costing Driver
Ashton (2000)	Water and Sewerage	Model for relative operating cost efficiency of service providers	Finance & Company performance
Bell (1999)	Infrastructure	High level regulatory, risks, challenges of financing investment	Finance & Company performance
Bennett (2006)	Industrial water systems	LCC worked example industrial WTP, cost vs water grade	Industrial WTP
De Gussem et al. (2010)	Sewage non-infra	Environmental/Operational, modelling plant operation, no TLC	Operational costs, Environmental
Engelhardt et al. (2002)	Water Infrastructure	Maintenance requirements and costing, WLC decision tool, high level costs	Maintenance costs
Jayaram and Srinivasan (2008)	Water Infra	LCC, multiobjective function to optimise network design including rehabilitation	Design stage
Lim et al. (2008)	Industrial water systems	LCC/LCA assessment, mathematical programming comparison	Industrial WTP
Palmer (2010)	Sewage non-infra	Operational costs, compare process options and new vs refurbished	Operational costs
Peet et al. (1976)	Water Industry	Estimating capital and operating costs, single parameter functions	Operational costs
Rowan et al. (1961)	Sewage non-infra	Estimating operational and maintenance costs through inverse log function and plant type	Maintenance and Operational costs
Shu et al. (2011)	Water infra	Life cycle assessment to predict life of pipes vs water quality	Life prediction
Tanimoto et al. (2003)	Water infra	Modelling Cost of Maintenance, PM must be considered	Maintenance costs

The industry sub-sector showed an even spread between water and sewerage assets, with more focus on below ground (infrastructure) than above ground (non-infrastructure) assets. The cost drivers identified were operational and maintenance costs, environmental considerations, costing of industrial water systems, network design, life prediction and high level company performance and finance issues. The importance of cost estimation and efficiencies, and challenges such as climate change, regulation and population were

highlighted (Palmer, 2010). Engelhardt (2002) proposes that maintenance policy should encompass a combination of strategic and tactical approaches to meet short-term performance requirements whilst also ensuring that performance levels are sustainable in the longer term. The approaches to evaluating the effects of maintenance strategy on in-service costs were found to have evolved from simple numeric approaches to more complex modelling methods. Early research in the area (Rowan et al., 1961) suggested a parametric approach, based on the observation that cost of operation and maintenance per capita or volume treated decreases logarithmically with average daily flow rate. Engelhardt et al. (2002) used software combining Activity Based Costing (ABC) and Life Cycle Assessment (LCA) to determine the effect of varying maintenance strategies on Through Life Cost (TLC) for water distribution networks over a 50 year asset life. Tanimoto et al. (2003) propose a mathematical modelling approach to evaluate alternative maintenance policies for a water distribution system. A Markov decision process model was developed to evaluate the effect of alternate maintenance policies on TLC.

Whilst the techniques used for in-service cost estimating have evolved over time in the water sector, research has been found to be relatively immature, and the effects of PM and CM on in-service costs have not been effectively considered in research or practice (Tanimoto et al., 2003). There is no consistent analysis or modelling approach suggested in the literature.

2.4 Maintenance modelling approaches

There are various approaches to model maintenance such as Wong et al. (2008) modelling corrective maintenance or an assumption of negligible maintenance time (Wang, 2002). Kumar et al. (2007) consider both PM and CM aimed at maximising operational availability. Asiedu and Gu (1998) propose a bottom-up approach, breaking the maintenance activity into individual steps, and aggregating the cost of those. Similarly, Park and Seo (2004) propose a model based on evaluating the cost of corrective maintenance in terms of downtime and materials, defining the constituent parts of maintenance activities. The cost of maintenance is defined as:

$$C_{maintenance} = (LC_{Fixed} + L_R\, L_T + C_R)\, F_R \qquad (1)$$

where

$C_{maintenance}$	=	corrective maintenance Cost (US\$)
LC_{Fixed}	=	fixed labour cost (US\$)
L_T	=	labour time (hours)
L_R	=	labour rate (US\$/hr)
C_R	=	replacement cost of parts or materials (US\$)
F_R	=	failure rate

However, the model presented does not include preventive maintenance cost, a limitation in situations where PM costs are significant to total in-service costs.

From the available modelling approaches in the literature, it is necessary to select, and enhance if required, a suitable approach for the research, considering the scope and aims of the modelling approach and the system to be modelled as described in the following section.

3 Selection of approach for modelling in-service cost

Previous reviews propose that the most appropriate approach for estimating in-service cost for long-life high-value assets is a quantitative parametric approach (Niazi et al., 2006), using

Cost Estimating Relationships (CERs), defined as 'a mathematical expression that describes, for estimating purposes, the cost of an item or activity as a function of one or more independent variables' (Woodward, 1997, p336), which are encoded within a model to estimate in-service cost. The quality of the CER may be indicated by statistical properties, such as an index to show the degree of correlation between the independent and dependent variables (Goh et al., 2010).

A robust model should measure how well cost requirements are met in conjunction with performance requirements (Blanchard, 1988), providing an overall evaluation of asset effectiveness in response to varying maintenance strategies. However, many current maintenance cost models aim to minimise cost but ignore the effect on performance (Wang, 2002). To address this limitation our research investigates whether parametric techniques can be used to model asset performance and variables affecting the performance through Performance Estimating Relationships (PERs), providing a methodology which considers cost and performance and enables trade-offs to be assessed. Figure 2 depicts how asset effectiveness can be broken down into cost parameters and system effectiveness (performance) parameters. These parameters can be encoded within the CERs and PERs, and combined with an objective function to evaluate alternative modelling scenarios. The model proposed for this research follows this methodology, initially as a simple representation of the system inputs, outputs and operation. This can be refined and modified following feedback on performance, and to incorporate further data and knowledge of the system as it becomes available.
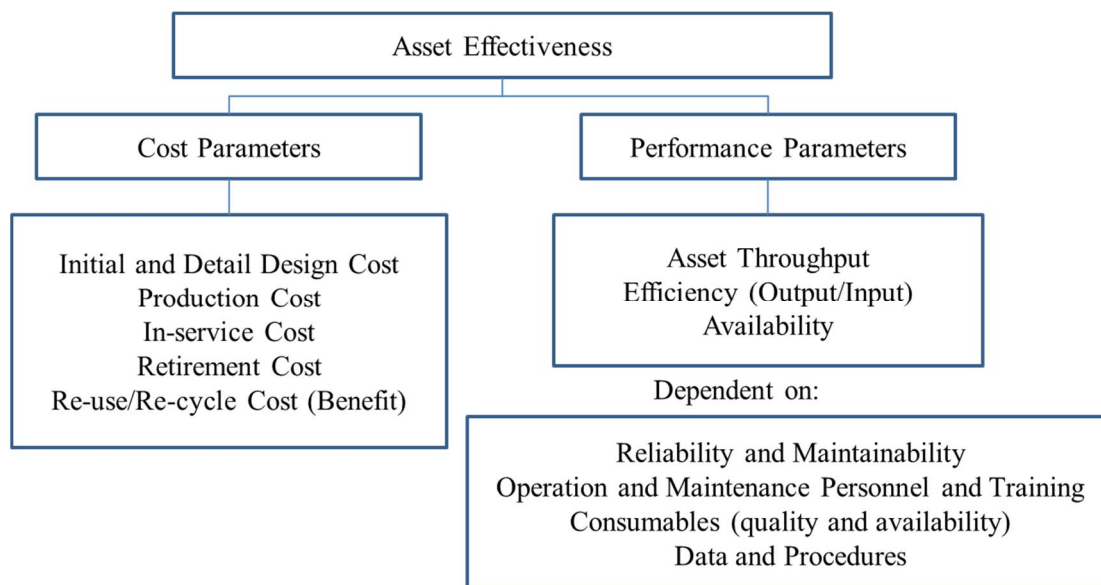

Figure 2. Asset effectiveness parameters

Selection of the modelling approach should also consider the availability and reliability of data, and sources of data. A combination of historical data, regression analysis, and expert opinion to form the 'best' estimate can be used as required to build and populate the model. An initial robust cost model is proposed based on the definition of the system and data available for preventive and corrective maintenance and cost of consumables, which together enable an estimate of total cost of maintenance. This extends the model by Park and Seo (2004), which focussed on solely on corrective maintenance. The model is required to

function based on runtime or elapsed time, in accordance with the operating and maintenance conditions of the asset, in order to accurately represent the industrial situation.

The estimated cost of maintenance can be represented as:

$$C_M = (L_R\,L_{CT} + P)\,FR_C + (L_R\,L_{PT} + P)\,MR_P + MR_{MS}\,C_{MS} \qquad (2)$$

where

C_M	=	Cost of Maintenance
L_{CT}	=	labour time per CM event (hours)
L_{PT}	=	labour time per PM event (hours)
L_R	=	labour rate (£/hour)
P	=	replacement cost of parts or materials per maintenance event
FR_C	=	Corrective Maintenance Failure Rate
MR_P	=	Preventive Maintenance Rate
MR_{MS}	=	Major Service Rate
C_{MS}	=	Major service cost

A phased approach, based on previous research within aerospace (Newnes et al., 2011), was used to define and build a model to effectively represent and evaluate the in-service cost and performance for the water industry assets. The original approach has been extended to a six step methodology, incorporating system definition and data collection, continuing into system development, validation, and proof of concept in industry (Figure 3).
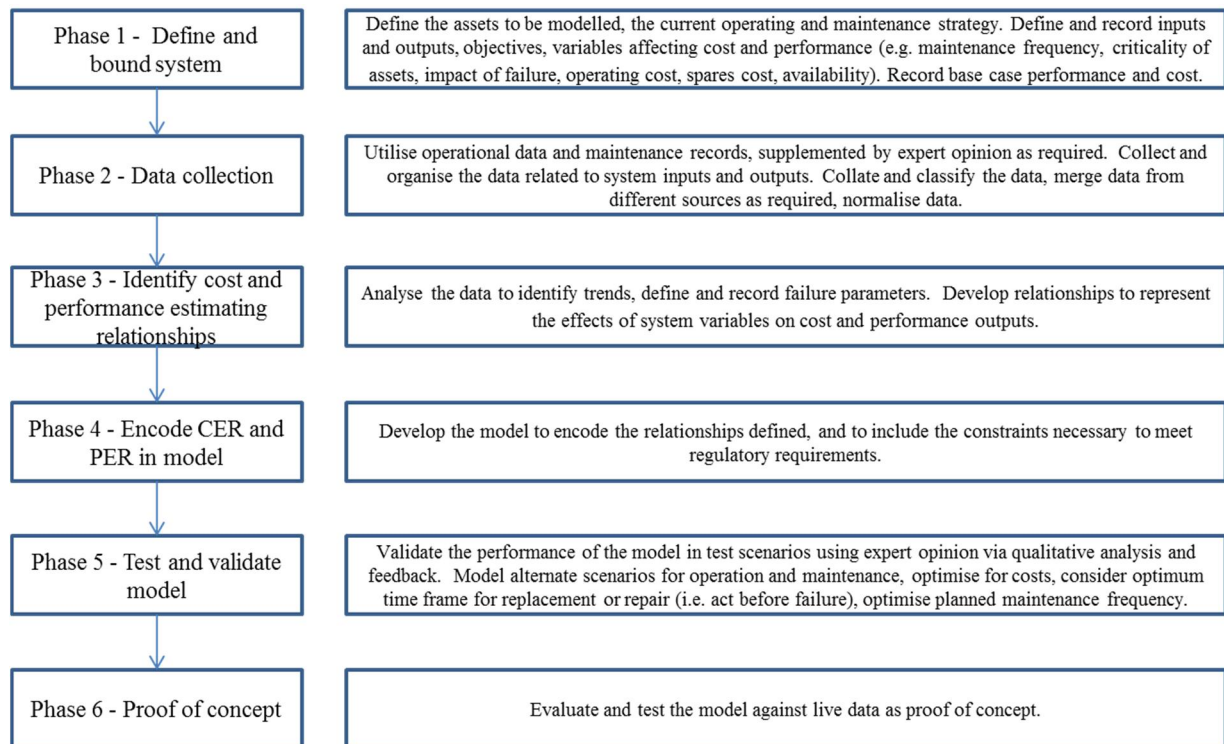

Phase 1 - Define and bound system	Define the assets to be modelled, the current operating and maintenance strategy. Define and record inputs and outputs, objectives, variables affecting cost and performance (e.g. maintenance frequency, criticality of assets, impact of failure, operating cost, spares cost, availability). Record base case performance and cost.
Phase 2 - Data collection	Utilise operational data and maintenance records, supplemented by expert opinion as required. Collect and organise the data related to system inputs and outputs. Collate and classify the data, merge data from different sources as required, normalise data.
Phase 3 - Identify cost and performance estimating relationships	Analyse the data to identify trends, define and record failure parameters. Develop relationships to represent the effects of system variables on cost and performance outputs.
Phase 4 - Encode CER and PER in model	Develop the model to encode the relationships defined, and to include the constraints necessary to meet regulatory requirements.
Phase 5 - Test and validate model	Validate the performance of the model in test scenarios using expert opinion via qualitative analysis and feedback. Model alternate scenarios for operation and maintenance, optimise for costs, consider optimum time frame for replacement or repair (i.e. act before failure), optimise planned maintenance frequency.
Phase 6 - Proof of concept	Evaluate and test the model against live data as proof of concept.

Figure 3. Phased methodology

The research project commenced with a pilot scheme for a small group of assets in order to validate the methodological approach, the available data, and the potential for defining cost and performance estimating relationships, and modelling and evaluation of alternative scenarios. The creation of the robust model and the phased approach is described in the next section.

4 Industry exemplar benchmark model

To illustrate the proposed modelling approach a group of biogas generators at a single site were chosen, where it was possible to define the system envelope, to obtain maintenance and financial data, and to measure performance through energy output. The service components range from filters and lubricants, through to turbochargers, and in-service costs were estimated based on current operational conditions. The asset management planning objective is to optimise availability and efficiency in order to maximise income from renewable fuel.

4.1 Pilot Study Phase 1 – System Definition

The system to be modelled was defined in terms of the system components, inputs and outputs. Current operating and maintenance schedules are largely driven by the manufacturer's recommendations. Table 5 shows the standard planned maintenance activities for the assets. Activities A, B and C can be classified as variants of the periodic PM policy (Wang, 2002), i.e. preventive maintenance at fixed run time intervals independent of failure history. Within activity C, components may be replaced after they have reached a certain run time, i.e. age replacement PM policy. As a result of maintenance activities D and E (monitoring events), condition based maintenance or component replacement may take place.

Table 5. Standard planned maintenance schedule

Planned Maintenance Activity	Downtime	Frequency	Comments
A	4 weeks	After X hrs run time	Off site service, parts and labour
B	2 weeks	After Y hrs run time	On site service, parts and labour
C	1 day	After Z hrs run time	On site
D	n/a	Weekly	Health check, oil quality sample, in-house technician
E	n/a	Daily	Control room on-line monitoring

4.2 Pilot Study Phase 2 - Data collection

Data collection was limited to data which was reliably available for the pilot study assets. This included PM and CM downtime for the past 3 years from the company maintenance management system, consumable cost data from the finance system and locally held spread sheets of asset run time and written records of PM activities. The data collection process highlighted that robust methods are required in order to consolidate disparate data sources, handle incomplete data, and ensure access to additional data where the original data proves insufficient or raises further questions. Whilst the model created is based primarily on data, where necessary expert judgement can be used to augment data. When data is uncertain or incomplete, or if there is high epistemic uncertainty in estimation methods, techniques such as cross validation can be used to improve the confidence in the model (Goh et al., 2010).

4.3 Pilot Study Phase 3 & 4 - Relationship definition and initial cost estimating model

For the pilot study preliminary work was undertaken on the definition of relationships and the creation of an initial cost-estimating model based on the available cost data. From analysis of the data, relationships could be inferred for the probability of failure (a CM event), or the probability of being unavailable (either CM or PM event). The initial relationships were encoded within the model as described in section 3. Figure 4 shows cumulative maintenance

costs over a 25 year life as predicted by the model, shown as percentage of purchase and installation cost in order to protect company confidentiality.
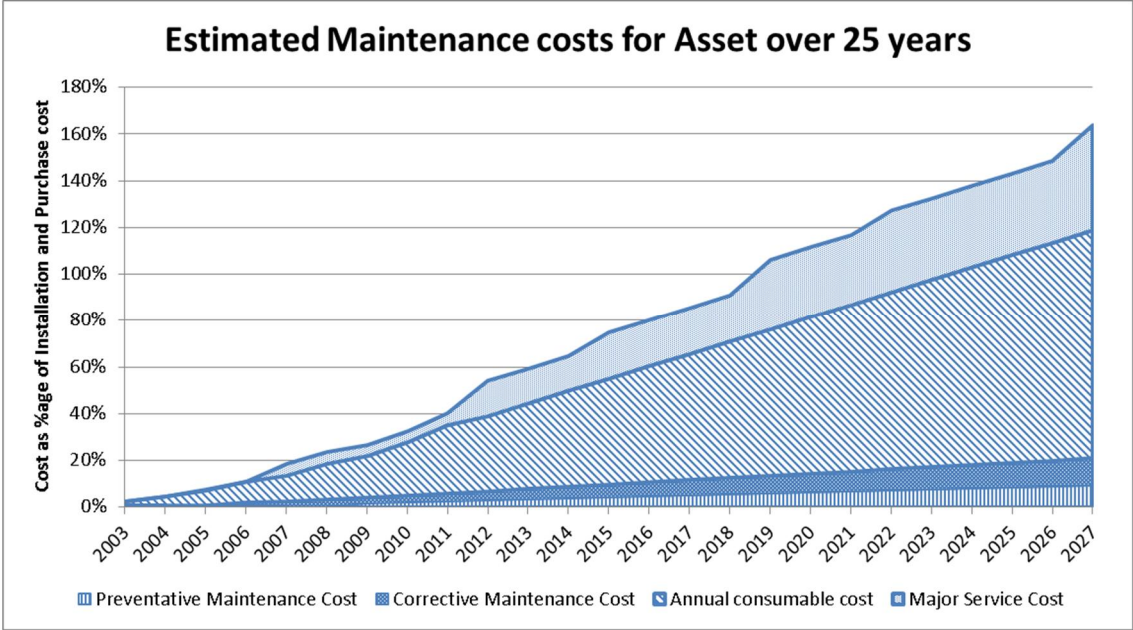

Figure 4. Estimated maintenance costs over a 25 year period.

4.4 Pilot Study Phase 5 - Scenario modelling of impact on cost and availability

To represent in-service costs as described, the first stage was to develop a representative model of the base case to provide a reference point and robust benchmark against which future modelling can be evaluated. The model outlined in the previous sections was created, and populated with data from a 3-year reference period where the quality of data was known to be acceptable.
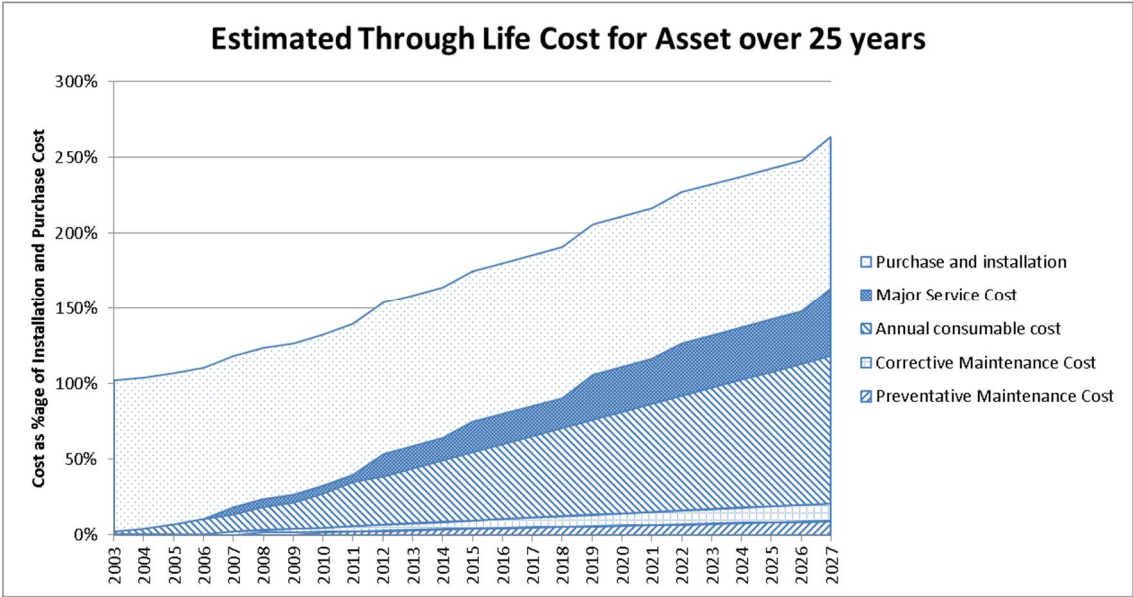
Figure 5. Estimated through life cost over a 25 year life

Estimated Through Life Cost for Asset over 25 years - Reduced Consumable Cost Scenario
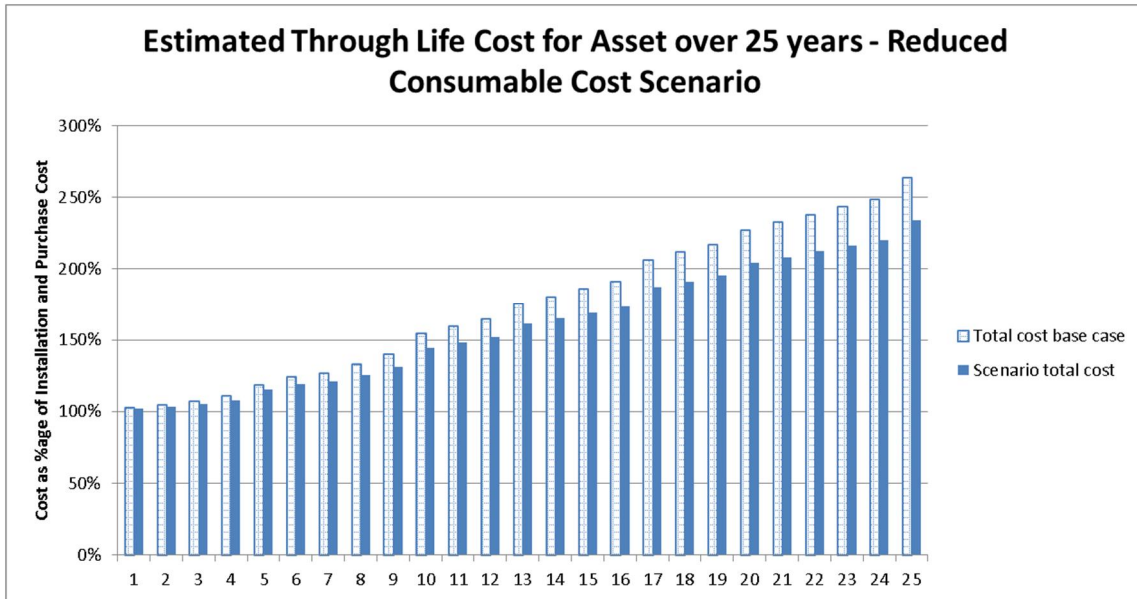
Figure 6. The effect of reducing consumable cost by 30% on through life cost over 25 years

Estimated Maintenance costs for Asset over 25 years Reduced Major Service Frequency Scenario
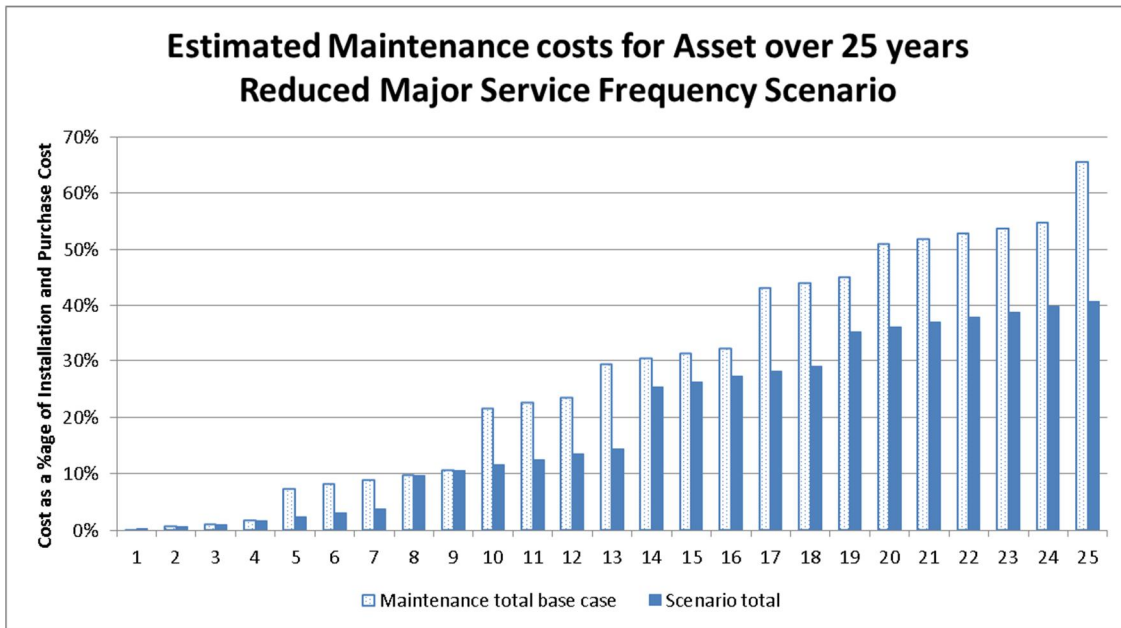
Figure 7. Effect of extending major service intervals by 50% on the total maintenance cost over 25 years

As usage rates for the assets were known for a 10-year period, it was possible to estimate maintenance costs for the whole 10-year period. The assumption was that costs were proportional to level of usage. To estimate the costs for the remainder of the 25-year life chosen to represent the base model, an average 70% usage rate was chosen to calculate future costs. Figure 4 shows the predicted maintenance costs over the 25 year period. The initial model is able to show the effect of changes in maintenance cost on in-service cost, and on through life cost with the addition of data representing equipment and installation cost. Figure 5 shows the estimated through life cost for the base case model over a 25 year life. Figures 6 and 7 illustrate example scenarios. Figure 6 shows the effect of reducing consumable cost by 30% on in-service costs (for example through purchasing negotiation or increased bulk buying), and Figure 7 shows the effect of changing maintenance strategy on the total

maintenance cost over 25 years (through extending major service intervals by 50%, affecting maintenance activities A and B in Table 5).

As the model is extended to include the performance of the system, rather than estimating cost in isolation, the effects of changing parameters on asset availability and performance can be estimated. Performance scenarios can then be considered, such as the effect of unlimited in-service budget on performance, the effect of increasing or decreasing planned maintenance, and the likely effects of extending asset life.

5 Practical implications from the research

The initial model is defined as a simple representation of the system comprising maintenance events and associated labour and consumables costs. Asset managers could use this simple model to estimate the effects of changing system parameters, such as major service intervals, on the cost of maintenance for the pilot system.

As the model is extended, more detailed scenarios can be evaluated. From discussions with the industrial collaborator, modelling and evaluating scenarios will provide benefits in planning for new investment, comparison of alternative technologies, setting budgets, benchmarking, and activity planning. A table describing some potential modelling scenarios is given in Table 6 below.

Table 6. Potential modelling scenarios for asset management

Scenario	Action	Benefit	Risk
Define operating and maintenance schedule to give maximum availability and efficiency	Maximise availability, minimise cost	Optimised system (lowest cost/highest output)	System imbalance – Cost is increased, availability decreases
Operate and maintain at theoretical optimum	Operate and maintain strictly to manufacturer's recommendations	Maximum performance levels	Increased cost
Optimum replacement time for asset	Replace asset at 20 years, 25 years, 30 years	Reduce overall replacement cost (long life) or gain efficiency/technology improvements (short life)	Older assets may have increased failure rate. Equipment and installation cost penalty for new asset
Optimum utilisation rate of assets if increased capacity required	Run k assets at full capacity or run (k+1) at lower capacity	Reduced failure rate and CM cost if utilisation kept lower	Equipment and installation cost penalty for new asset. Increase in PM costs
Unlimited maintenance budget effect on overall availability	Increase PM to saturation level	Reduced failure rate	Increase in PM cost and PM downtime

The modelling approach provides benefits in the management of assets with long life cycles and high value, particularly where the usage cycle approaches continuous operation, offering decision making support at both strategic and tactical levels. Use of such asset management and modelling techniques will become more important especially within the water industry, to meet the multiple challenges to asset value and in-service costs (Palmer, 2010).

6 Overall conclusions

This paper introduces the concept of combining cost estimating techniques with maintenance modelling methods in order to effectively manage in-service costs within the water sector. A phased modelling approach was used to create a robust in-service cost estimation model, extending previous work within the aerospace industry, and tested using an industrial case study. Using the pilot study to illustrate the system definition and data collection stages of the methodology has assisted in identifying challenges in the 'quality' of data and how different approaches are assessed and combined. Robust methods are required to address issues such as disparate data sources, incomplete data, and to build links to address data queries, and obtain expert judgement where required.

The research introduced within this paper aims to find robust methods of managing in-service costs which, as the greatest proportion of asset through life cost, have a major influence on the effective use of assets within an enterprise. This research proposes how techniques to model and assess maintenance policy, and the extension of quantitative parametric techniques in the form of Cost Estimating Relationships and Performance Estimating Relationships, can be used to model asset cost and performance. The research addresses the following gaps which exist in current research:

The model includes all maintenance activities, rather than focussing solely on PM or CM cost, a limitation found in many models. The influence of PM and CM on in-service costs have not been effectively considered in research or practice within the water industry, and a combined approach offers a robust methodology for use in a global industry under increasing pressure.

The model incorporates features of the standard periodic PM policy (Wang, 2002), age replacement PM policy, and condition based maintenance, extending current models based on single maintenance policies.

The modelling approach encodes the variables affecting performance through Performance Estimating Relationships (PERs), addressing the limitation in many models which aim to minimise cost but ignore the effect on performance (Wang, 2002). The research investigates whether parametric techniques can be used to model asset cost and performance, dependencies and inter-connections, and provides a methodology to enable trade-offs to be assessed.

The model considers the asset as part of a system with defined inputs and outputs. There is little existing research on modelling asset performance and cost optimisation, particularly when considering the asset system rather than the asset in isolation. Developing techniques to estimate and manage in-service costs within the water industry contributes within this field.

7 Future Research

The next stage of the research is to evaluate whether the proposed approach is suitable for further asset groups. This will build on lessons learned from the pilot study on system definition and data collection. The modelling approach will then be extended to encompass

defined cost and performance data, including maintenance and operational costs, performance measures, reliability, availability, and fulfilment of contractual and regulatory obligations. encoded within Cost Estimating Relationships (broadly representing the cost of a system input such as cost of consumables) and Performance Estimating Relationships (broadly representing the value of an output such as availability or process throughput). As the modelling framework is developed, test scenarios will be evaluated and assessed, using industrial data/information in order to ensure that the model itself is robust, and the modelling scenarios align with the aim of supporting effective asset management.   This will enable the wider potential for the application of the methodology and modelling approach to be assessed, and conclusions drawn regarding the research hypothesis.

8 Acknowledgements

References

Asiedu, Y.and Gu, P. (1998) 'Product life cycle cost analysis: State of the art review', *International Journal of Production Research*, Vol. 36, No. 4, pp. 883-908.

Bennett, A. (2006) 'Process water: analysing the lifecycle cost of pure water', *Filtration & Separation*, Vol. 43, No. 2, pp. 28-32.

Blanchard, B. S. (1988) 'The measures of a system-performance, life-cycle cost, system effectiveness, or what?', *National Aerospace and Electronics Conference (NAECON 1988),* 23-27 May 1988, Dayton, OH, USA.

Cornwell, H. and Newnes, L. (2012) 'Estimating through-life in-service costs for long-life high-value assets in the water industry', *10th International Conference on Manufacturing Research*, 11-13 September 2012, Aston, UK

Deutsche Bank Research (2010): World water markets. Available via http://www.dbresearch.com/PROD/DBR_INTERNET_EN-PROD/PROD0000000000258353.pdf [accessed March 13 2013]

Engelhardt, M. (2002) 'Determining maintenance requirements of a water distribution network using whole life costing', *Journal of quality in maintenance engineering*, Vol.8, No. 2, pp. 152-164.

Fabrycky, W. J. and Blanchard, B. S. (1991) *Life-cycle cost and economic analysis.* Englewood Cliffs, N.J: Prentice Hall.

Gitzel, R.and Herbort, M. (2008) 'Optimizing life cycle cost using genetic algorithms', *Cost Management*, Vol. 22, No. 6, pp. 34-47.

Goh, Y.M., Newnes, L.B., Mileham, A.R., McMahon, C.A., Saravi, M. E. (2010) 'Uncertainty in Through-Life Costing - Review and Perspectives', *IEEE Transactions on Engineering Management*, Vol. 57, No. 4, pp. 689-701.

HM Treasury (2011) 'National Infrastructure Plan 2011'. Available via http://cdn.hmtreasury.gov.uk/national_infrastructure_plan291111.pdf [accessed June 2012]

Ignizio, J. P. (2010) 'The Waddington Effect, C4U-Compliance, and Subsequent Impact on Force Readiness', *Phalanx*. Available online at http://cmapspublic.ihmc.us/rid=1HTKPYHY3-10D9MZ0-11ML/Waddington%20Effect.pdf.

Kumar, D.U., Nowicki, D., Ramirez-Marquez, J.E, Verma, D. (2007) 'A goal programming model for optimizing reliability, maintainability and supportability under performance based logistics', *International Journal of Reliability, Quality and Safety Engineering*, Vol.14, No.3, pp. 251-261.

Lim, S.-R., Park, D., Park, J. M. (2008) 'Analysis of effects of an objective function on environmental and economic performance of a water network system using life cycle assessment and life cycle costing methods', *Chemical Engineering Journal*, Vol.144, No.3, pp. 368-378.

Newnes, L., Mileham, A., Rees, G. and Green, P. (2011) 'Costing for avionic through-life availability', *Glocalized Solutions for Sustainability in Manufacturing - Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, New York: Springer Science and Business Media, pp. 675-680.

Niazi, A., Dai, J. S., Balabani, S., Seneviratne, L. (2006) 'Product Cost Estimation: Technique Classification and Methodology Review', *Journal of Manufacturing Science and Engineering*, Vol.128, No.2, pp. 563-575.

Palmer, S. J. (2010) 'Future challenges to asset investment in the UK water industry: the wastewater asset investment risk mitigation offered by minimising principal operating cost risks', *Journal of Water and Climate Change*, Vol.1, No.1, p. 17.

Park, J.-H., Seo, K.-K. (2004) 'Incorporating life-cycle cost into early product development', *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, Vol.218, No.9, pp. 1059-1066.

Rowan, P. P., Jenkins, K. L., Howells, D. H. (1961) 'Estimating Sewage Treatment Plant Operation and Maintenance Costs', *Journal (Water Pollution Control Federation)*, Vol.33, No.2, pp. 111-121.

Sachdeva, A., Kumar, D., Kumar, P. (2008) 'Planning and optimizing the maintenance of paper production systems in a paper plant', *Computers & Industrial Engineering*,Vol.55, No.4, pp. 817-829.

Sherwin, D. (2000) 'A review of overall models for maintenance management', *Journal of quality in maintenance engineering,* Vol.6, No.3, pp. 138–164.

Tanimoto, K., Matsushita, M., Tatano, H. (2005) 'Lifecycle Cost Evaluation of Maintenance Policy—The Case of the Water Transmission System in Kobe' in: *Systems and Human Science - For Safety, Security and Dependability*, Elsevier, 147-158.

Veldman, J., Klingenberg, W., Wortmann, H. (2011) 'Managing condition-based maintenance technology: A multiple case study in the process industry', *Journal of quality in maintenance engineering,*Vol. 17, No.1, pp. 40–62.

Waghmode, L., Sahasrabudhe, A. (2011) 'Modelling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems', International Journal of Computer Integrated Manufacturing, Vol.25, No.4-5, pp. 353-367.

Wang, H. (2002) 'A survey of maintenance policies of deteriorating systems', *European Journal of Operational Research,* Vol.139, No.3, pp. 469–489.

Wong, J.S., Scanlan, J.P., Eres, M.H. (2008) 'Modelling the Life Cycle Costs of Aero-engine maintenance' in: Curran, R., Chou, S.-Y, Trappey, A.(Eds.). *Collaborative Product and Service Life Cycle Management for a Sustainable World. Proceedings of the 15th ISPE International Conference on Concurrent Engineering (CE2008)*. London: Springer, 233–240.

Woodward, D. G. (1997) 'Life cycle costing-theory, information acquisition and application', *International Journal of Project Management*, Vol.15, No.6, pp. 335-344.

Monitoring System for arc furnace Casting processes

Loredana Cristaldi[1]*, Daniele Clerici*, Marco Faifer* and Alessandro Ferrero*

[1]Corresponding author: Loredana Cristaldi
*DEIB
-Politecnico di Milano
Piazza L. Da Vinci, 32 – 20133 Milano - Italy
e-mail: loredana.cristaldi@polimi.it
e-mail: daniele.clerici@polimi.it
e-mail: marco.faifer@polimi.it
e-mail: alessandro.ferrero@polimi.it

Abstract

The melting process in arc furnaces depends on the presence and propagation of the electric arc between the electrodes and the scrap charge. The heat produced by the arc current melts the scrap down to create the molten steel.

The characteristics of the electric arc depends mainly on two factors: the "quality" of the scrap charge and the "quality" of the electrical supply and components that contribute to the generation of the electric arc.

In this paper the correlation between melting process effectiveness and the deviations of the actual electrical quantities from the preset values for different scrap mixtures will be investigated. Furnace linings and electrodes degradation is also taken into account.

Key words: Condition Based Maintenance, Arc furnaces, Signature Analysis.

1 Introduction

Arc furnaces have seen a widespread diffusion in melting facilities in the last decades. Instead of Bessemer oxygen converters, for example, they favor a better flexibility of the process. Key factors are more accurate melting process control, less expensive melting charge material (steel scrap), small production batch capabilities, and lower energy requirements (The AISE Steel Foundation, 1998).

It is well known that melting process depends on the presence and propagation of the electric arc between electrodes and scrap charge. The heat produced by the arc current melts the scrap down to create the molten steel (Paschkis, 1945).

The characteristics of the electric arc depends mainly on two factors: the "quality" of the scrap charge and the "quality" of the electrical supply. The furnace process control is automatically set to maintain a specific energy delivery from electrodes to scrap charge; this is done by continuously raising and lowering the electrodes in order to increase or decrease the energy associated to the electric arc following the process requirements (Gandhare and Lulekar, 2007). This action

effectiveness is reduced if the feeding voltage is unstable and/or the scrap charge density is uneven or too low (presence of holes and spots inside the charge or poorly conductive pieces of scrap).

The scrap charge composition is usually classified starting from the type and origin of the steel scrap and relative percentages of each type employed; in this way each scrap charge results in a mixture of various types of materials, selected with respect to their metallurgical properties.

Scrap charge density is indirectly influenced by charge composition, so melting process performance is in a way correlated to the type of employed scrap mixture (Paschkis, 1945). How strong is this correlation depends on the various other factors involved in the melting process and scrap selection.

Moreover, due to the huge amount of produced heat and high electric energy consumption, furnace parts and its ancillaries require a frequent maintenance; in some cases this is done following a preventive maintenance policy on a fixed time interval (every two weeks), like tub and roof lining replacement, while in other cases this is done when needed, like electrodes lengthening and replacement.

In this paper we want to focus on the analysis of the correlation between scrap charge composition, deviations of actual electric quantities from preset reference values, overall degradation of furnace, and actual melting process performances. In particular, the effects of supply voltage quality and type of employed scrap charge will be analyzed and discussed.

This paper is organized as follows: section two is devoted to the analysis of the test plan architecture, section three analyzes the furnace melting process, while the experimental results are analyzed in section four. A discussion about these results is reported, with the conclusions, in section five.

2 The architecture of the analyzed system

In order to verify the applicability of a condition monitoring policy to this kind of system, a plant has been chosen as case study. In this plant, a monitoring system has been specifically designed and installed, in order to implement the analysis described in the previous section.

2.1 The electric system

Calvisano steel plant has been chosen as case study. It is supplied by a dedicated 132kV connection to the 132 kV line that interconnects the 380 kV station in Lonato to the 220 kV station in Marcaria. Both stations are located in the district of Brescia, in Lombardia region, in the Northern part of Italy. The dedicated connection to Calvisano plant is about 10 km long, and is connected to the above 132 kV line with a T-connection placed few kilometres after the sub-station of Montichiari, 10 km from the main station in Lonato.

The electric system of Calvisano steel plant is schematically shown in Fig. 1. The 132 kV line feeds a HV bus bar to which two transformers are connected. The main transformer has two secondary windings. One of them supplies the arc furnace (EAF) and the Static VAR Compensator (ABB FACTS, 2012) through a 32.4 kV bus, while the second one supplies the ladle furnace (LF) through a 15 kV bus. The second transformer supplies a 15 kV auxiliary.

The Static VAR Compensator is tuned to compensate, in particular, the second, third and fourth harmonic components, that are supposed to be the largest ones. The same compensator has been

designed to compensate the reactive power at fundamental frequency (Grunbaum et al., 2005) . The compensator can be controlled according to different strategies: two of them are power factor regulation at power grid connection point, and EAF bus bar voltage active regulation. The supply system is completed by an on-load tap changer installed immediately after the 32.4kV secondary winding of the main transformer. Its main purpose is to maintain the bus bar voltage inside the allowable range for the compensator.

The EAF subsystem connected to the 32.4kV bus bar is composed by the EAF itself, a supply transformer with 30kV primary voltage and secondary voltage that can be regulated from 506 to 922 V by a tap changer (Tap 1 through 21); its rated power is 80MVA.

The measurement systems have been installed on all buses and are represented by the red boxes in Fig. 1.

2.2 The monitoringsystem

The monitoring architecture is based on instruments that are connected to the current (CT) and voltage (VT) transformers already installed in the plant. The CTs and VTs output signals are scaled further on to the ±10 V range, compatible with the input dynamics of the employed Analog-to-Digital conversion (ADC) board. The transducers employed to this purpose have been specifically designed following the same specifications as those followed in (Ferrero et al., 2002a, 2002b). In particular, the voltage transducers are based on non inductive, resistive voltage dividers and the required insulation level is provided by an isolation amplifier. The current transducers are based on non inductive shunts and the required gain and insulation level is provided again by an isolation amplifier. The voltage transducers show a relative standard uncertainty on the gain of 0.04% of the full-scale value and the current transducers show a relative standard uncertainty on the gain of 0.05% of the full-scale value up to 5 kHz. The phase shift between the voltage and current channels is $6 \cdot 10^{-3}$ rad at 50 Hz and is linear up to 5 kHz. Therefore, these contributions to uncertainty can be neglected when compared to the uncertainty contributions coming from the CTs and VTs.
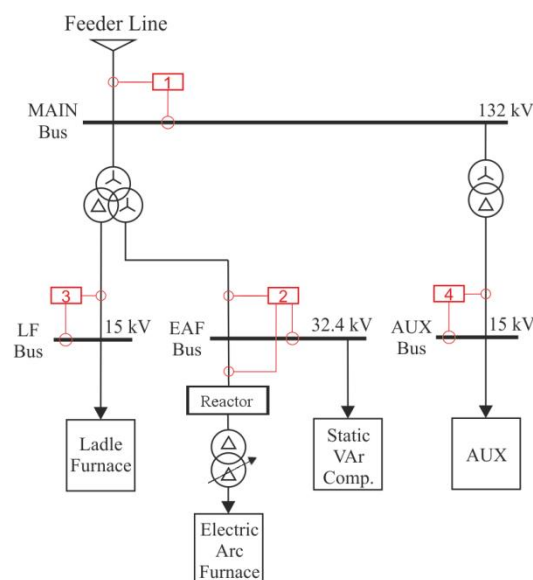

Fig.1 – Calvisano steelwork plant electric system

The voltage and current signals are acquired and converted into digital by NI USB-6351 acquisition boards, featuring 16 analog input channels, 16-bit resolution and 1 MHz/channel sampling rate in multichannel acquisition mode. These ADC boards do not feature a simultaneous sampling of the

input channels. However, the time delay between two contiguous channels introduced by the non-simultaneous sampling is within 2 µs, and does not add a significant contribution to the phase-angle error of the CTs and VTs. Therefore, these ADC boards have been considered an effective trade-off between cost and metrological performances.

The ADC boards are triggered by the furnace control signals, so that voltage and current samples can be acquired and stored during furnace operation and can be correctly referred to each phase of the fusion process. All samples are then post-processed and the significant electrical parameters, i.e. voltages and currents, active and reactive powers from fundamental frequency up to the 11th order harmonic, are computed and analyzed in order to perform the monitoring activity.

Due to technical, production and safety issues, it has not been possible to connect any measuring system to the terminals of the EAF transformer or nearby the EAF area, nor interfacing it with the measuring and control system of the furnace itself; so the electrical quantities at the primary and secondary windings of the EAF transformer are derived from those measured at the 32,4kV bus bar, using technical specifications data of EAF subsystem parts provided by Calvisano steelwork staff.

3 The Furnace Melting Process

The steel production process from scrap is based on the overheating and consequently melting of the scrap charge by means of the arc current passing through it. There are three main steps in this process:

- the scrap melting,
- the steel refining in the Ladle Furnace
- the casting.

This paper will focus only on the first step, performed by the EAF (Paschkis, 1945).

The key factors of scrap melting are the composition of the scrap charge - which depends on the origin, form and metallurgical and chemical properties of the metal scrap -, the thermal energy needed and the way it has to be delivered to the scrap, and the control of chemical reaction and chemical properties of the molten steel bath, during the melting stage and before the tapping stage. The metal scrap comes from car wrecks, steel frameworks of reinforced concrete, machining scrap, sheet metal forming scrap, etc.. A scrap charge is a mixture of two or more of these source materials. In Calvisano plant a scrap charge batch, based on the percentage of certain chemical elements, including copper, nickel and others, is adopted; each batch is marked with an alphabetical letter, ranging from B to K. The more frequently used mixtures are H and K: the first one is composed for the most part of machining scrap and small pieces of framework scrap, the second one contains a high percentage of heavy and bigger framework scrap pieces. By the way, big pieces, and car wrecks also, are cut in smaller parts. This classification is based only upon the supposed quantities of chemical elements contained in the scrap, not on the density of the scrap charge, nor on the thermal or electrical characteristics of the materials composing the scrap.

To help the melting process, the furnace tub is loaded in successive steps; in Calvisano plant four steps are the standard, though sometimes only three steps are adopted. So, the loading process, and consequently the melting process, is divided into four stages, corresponding to four baskets of scrap charge. The whole charge weighs approximately 85-90 tons and is usually divided into the baskets following these approximate quantities: 45% of charge in the first basket, 30% in the second basket, 18% in the third basket, and the remaining 7% in the fourth basket. Usually the first basket is loaded

with more fine materials in order to help the formation of the steel bath and to speed up the furnace heating (Paschkis, 1945), the roughest materials are added to the second and third baskets, and fine materials are used again in the fourth basket to facilitate the refinement process, which starts immediately after the end of the fourth basket melting.

The energy required by the melting process is delivered to the scrap by graphite electrodes, which are electrically connected in delta configuration, and are connected to the secondary windings of the EAF transformer via water cooled bars, flexible conductors and hydraulically operated holders. The amount of energy transferred to the scrap, and also the arc characteristics, have to be constantly changed during the process, to adapt the actual melting conditions to the required ones set by the control system. Both these tasks are performed varying the arc voltage and current following a preset series of steps, which are named furnace gears. A given arc voltage value and three arc current values, one per phase/electrode correspond to each step. The arc voltage is regulated using the tap changer installed on the primary winding of the EAF transformer; the arc currents are independently regulated on each phase by raising or lowering the electrodes with the hydraulic actuators.

The transition between two consecutive steps is based on energy measurement: the control system switches to the next step only when a preset energy threshold is reached. These threshold values are set in form of a specific energy upon weight, so they vary depending on the weight of each scrap charge, i.e. basket. A specific furnace gear is selected for each melting process depending on the characteristics of the employed scrap charge and the desired steel specifications.

The refinement stage starts immediately after the end of the fourth basket melting; it is performed in two steps, the first one energy controlled - the weight of the whole scrap charge is now considered - and the second one time controlled and, very often, manually overridden. For some gears refining is performed in one step, time controlled. The refinement stage is often used to correct the melting process and to add more energy if needed, this is why manual control override is so frequent.

At the end of the refinement stage, chemical analysis are performed and some elements, like lime (CaO) and ferroalloys (FeSi, etc.) are added to attain desired chemical specifications of the molten steel (The AISE Steel Foundation, 1998). Lime helps to form the slab which is very important to reduce heat transfer from bath to air. The chemical reaction evolution during melting depends strongly on the bath temperature (on which depends the formation of some unwanted by-products or lining chemical aggression from elements like phosphorous or fluorum). Bath temperature during melting is controlled, apart from electric energy delivering, also by oxygen insufflation; oxidation reactions take place in the bath and raise the temperature. Oxygen is used also to reduce the quantity of carbon, through carbon dioxide formation. The amount of the elements added after the melting process, together with its duration, specific power applied and energy delivery during the refinement stage, can provide useful information about the effectiveness of the previous stages of the melting process.

4 Experimental results

4.1 Analysis methodology

The Calvisano plant activities, has been monitored and recorded for several months, starting from November 2011in terms of electrical signal recording. The present work focuses on the analysis of a four months interval ranging from November 2012 to March 2013 (during the whole December 2012 until second week of January 2013 the plant was not operating because of periodic

maintenance tasks).All data taken from the monitoring system presented in Section 2.1 have been recorded and post processed in order to evaluate the electrical quantities of interest.

The analysis has firstly focused on the load conditions, reactive and harmonic power consumption and supply voltage analysis for almost all main loads and busbars of the steel plant electric system (see Fig.1). This activity was performed in order to build a solid knowledge about the normal operating conditions of the plant. During this initial observation activity, a lot of attention was dedicated to the actual electric supply conditions, in particular to voltage levels and transients at the coupling point to the electric grid (Marconato, 2002). An harmonic power analysis has also been performed (White et al., 2010;Clerici et al., 2012).

The main objective of this analysis was to discover specific electric supply conditions that could be correlated with poor melting performances of the EAF. For this task, production records and statistics provided by the steel plant staff have also been analyzed and investigated in order to classify the melting processes on the basis of the amount of chemical elements added at the end of the melting process and the weight deviation between the steel produced and the metal scrap utilized.

This study has revealed that sudden variations of the supply voltage at the point of common coupling (PCC) can strongly affect the performance of the melting process, primarily when scrap "quality" and metallurgical conditions are not good. These voltage transients are typical of HV grids and are originated by the insertion and disconnection of capacitor banks used for grid voltage regulation (Miller, 1982; Hofmann et. al., 2012). The analysis of the collected data (Clerici et al., 2012) shows that these voltage transients are present only at sometimes during the day and the week, depending on the grid load conditions. Most, though not all, of melting processes performed during those periods showed problems or poor performances.

A further investigation showed that voltage variations and transients have different impact on the melting performances depending on when they occur during the process; as described in the previous section, each melting stage has its own requirements in terms of energy, voltage and current settings. In few cases higher grid voltage set-point led to better melting conditions and good EAF performances.

In order to attain a better knowledge about the influence of voltage, and currents, on the melting performances, electrical quantities at the secondary windings of the EAF transformer have been estimated, by computing them from the measured quantities at the EAF/SVC bus bar, using equivalent models of cable line, reactor and EAF transformer based on data and specifications given by plant staff. The EAF control system measures voltage and current directly on the secondary windings of EAF transformer, so a direct comparison between preset values and actual values can be done.

More attention has been given to scrap mixtures, as well as to the amount of added chemical elements, in order to create a better classification of the melting processes from the metallurgical point of view.

Refinement stage duration, along with the delivered energy amount and the specific power applied, was also taken into account in order to verify if corrections were made by furnace operators and how much they affected the overall result of the melting process.

Finally, data obtained from maintenance records were considered to investigate correlations between melting performances and the health conditions of the furnace and its ancillary parts.

4.2 Analysis results

During the monitoring period, some critical electrical events were reported by the plant technical staff. First, sometimes during January, a very unstable voltage supply was observed, which led to poor and unpredictable performances of the furnace; secondly, the SVC control criteria has been switched from power factor control mode to bus bar voltage control mode (Hingorani and Gyugyi, 2000) and the consequent set-up tests run in February led to very poor voltage regulation on the EAF subsystem for at least fifteen melting processes.

The analysis described in Section 4.1 has been applied to all melting processes performed during the considered observation period. In particular the considered metallurgical quantities were the amount of lime (CaO) and FeSi ferroalloy added during tapping stage, and the volume of oxygen injected during the whole process. High amounts of lime added could mean a poor slag formation or a consistent contamination of bath from unwanted elements, i.e. poor melting or poor quality scrap. High amounts of FeSi could mean poor quality scrap; in some cases, when scrap melting is not complete the chemical composition of the bath may be incorrect, so ferroalloys addition is recommended. This is not frequent and does not imply a poor furnace performances. High volumes of oxygen are generally injected when arc heating is not sufficient, or when the molten steel is in excess of carbon. Sometimes, plant management may decide to use more oxygen than electric energy for heating the bath, depending mainly on economical reasons, like cost and availability of oxygen and cost of energy (Toulouevski and Zinurov, 2010). In addition, the employed steel scrap batch and the deviation between the amount of charged scrap and the amount of tapped steel have been recorded. Deviations larger than 12% are considered as undesired, and those larger than 15% are flagged as excessive.

The considered electrical quantities can be divided into two parts, those related to the supply side (i.e. voltage rms values and their deviations from the rated ones both at the PCC and at the EAF/SVC bus bar), and those related to the EAF side, such as arc voltage and energy delivered to the electrodes. In this case, ideal electrical parameters derived from furnace gears value settings have been considered and the deviations of the actual quantities from the ideal ones have been evaluated; in particular, the arc voltage deviations, the electric energy deviations and the difference between the duration of the actual melting stage and the ideal one have been considered for each melting stage.
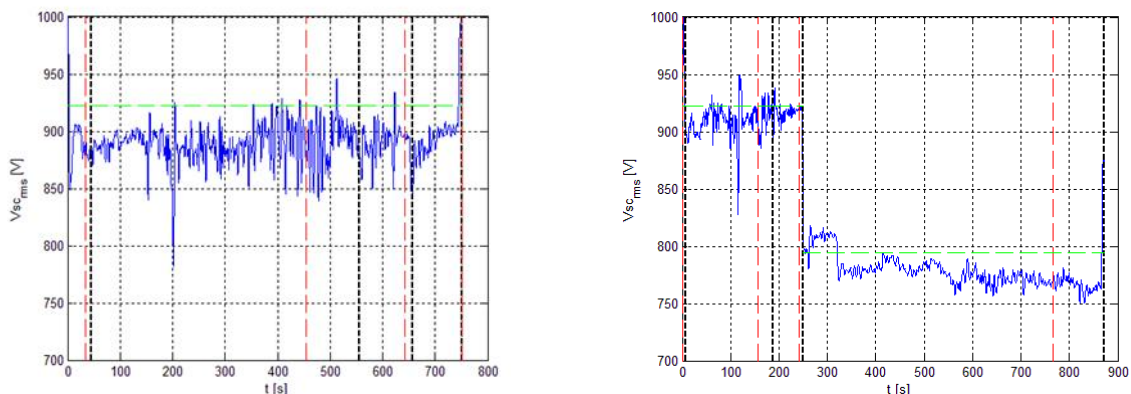

Fig.2 – First and refinement stages of a process with low weight deviation, low arc voltage, H type mixture

Melting processes with low weight deviations have been first considered. In some cases low voltage levels were observed both at supply side and at the EAF side, along with a significant variation from their rated values. In particular (see Fig. 2; horizontal green dotted lines represent arc/current voltage setting values; vertical dotted lines are the time limits of furnace gears steps– actual in

black, ideal in red) arc voltage results very low during the first stage and remains low during the next two stages; stage durations are longer and an extra energy is delivered to scrap. Refining stage shows an higher arc voltage; duration and power delivered values are in the normal range (10 to 12 min, 64 to 66MW). H type scrap blend was employed and low amount of additives were added. In this case it is quite evident that scrap mixture, extra energy delivered to scrap and good refinement conditions were enough to overcome the poor voltage characteristics and led to a very low weight deviation, i.e. 8,5%.

This behaviour was observed also with K type scrap mixture (Fig. 3), but with lower deviations of the arc voltage from the rated value, better electric conditions in the last two melting stages and refinement stage with longer duration (more than 13 minutes) and extra power delivering in all stages. All these factors led to a weight deviation of 8,6%.

In both these cases, the key factor for the good quality of the melting process seems to be the extra power delivering and the effectiveness of the refinement stage. For supposed better scrap charge quality (type H), voltage deviation and poor electrical conditions seem to have limited influence over the overall quality of the process, but they become more critical for a lower quality of the scrap (type K).
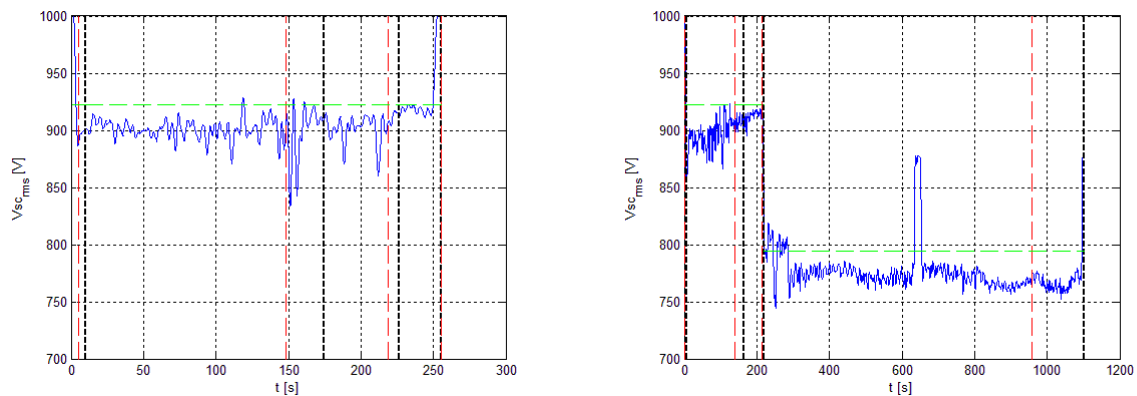

Fig.3 – Third and refinement stages of a process with low weight deviation, low arc voltage, K type mixture
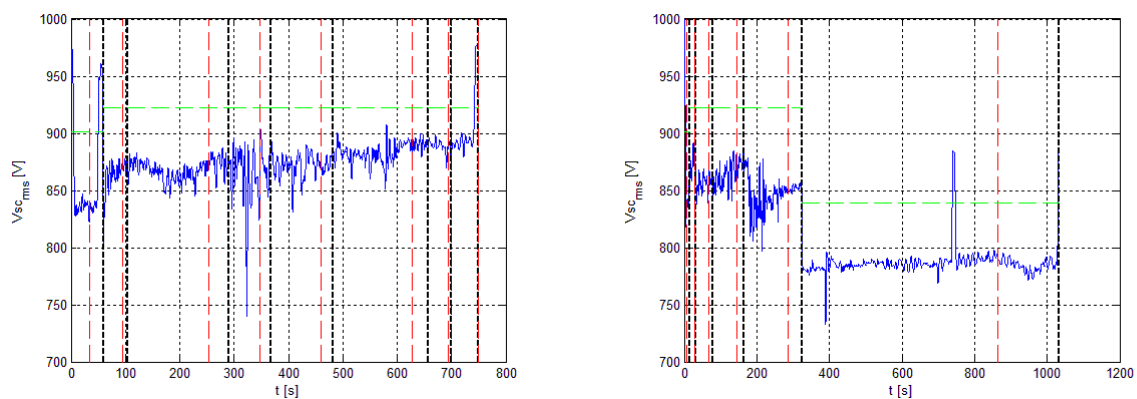

Fig.4 – First and refinement stages of a process withvery low arc voltage due to wrong voltage regulation

Moreover, a good result can be obtained also when the quality of the energy supply is low and the voltage set-point regulation on EAF bus bar is not effective (Fig. 4, Fig. 5a). This condition has occurred when the SVC control mode was changed.
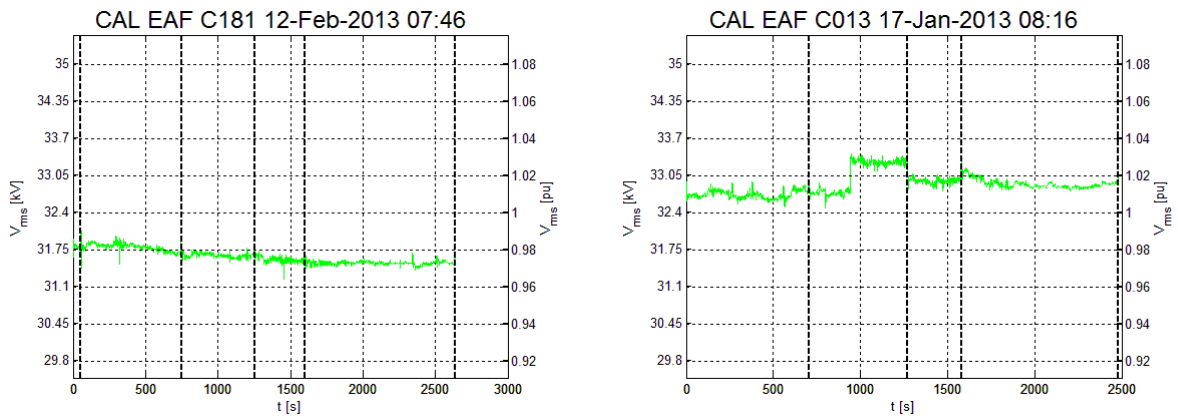
Fig.5 – EAF busbar voltage profiles: (a) wrong voltage regulation, (b) variations in supply voltage

Some melting process during this period showed weight variations below 12% even if the arc voltage deviation was very high (50-70 Volts, see Fig. 4; from a transformer tap to the next, voltage difference is nearly 20Volts) and consequently power delivery during the whole melting and refinement processes was also very low: this can be possible only using type H scrap mixture and with a process duration consistently longer (at least 8-10 minutes) than expected. A significant amount of lime and ferroalloys additions was observed. In the same situation the use of K type scrap blend led to an excessive weight deviation (more than 15%), while low figures (8,6%) like the first ones described were obtained again only using E type scrap mixture.

In some cases with nearly optimal electric conditions, low arc voltage deviations, extra power added and longer refinement duration, weight deviations are in excess of 15% along with a discrete amount of *lime* and ferroalloys additions. This happens mainly when type K mixtures are used: a logical explanation could be that some basket charges are rough, with bulky pieces of scrap which led to an uneven media full of holes, and so very difficult to be molten correctly. Obviously these conditions can happen frequently when rough, low quality, steel scrap is used.

The differences in the quality of scrap charges and their influence upon arc electrical quantities, is observed in several melting processes.
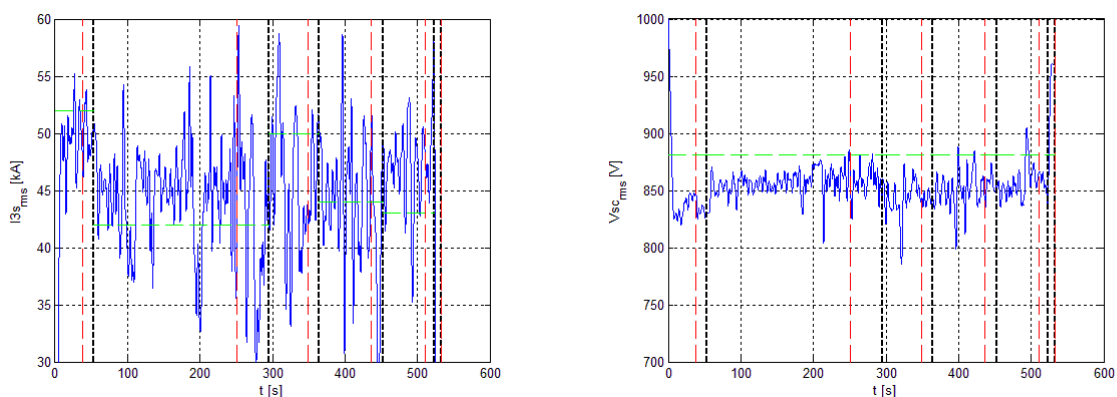

Fig.6 – Typical arc current and voltage trends of a melting stage with rough scrap charge

Considering only melting processes with a supply voltage with a stable profile, without significant variations and transients, and the same scrap mixture type, it is clearly visible that the arc current variation is more consistent and deviates significantly from the setting value during the second and third melting stages; this behaviour has a negative influence on the arc voltage deviations which

become greater (Fig. 6) (as explained in Section 3, the first and last baskets are usually loaded with good quality scrap with small pieces and better metallurgical properties, while the second and third ones are loaded with rough materials of poor quality). After having changed the SVC operating mode and when the EAF bus bar voltage set-point is in excess of 1.01 p.u. a mitigation of this effect was observed. This led to conclude that a voltage set-point regulation improvement is necessary.

A similar situation occurred during short periods in January 2013. In this case several variations in the supply voltage were observed (Fig. 5b), resulting in a unstable arc voltage from one melting stage to another and also during a single stage. This led to weight deviation higher than 15%, and only in some cases, in the presence of a type E scrap mixture, a little more than 12%.

As mentioned before, maintenance records have been considered in order to investigate any correlation between melting performances and furnace ageing. From the observation of the recorded data there is no evidence of a direct and consistent influence of the melting performances by the furnace tub linings and ancillaries; explained phenomena happened even in the presence of a new tub lining than when lining is nearly to rebuild.

Also electrode consumption does not reflect into any significant changes in melting performance; they are lenghtened as needed and sometimes new sections are added, when they become too short to be lengthened anymore. Anyway, when electric arc quantities are very close to the reference values, mainly during refinement stage, electrodes lengthening is more frequent. In fact, in correct operating conditions, they draw more power so they wear out faster.

5 Discussion and Conclusions

The results of this analysis showed that melting performances are largely affected by the lack of energy delivering from the EAF furnace to the scrap charge.

The more critical influence factor is the scrap charge composition and its physical characteristics, i.e. its "quality". It was showed that, under correct melting conditions, bad composition and poor quality of the scrap charge can completely upset the expected melting process result, or at least get it worse.

Also, a non-efficient electric supply is the second main cause of poor melting process. In the majority of cases this situation can be recovered by adding more energy to the molten steel bath by extending the duration of the melting and refinement stages. In this way some processes affected by poor EAF performance can be corrected resulting in a weight deviation less than 12%. Unfortunately this action could be ineffective if the quality of scrap is low or if the EAF melting capability is strongly reduced by electric supply inefficiency.

The influence factors of electric supply conditions are: the stability of the grid voltage, the effectiveness of the EAF bus bar voltage regulation and the effect of scrap composition on the arc currents and consequently on voltage drop.

The first two factors can be easily managed by using a more accurate bus bar voltage regulation system or simply upgrading the present one. The new control criteria should take into account both the load conditions of the furnace and the grid voltage level; in this way the bus bar voltage will be properly tuned for every operating condition.

A new classification of scrap charges, which involves also electrical and thermal considerations, could help to manage the third factor: by doing this, the evolution of the melting operation may be

more predictable, and both voltage bus bar settings and *furnace gears* definition could be done with better accuracy. In this way, when switching from a first to a second stage of melting, for example, the EAF subsystem settings could be changed in order to improve furnace melting capability when a rough and uneven scrap charge is loaded.

In conclusion, it is worth noting that an EAF system is extremely complex to investigate. Therefore, this analysis has to be developed further on, and a set of conventional electrical parameters should be considered, related to each type of scrap mixture. These parameters can be obtained starting from data acquired by the implemented monitoring system, and they can be used to define and implement an improved monitoring system, interfaced with the furnace control system, capable of providing real-time information about melting process evolution. By doing this, a new and effective process management system will be implemented, capable of automatically set EAF furnace and voltage set-point regulation parameters, thus attaining better melting performances in every operating conditions.

6 Acknowledgements

References

Various authors, *"The Making, Shaping and Treating of Steel - Steelmaking and Refining Volume"*, The AISE Steel Foundation, USA, 1998

V. Paschkis, *"Industrial Electric Furnaces and appliances"*, Interscience Publishers Inc., New York, 1945

W.Z. Gandhare, D.D. Lulekar, "Effect of Electrode Regulation System on Arc Parameters in Furnace Operation", *IECON 2007 conference proceedings*, pp. 921-925.

"Reference List – Dynamic Shunt Compensation", ABB FACTS division, 2012

R. Grunbaum, D. Dosi, L. Rizzani, *"SVC formantainingof Power Qualityin the feeding Grid in Conjunction with an Electric Arc Furnace in a Steel Plant"* , proceedings of *18th International Conference on Electricity Distribution (CIRED 2005)*, Section 2

L. Cristaldi, A. Ferrero, and S. Salicone, "A distributed system for electric power quality measurement," *IEEE Trans. Instr. Meas.*, vol. 51, no. 4, pp. 776–781, 2002.

A. Ferrero, M. Lazzaroni, and S. Salicone, "A calibration procedure for a digital instrument for electric power quality measurement," *Instrumentationand Measurement, IEEE Transactions on*, vol. 51, no. 4, pp. 716 – 722, Aug. 2002.

R. Marconato, *"Electric Power Systems"*, CEI, 2002

R.S. White, T.J. Dionise, and J.A. Baron, "Design, analysis, and operation of the electrical distribution system for a modern electric arc furnace and ladle melt furnace," *Industry Applications, IEEE Transactions on*, vol. 46, no. 6, pp. 2267 –2275, Nov.-Dec. 2010.

D. Clerici, L. Cristaldi, A. Ferrero, M. Prioli, "The impact of electrical disturbances on the casting of an arc furnace", proceedings of *IEEE International Workshop on Applied Measurements for Power Systems (AMPS 2012)*, pp. 1 – 6

T.J.E. Miller, "Reactive Power Control in Electric Systems", Wiley, 1982
W. Hofmann, J. Schlabbach, W. Just, *"Reactive Power Compensation"*, Wiley, 2012

N.G. Hingorani, L. Gyugyi, *"Understanding FACTS – Concepts and Technology of Flexible AC Transmission Systems"*, IEEE Press, 2000

Y.N. Toulouevski, I.Y. Zinurov, *"Innovation in Electric Arc Furnaces"*, Springer, 2010

Photovoltaic Plant Maintenance: a method base on Economic evaluation of PV system losses

Loredana Cristaldi[1]*, Marco Faifer*, Massimo Lazzaroni**, Marco Rossi* and Sergio Toscani*

[1]*Corresponding author: Loredana Cristaldi*
*DEIB
Politecnico di Milano
Piazza L. Da Vinci, 32 – 20133 Milano - Italy
e-mail: loredana.cristaldi@polimi.it
e-mail: marco.faifer@polimi.it
e-mail: sergio.toscani@polimi.it
e-mail: marco4.rossi@mail.polimi.it
**Dipartimento di Fisica - Università degli Studi di Milano
Milano (MI), Italy
massimo.lazzaroni@unimi.it

Abstract

In literature few studies analyze the efficiency degradation due to the presence of dust on Photovoltaic (PV) modules (*e.g.* Meyer and Van Dyk, 2004; Hamdy et al. 2006; Powers et al. 2010; Mani and Pillai 2010). Since photovoltaic panels have to work in open space, the dust deposition cannot be avoided thus determining a reduction of energy production with respect to the clean condition. In order to quantify the effect of the reduced energy production on the payback ratio and to evaluate the long-term system performances of a photovoltaic plant, an accurate prediction of the plant efficiency and of the maintenance cost is mandatory.
In this paper an economical model that takes into account the relation between the losses in the energy production (predicted by means of an electric model of a PV reference panel) and the maintenance operations cost will be presented. The opportunity of using environmental data, acquired by means of public weather station will be also discussed.

Key words: Condition Based Maintenance, Measurements, Photovoltaic plant.

1 Introduction

Renewable energy systems are fairly reliable but, like any complex system, they may fail. Hence the effects of their failures should be analyzed and taken into due account. Photovoltaic panels represent the most reliable element of a PV system. Several efforts in the manufacturing process have been performed in order to obtain long life-times. Nowadays few reliability tests for photovoltaic components are available and they have demonstrated that the mean life-time of a typical PV panel is higher than 20 years. The reliability issue becomes more complex when a combination of PV panels in a PV field is considered (Mani and Pillai, 2010). In this case the reliability model has to include, in addition to the PV panels, several other components (by-pass diodes, string diodes, cables, connectors…). Despite some of these

components increase the reliability making the PV plant fault-tolerant, they also render more difficult the fault detection. For this reason, a continuous monitoring of the photovoltaic plant is mandatory so as to promptly detect the presence of an abnormal situation and for the planning of the maintenance operation.

In this scenario it is not only fundamental to guarantee the functionality of both the plant and the PV panels but also the reliability and maintainability performances. It is well known that the evaluation of reliability and maintainability performances can be done only if the failure conditions for the equipment under test are known. In order to maximize the aforementioned characteristics, failure modes must be taken into account, studied and predicted (Mishra, 2006; Catelani et al. 2011, Lazzaroni et al. 2011).

Among maintenance tasks one of the less considered activities is that related to the cleaning of the panel surface. It is important to highlight that losses due to the dust have a very important impact in PV module and plant performances. In fact this factor can results in a performance reduction up to about 7% (Detrick et al. 2005). Despite of this, cleaning is not usually considered by maintenance contracts and when it is taken into account it is often not well scheduled. In fact the cleaning strategy for PV plant is usually preventive and not condition based.

In order to optimize the production of a photovoltaic plant by also considering the maintenance effects, Cristaldi et al. (a, b 2012) have proposed an economical model which can take into account the impact of dust and pollution in terms of efficiency reduction and economic energy loss evaluation. In the cited paper the authors assume that radiation data are provided by a measurement station located in the same place of the plant.

In this paper, the authors propose a new approach where the electrical model of a PV panel is used to define the energy profile related to the plant and suitable for the economic loss evaluation. In order to overcame the technical problem related to the monitoring of every single panel installed in large plant, the monitoring system is based on the use of a reference qualified panel.

So as to simplify and reduce the cost of maintenance activity, in this paper the opportunities and drawback of using environmental data acquired by means of public weather station have been also evaluated. This evaluation considers a weather station located in the same climatic area of the PV plant but far from it.

In Section 2 strengths and drawback of monitoring systems are considered and highlighted, whereas in Section 3 the role of a public weather station in a monitoring system is evaluated and, finally, in Section 4 an economical model is introduced and discussed.

2 The role of a monitoring system: strengths and drawback

In order to quantify the payback ratio and to evaluate the long-term system performances of a photovoltaic plant, an accurate prediction of the plant efficiency and of the maintenance cost is mandatory. In fact, the business plan should take into account not only the investment cost and the revenues based on rated data but also all the possible loss factors. Among these factors maintenance operations play a fundamental role. From a practical point of view, after the implementation of a photovoltaic plant, several maintenance plans are usually available: from a simple monitoring of plant performance to a more advanced "performance based contract" in which the customer pays for a guaranteed plant performance (corresponding to guaranteed annual revenue).

As mentioned in the previous section, the losses due to the dust can be reach the 7% but cleaning is not considered by maintenance contract and this activity follows preventive policy. In order to realize an effective condition based approach (CBA) the knowledge of the performances of the plant for different solar radiation and temperatures is required. The difference between the energy forecast and the energy production can be considered as a strong parameter in the definition of maintenance scheduling. In fact, when a reduced efficiency is registered, the cumulated losses can be economically evaluated in terms of profit reduction. Thanks to this evaluation, the maintenance operations can be planned more efficiently as discussed by Cristaldi et al. (a, b 2012).

Starting from this assumption the knowledge of the environmental parameters (solar radiation, air and panel temperature) and electrical ones (voltage and current) is mandatory. Unfortunately, the instruments devoted to the evaluation of solar radiation (pyranometers) requires the definition of a suitable maintenance policy. In fact pyranometers require an accurate cleaning of the external surface and a control of the humidity inside the case of the instrument. Without a correct maintenance policy measurement information can lose effectiveness. On the contrary, the measuring process of the electrical quantity cannot be considered a problem: it is possible reaching good accuracy in a cost effective way and the apparatus devoted to the measurement of the electrical quantity does not require the definition of procedures for a scheduled maintenance.

The main drawback of a monitoring system of a large PV plant could be represented by the complexity in the management (in term of hardware and software) of a large number of measurement sections. In order to overcome this drawback it is important to define in a clear way the target of the monitoring system. A system devoted to energy monitoring can observe, for example, only the status of the different strings of the plant by means the electrical quantities while a condition monitoring strategy requires, in addition, the knowledge of the panel temperature and solar radiation.

In order to define a flexible but easy monitoring architecture the authors have presented a solution based on the use of a reference panel. This architecture can support the energy monitoring and can be used to analyse the failure mode represented by the dust deposition on the panel surface. If the reference panel has been chosen following a statistical approach it could represent, with a given confidence level, the behavior of the PV plant in different condition of dust deposition and aging (Catelani et al. 2012).

2.1 Reference panel supported by a PV panel model

In order to define an electrical model of a PV panel, Cristaldi et al. (2012, c) have proposed a simplification of the traditional single diode model. The proposed simplified single diode model that will be used in the following is depicted in figure 1. This innovative model is particularly suitable for the simulation of photovoltaic cells and panels which operate in the typical working conditions of a photovoltaic power plant, where the definitional uncertainty of this model is comparable to the uncertainty of the measured environmental conditions and other contributions.
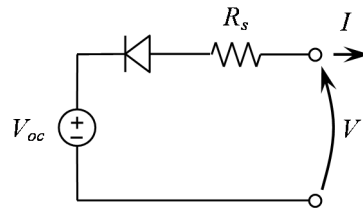

Figure 1. Simplified single diode model

The model has been tested with two different kinds of module technologies: mono and poly crystalline. A 180 watt mono crystalline and a 5 watt poly crystalline modules were used to verify the accuracy of the proposed model using the measurement set-up shown in figure 2.
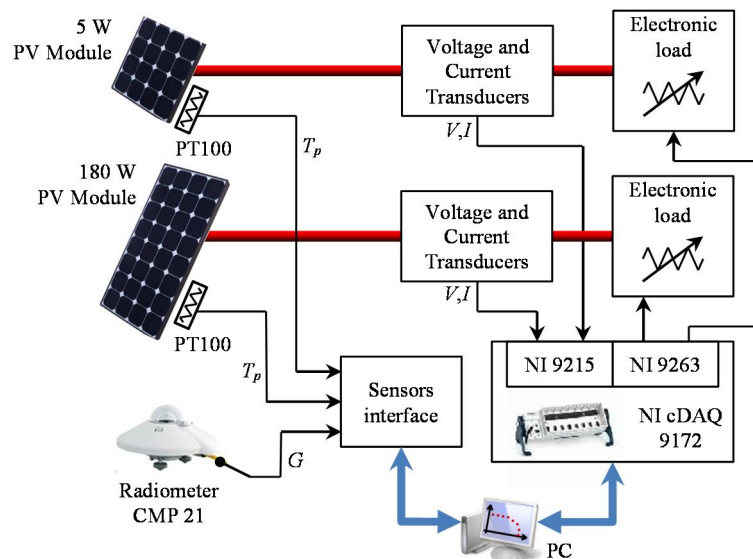

Figure 2. Monitoring technique based on the comparison of the energy production: The PC manage the electronic loads and compute the comparison between the produced and estimated energy panels.

PV panels should work such as to maximize the energy production by working in a particular point of their voltage current characteristic, the so called Maximum Power Point – MPP. The validation of the model has been performed by comparing the actual Maximum Power (MP) Voltage and Current with those provided by the model for the two panels in outdoor conditions. The results of the comparison are shown in figure 3 and 4.

The predicted energy W_{est} is provided by computing solar radiation G and panel temperature T_p by means of the PV model equation presented by Cristaldi et al. (2012, c). Since the electronic loads (depicted in Figure 2) extract the MP from the panels under test, the power

production can be estimated by means of the model equation which provides the MP point, in term of voltage V_{mp} and current I_{mp}, for each given environmental condition. The energy production can be successively estimated as:

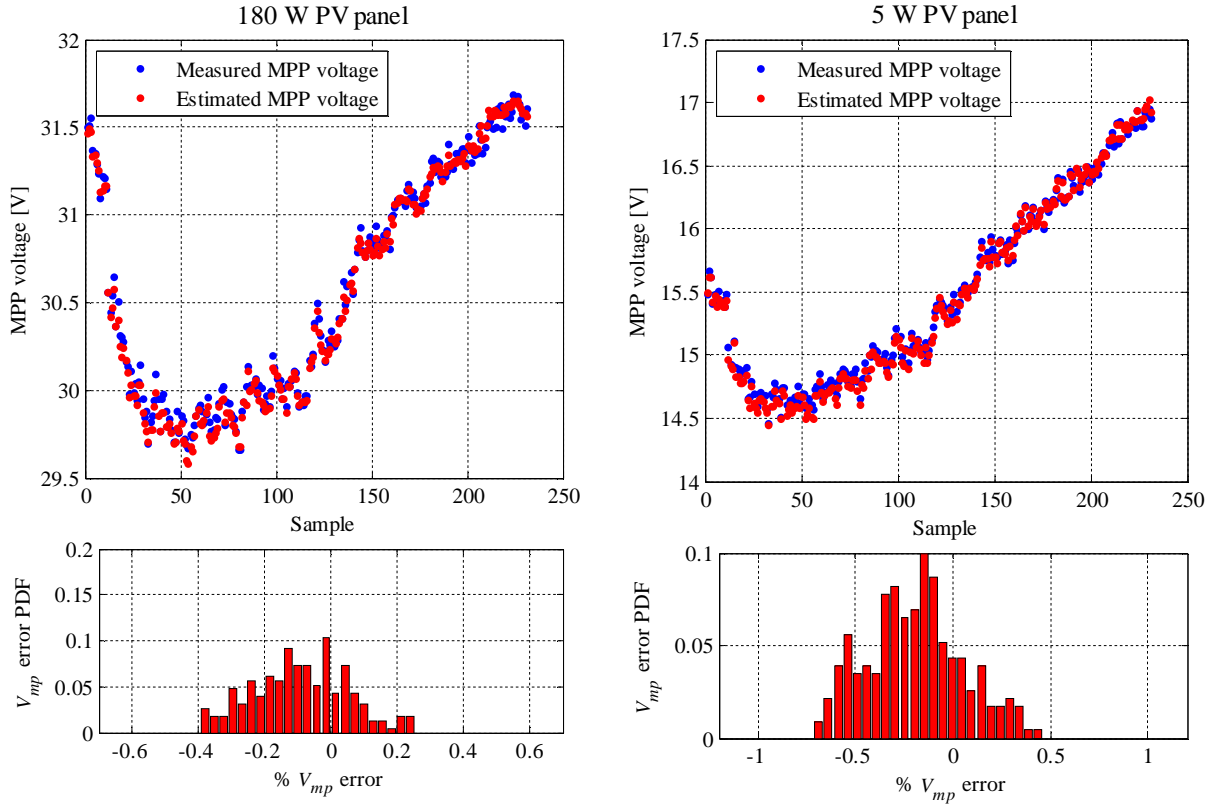$$W_{est} = \int_{t_1}^{t_2} V_{mp} I_{mp} dt \qquad (1)$$

Figure 3. Comparison between measured and estimated MPP voltage

The procedure for the estimation of the production has been tested for twenty days. The computation of W_{est} has been performed daily for a time range of 24 hours (t_1 corresponds to midnight and t_2 to midnight of the following day). The electrical and environmental quantities have been acquired thanks to the measurement setup described in Figure 2 with a sampling frequency of 180 Samples/hour. Processing these quantities by means of the proposed electric model and by applying (1), it is possible to estimate the energy production related to the panel.

In Table 1, a list of the analyzed days is reported. For all of them, the weather conditions, the produced energy and the error, estimated at the end of the day are synthesized.
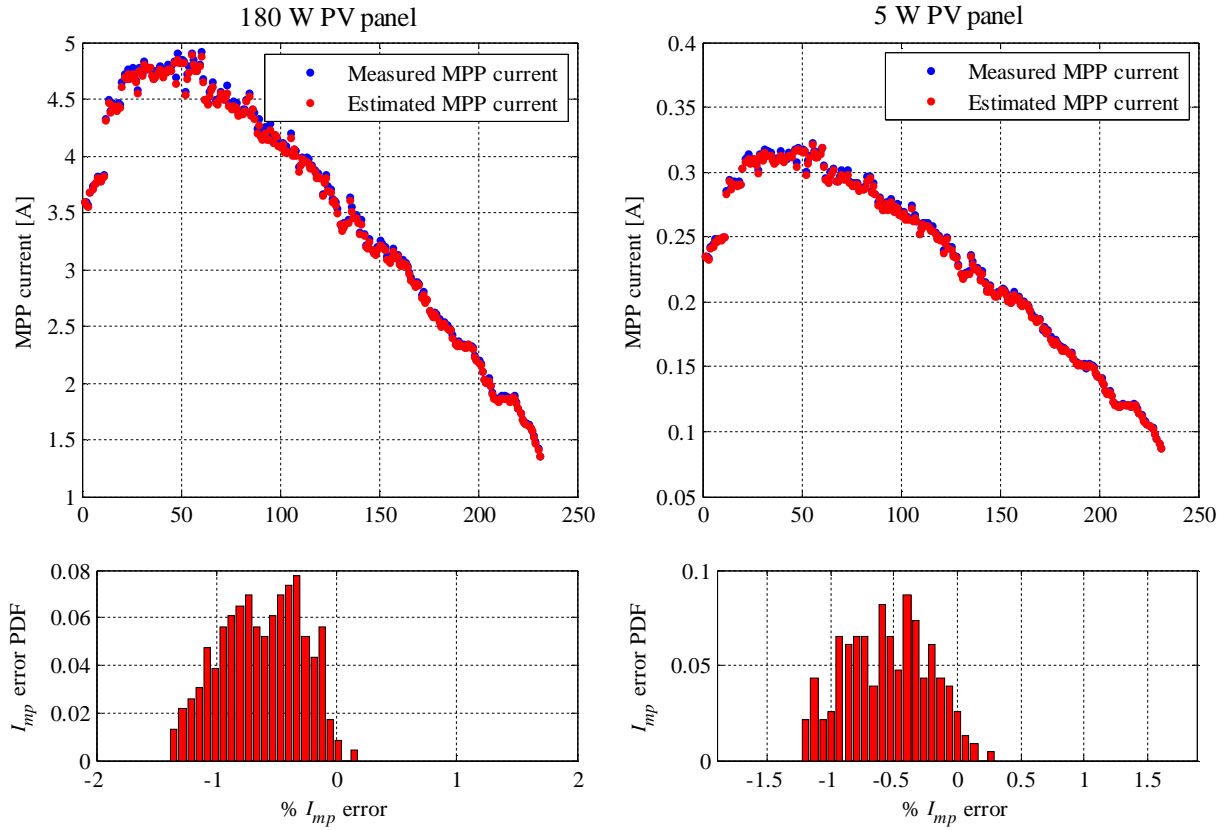
Figure 4. Comparison between measured and estimated MPP current

Table 1: Energy production error analysis

Day	Weather	Produced Energy	Estimation error
July 9th, 2011	Rainy	1.24 MJ	-1.95 %
July 10th	Partly Cloudy	2.51 MJ	-1.18 %
July 11th	Sunny	3.26 MJ	-1.08 %
July 12th	Rainy	2.30 MJ	0.10 %
July 13th	Rainy	0.60 MJ	-2.69 %
July 14th	Partly Cloudy	2.33 MJ	-1.51 %
July 15th	Partly Cloudy	3.05 MJ	-0.44 %
July 16th	Partly Cloudy	1.30 MJ	-2.14 %
July 17th	Rainy	0.88 MJ	-2.06 %
July 18th	Sunny	3.27 MJ	-1.06 %
July 19th	Rainy	1.13 MJ	-2.29 %
July 20th	Sunny	3.51 MJ	0.71 %
July 21st	Sunny	3.47 MJ	0.46 %
July 22nd	Sunny	3.40 MJ	0.43 %
July 23rd	Partly Cloudy	2.36 MJ	-1.05 %
July 24th	Sunny	3.33 MJ	0.53 %
July 25th	Partly Cloudy	3.18 MJ	0.54 %
July 26th	Rainy	2.69 MJ	0.92 %
July 27th	Partly Cloudy	1.92 MJ	-1.08 %
July 28th	Partly Cloudy	2.77 MJ	-1.01 %

In Figure 5 the daily actual production W_m (measured) is also plotted and then compared with the estimated one (the relative error, registered at the end of the day, corresponds to -1.08 %).

Results demonstrate that, when the solar radiation and the temperature are measured locally, the prediction of the production of a photovoltaic panel is accurate: comparing model output and actual one for the reference panel, it is possible to estimate, day by day, the energy reduction related to the dust deposition on the panel surface or, in clean condition and the aging effect.

The bottle neck of this approach is represented by the pyranometer: it is an expensive instrument that requires, as just recalled in the previous Section, a maintenance policy.
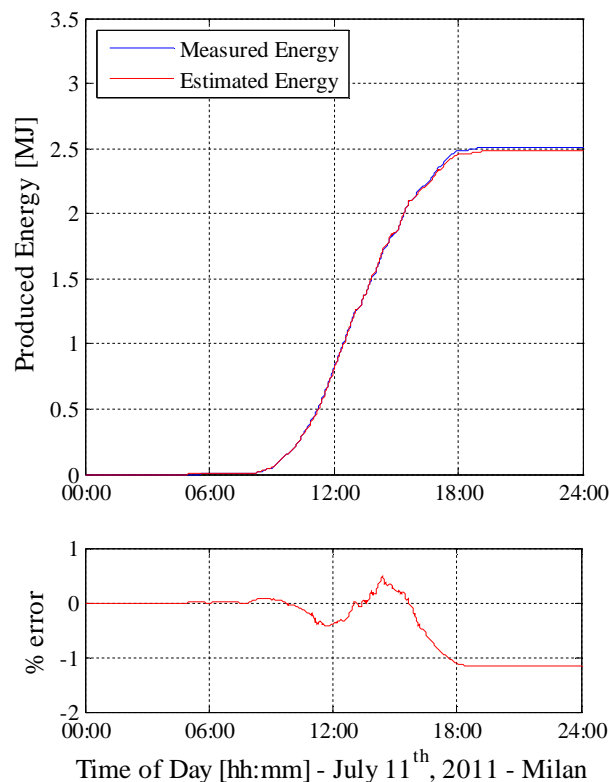

Figure 5. Monitoring Comparison between measured and estimated production on July 11th, 2011 – Milan

3 Use of data collected by public weather station: discussion

In order to overcome the problem related to the use of a pyranometer installed in the plant, it is possible to evaluate the effect on the measurement resolution when the radiation data are collected by a public weather station. This approach has the advantages the information is guaranteed in term of validation of the data and completeness for the manner in which the data are collected. It is important to highlight that this solution shows few drawbacks which are mainly related to:

   - the time resolution of the provided data;

   - the distance between the PV panel and the weather station.

In order to verify the effect of the time resolution it is possible to evaluate the energy production by means of the electric model and by using data of solar radiation with different time resolutions. In Figure 6 the effect on energy production, which has been estimated for two different situations, is shown: clear day and mostly cloudy day. In this figure, the data of solar radiation has been obtained as average on different time windows of measurements collected near to the PV panel with a sampling period of 20 s. The error has been computed with respect to the output of the model fed with no averaged data.
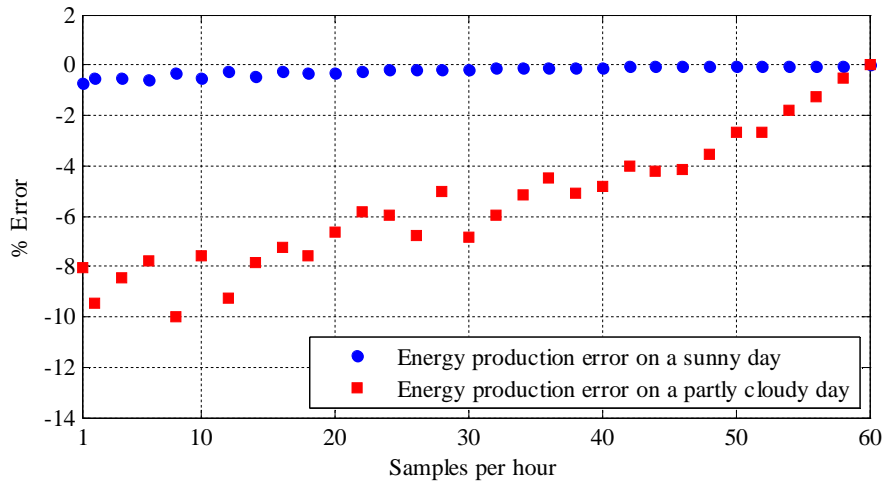

Figure 6. Effect of energy evaluation of the time resolution of the solar radiation

Figure 6 clearly shows that the error is low as far as the time resolution is high. However, low time resolutions do not introduce significant error in the energy estimation when it is computed for sunny days. In fact, as well shown, it is not possible to find a significant correlation between the error and the number of samples per hours.

Another factor which could impact significantly the estimation of the energy production is the distance between the weather station and the PV panel under test. Assuming that the weather station is close to the panel under consideration (on the order of few kilometers) the apparent position of the sun with respect to these two points can be reasonably considered the same. The only phenomenon which can introduce a relevant error is represented by the assumption that the solar radiation measured on the weather station and that in the place where the PV panel is installed are the same. In fact, this statement is not verified for each weather condition, since for non-uniform cloud coverage of the sky, the irradiation of the ground can vary significantly in the range of few hundreds of meters. In order to verify the effect of the distance between the PV panel and the weather station the solar radiation measured in two different locations have been compared. It can be seen that, despite the distance is only 2 km, in partly cloudy days the solar radiation measured in the two location are pretty different, as depicted in the right side of the Figure 7. On the contrary, the measurements performed during clear days result very similar (Figure 7, left side). When the sky can be considered in clear condition, the maximum error in the evaluation of the solar radiation using data acquired by a weather station placed 2 km far from the PV panel is in the range ± 5%.

In order to evaluate separately the effects due to the time resolution and those due to the distance, the solar radiation acquired locally has been averaged and resampled with time steps of 6 samples/h and 1 sample/h. The application of these two different resolutions impact on the error in the energy estimation, which have been called ε_{loc6} (6 samples/h) and ε_{loc1} (1 sample/h) respectively. Successively, the energy has been computed by using the data

provided by the weather station. The obtained estimation error, in this case, have been called ε_{ws6} (6 samples/h) and ε_{ws1} (1 sample/h).
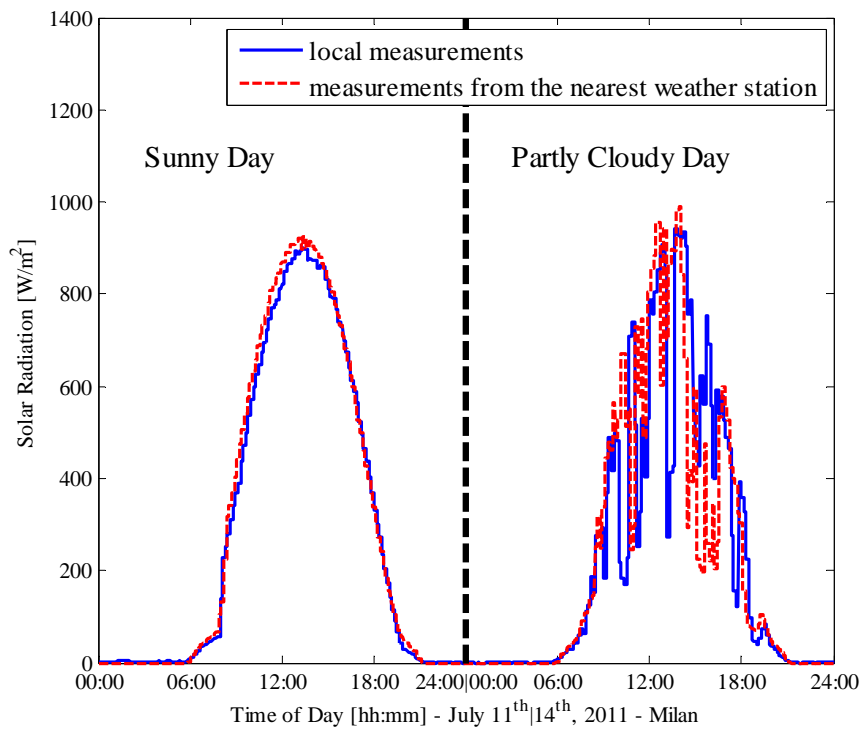

Figure 7. Solar radiation measured in two different locations (distance of 2 km) and different weather conditions

In Figure 8 and 9 the trends of the estimated production of the PV panel under test are plotted for a sunny and a cloudy day respectively.
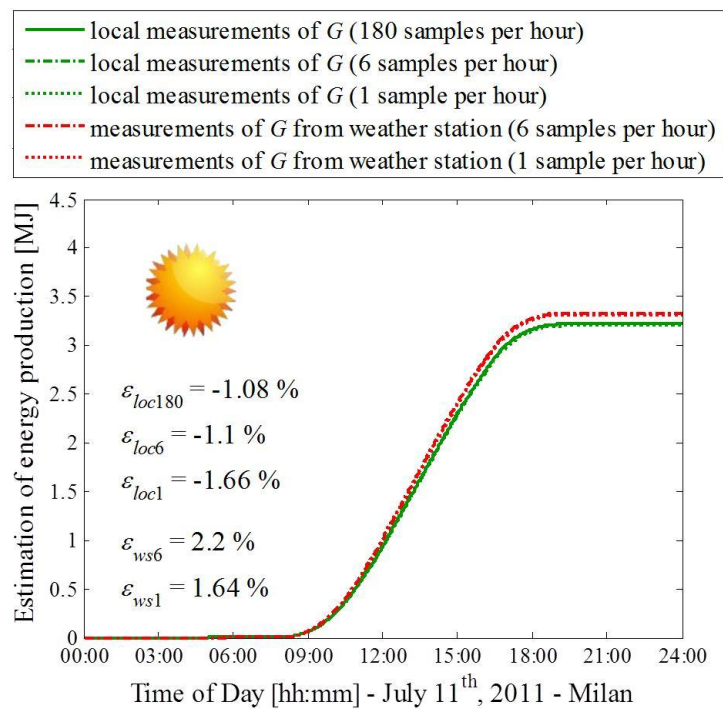

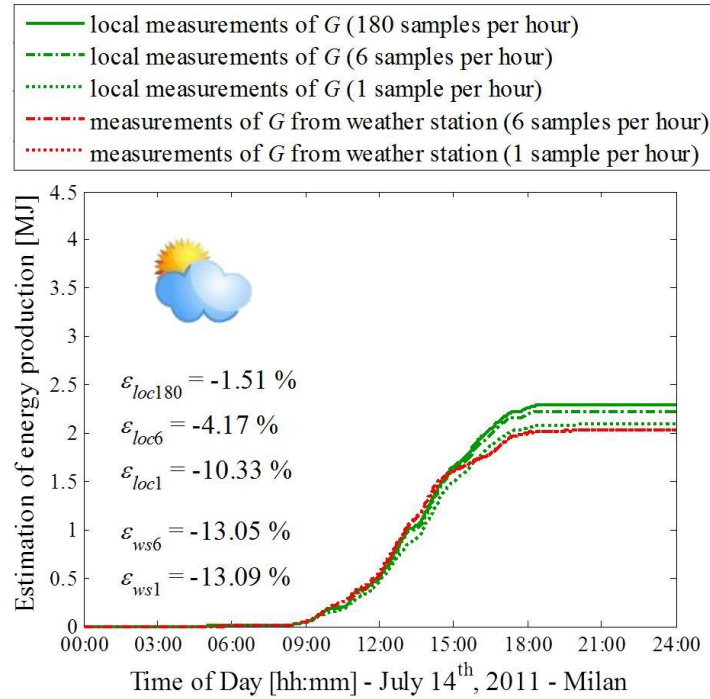**Figure 8 – Estimation of the daily produced energy during a sunny day**

Figure 9– Estimation of the daily produced energy during a cloudy day

In table 2, the errors in the energy production estimation aggregated according to the environmental conditions are reported.

Table 2: Evaluated energy production error

	ε_{loc6} %	ε_{loc1} %	ε_{ws6} %	ε_{ws1} %
Sunny days	-0.12±0.67	-0.72±0.65	2.41±0.54	2.91±0.55
Cloudy days	-4.1±2.2	-8.3±4.7	-3.9±6.3	-4.4±6.6
Rainy days	-6.9±4.8	-11±6.3	-12±4.8	-15±7.1

The effect of time resolution is visible, in particular, when the averaged solar radiation data collected in the same location of the PV plant are considered. The evaluated energy production error increases from -1.2% to -8.3% in cloudy days, while it remains practically constant in sunny days. This result is a further confirmation of what has already been mentioned, *i.e.* in case of sunny weather the error in the estimation of energy production is poorly affected by the sampling frequency (at least in the field of explored values). The data also clearly shows the effect of the spatial resolution of the environmental parameter measurements. In fact, during cloudy days, the use of data collected by the weather station causes the error to rise. The minimum errors have been achieved in estimating the energy production during sunny days. In this condition, the PV panel model is more accurate, and both the spatial and the time resolutions of the environmental data are less influential. On the contrary, in cloudy days, the errors are larger. This is mainly due to the high variance of the solar radiation intensity that cannot be considered by using data with low time resolution.

However, non-clear days still can participate to the evaluation of the produced energy reduction when a time period longer than a single day is considered. In this case, according to the fact that a low energy production is expected for cloudy/rainy weather conditions, the overall error is slightly influenced by the high uncertainty reported for these days. In fact,

even considering that most of the considered 20 days are not completely clear, the error of the estimated total energy production is still low, as deductible from values given in the table 3.

Table 3: Evaluated energy production error over 20 days

	ε_{loc180} %	ε_{loc6} %	ε_{loc1} %	ε_{ws6} %	ε_{ws1} %
Over 20 days	-0.75	-2.62	-5.44	-2.51	-3.01

4 Economical evaluation of the loss due to the dust

As abovementioned, in order to quantify the payback ratio and to evaluate the long-term system performances of a photovoltaic plant an accurate prediction of the plant efficiency and of the maintenance cost is mandatory. In particular, not only the investment cost and the revenues should be taken into account in the business plan but, in order to estimate the plant dependability and estimate the system energy production, accurate loss factors must be considered (Duffie and Beckman, 1991).

4.1 A new approach for the photovoltaic maintenance activity

In order to optimize the PV plant maintenance policy, it is important to study the relation between the losses in the electricity production and the maintenance operations cost. This reduction in efficiency can be translated into a voice of "induced cost" due to lack of electricity production.
It is possible to define the following parameters:
-   W_{losses} corresponds to the total energy losses due to the dust/pollution deposition;

-   C_S corresponds to the value of saving per produced energy unit;

-   C_{INC} is the value of the economic incentives per produced energy unit.

The cost of the PV plant due to the lack of the electricity production (cost of the production losses C_{PL}) between two consecutive maintenance operations can be estimated with the following expression:

$$C_{PL} = \left(C_S + C_{INC} \right) W_{losses} \tag{2}$$

W_{losses}, as above mentioned, is the energy which has not been converted by the PV panel under test because of the presence of powder on its surface or, more in general, a reduction of efficiency due to a fault. This quantity is a function of the time and can be evaluated by means of the following equation:

$$W_{losses}\left(t \right) = \sigma \int_{T_0}^{T_0+t} P_{gen} dt \tag{3}$$

where P_{gen} is the predicted power generated by the clean (and healthy) PV panel and T_0 is the instant in which the decreased efficiency is measured for the first time and σ is a reduction factor as described in the following.
In order to evaluate $W_{losses}(t)$ it is possible to compute it by means of the power directly estimated using the simplified proposed single diode model. In fact, the difference between the energy production predicted by the model of the reference panel and the actual one (the difference has to be divided by the nominal value of power of the reference panel) represents the reduction factor, σ, that allows to estimate the losses of the PV plant by means of (3).

Another important parameter to take into account is the maintenance activity costs, C_{MA}, related to a single cleaning operation. It is approximately given by the sum of the costs of material, C_m, used for cleaning and the cost of the workforce, C_{wf}:

$$C_{MA} = C_m + C_{wf} \qquad (4)$$

It is a well-known concept that the maintenance activity has to be performed when the monitoring shows that the following inequality is no longer verified:

$$C_{PL} \leq C_{MA} \qquad (5)$$

Therefore, considering (2), when

$$\left(C_S + C_{INC} \right) W_{losses} \leq C_{MA} \qquad (6)$$

Figure 10 shows the trend of the cost due to the lack of the energy production (in red) and the costs of the maintenance operation (in blue). The intersection of these two curves represents the optimal instant in which the maintenance activity should be performed (maintenance time T_M).
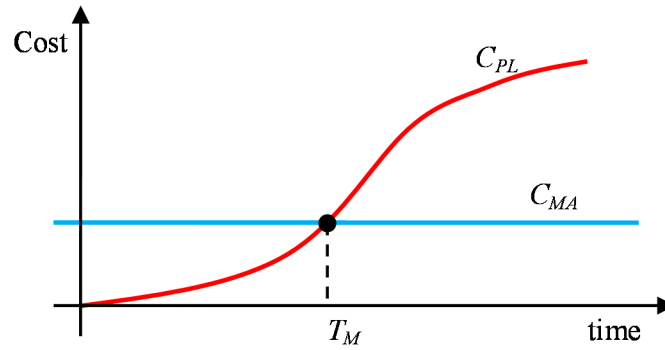

Figure 10: Trend analysis

It is clear that, in order to apply the proposed model, the knowledge of the energy production of a clean PV panel (or plant) is required.

4.2 Some consideration about the use of the economical model

The economic model requires the knowledge of the energy loss due to the dust deposition. By a general point of view it is possible to compute energy losses both using the electric model and a data base realized using the production data of the plant. The model based approach is applicable performing solar radiation measurement both with local and public weather station. The best accuracy is reached when the solar radiation measurement is performed in the same place where the reference panel is installed (as shown by Table 3). In order to evaluate the economic model, $W_{losses}(t)$ of equation (3) can be performed computing the difference between the actual energy evaluated by means the reference panel and the output of the model computed considering the radiation provided by the weather station (local or public).
When we use the data base approach, the evaluation of the $W_{losses}(t)$ is performed as in the previous case with the difference that data base values are considered instead of the output model. Energy loss evaluation by means of the data base related to the panel is possible but the accuracy of the estimation depends by the accuracy of the data base itself.

5 Conclusion

In this paper a maintenance policy devoted to PV plants has been presented. This approach is based on the use of two models: an electric model of the PV panels and an economical model that takes into account the economic losses due to the dust on the panel surfaces.
In order to reduce the cost of the maintenance activity and simplify the monitoring apparatus, the method is based on the use of a PV reference. The opportunity of using environmental data, acquired by means of public weather station located in the same climatic area of the PV plant, but far from it, has been also evaluated.

Finally, a simple method useful for the estimation of the optimal instant of time in which the maintenance activity should be scheduled has been proposed.

References

Catelani M., Ciani L., Cristaldi L., M. Faifer, M. Lazzaroni, M. Rossi, "Characterization of photovoltaic panels: The effects of dust", IEEE International Energy Conference and Exhibition (ENERGYCON), 2012, D.O.I.: 10.1109/EnergyCon.2012.6348198 Year: 2012 pp: 45- 50

Catelani M., Ciani L., Cristaldi L., Faifer M., Lazzaroni M., Rinaldi P., "FMECA technique on photovoltaic module" IEEE Instrumentation and Measurement Technology Conference (I2MTC), 2011, DOI: 10.1109/IMTC.2011.5944245, pp: 1- 6.

Cristaldi L., Faifer M., Rossi M., Catelani M., Ciani L., Dovere E., Ierace S., "Economical Evaluation of PV System Losses Due to the Dust and Pollution". Proceedings of 2012 IEEE International Instrumentation and Measurement Technology Conference, Pages 614-618.

Cristaldi L., Faifer M., Ierace S., Lazzaroni M., Rossi M., "An approach based on Electric Signature Analysis for Photovoltaic Maintenance", proceeding of MPMM 2012, Sunderland, UK, 12th & 13th September 2012.

Cristaldi L., Faifer M., Ponci F., Rossi M., "A Simple Photovoltaic Panel Model: Characterization Procedure and Evaluation Of the Role Of Environmental Measurements" IEEE Transaction on Instrumentation and Measurement, vol.61, n. 10, October 2012. DOI: 10.11097TIM.2012.2199196.

Detrick A., Kimber A., Mitchell L., "Performance Evaluation Standards for Photovoltaic Modules and Systems," IEEE 31st Photovoltaic Specialists Conference, pp. 1581- 1586, 2005.

Duffie J. A., Beckman W. A., "Solar Engineering of Thermal Processes," Third Edition, John Wiley and Sons: New York, 1991.

El-Shobokshy, M.S.; Mujahid, A.; Zakzouk, A.K.M., "Effects of dust on the performance of concentrator photovoltaic cells" Solid-State and Electron Devices, IEE Proceedings, vol.132, no.1, pp.5-8, Feb. 1985.

Hai Jiang, Lin Lu, Ke Sun, "Experimental investigation of the impact of airborne dust

deposition on the performance of solar photovoltaic (PV) modules", Atmospheric Environment, Vol. 45, Issue 25, Aug. 2011, Pages 4299-4304.

Hamdy K. Elminir, Ahmed E. Ghitas, R.H. Hamid, F. El-Hussainy, M.M. Beheary, Khaled M. Abdel-Moneim, "Effect of dust on the transparent cover of solar collectors", Energy Conversion and Management, Volume 47, Issues 18-19, Nov. 2006, Pages 3192-3203.

Lazzaroni M., Cristaldi L., Peretto L., Rinaldi P., Catelani M., Reliability Engineering: Basic Concepts and Applications in ICT, Springer, ISBN 978-3-642-20982-6, e-ISBN 978-3-642-20983-3, DOI 10.1007/978-3-642-20983-3, 2011 Springer-Verlag Berlin Heidelberg.

Meyer, E.L.; van Dyk, E.E.; "Assessing the reliability and degradation of photovoltaic module performance parameters", IEEE Transactions on Reliability , vol.53, no.1, pp. 83- 92, March 2004.

Mishra P.R., Joshi J.C., "Reliability estimation for components of photovoltaic systems", Energy Conversion and Management, Volume 37, Issue 9, September 1996, Pages 1371-1382.

Monto Mani, Rohit Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations", Renewable and Sustainable Energy Reviews, Vol. 14, Issue 9, Dec. 2010, Pages 3124-3131.

Powers, L.; Newmiller, J.; Townsend, T.,"Measuring and modeling the effect of snow on photovoltaic system performance", 35th IEEE PVSC 2010 , pp.973-978, 20-25 June 2010.

Model-based prognosis for rolling element bearings

Idriss El-Thalji* and Erkki Jantunen

Industrial Systems,
VTT Technical Research Centre of Finland, Espoo, 02044, Finland

*Corresponding author: Idriss El-Thalji
E-mail:erkki.jantunen@vtt.fi
E-mail:idriss.el-thalji@vtt.fi

Abstract

Rolling element bearing is one of the most critical components that determine the machinery health and its remaining lifetime. Rolling contact wear is responsible for the damages initiating on and beneath the contacting surfaces of rolling element bearings. Wear prognosis aims to predict the defect and its evolution progress before it occurs. It addresses the use of automated methods to predict the degradation of physical system performance and the remaining lifetime. Actually, the fundamental need for predictive intelligence tools is to monitor the degradation rather than just detecting the defects, otherwise it will be hard to optimise the asset utilisation in cost effective manner. The current prognosis models are based on predetermined probabilistic damage functions or constant damage factors. Therefore, the purpose of this paper is to develop a prognosis model which is able to predict the evolution of rolling contact wear, using systems dynamics approach. Instead of pre-determined damage functions, the dynamic development of wear process is proposed. The dynamic development of wear considers multiple wear mechanisms and their interactions with respect to surface topological and tribological changes. Moreover, it considers the stress concentration mechanisms and their propagation processes. Therefore, the paper utilizes a five-stage model to simplify the dynamic development of wear progress over the lifetime. The five stages are running-in, steady-state, defect initiation (dentations, pits, and inclusions), defect propagation (extended pits, propagated cracks), damage growth (spalls). The paper is relevant in enhancing the effectiveness of prognostics procedures of rolling element bearing wear.

Key words: Prognosis, Rolling bearings, Wear evolution, Systems dynamics.

1 Introduction

Prognosis is nowadays recognised as a key feature to achieve satisfactory level of asset cost effectiveness. Predictive health monitoring becomes one of the most complex systems that support condition-based maintenance in order to cut down operation and maintenance costs. It covers a chain of procedures: data acquisition, data manipulation, state detection, diagnosis assessment and prognosis assessment. Diagnostics deals with fault detection, isolation and identification of when abnormality occurs. Prognostics deal with fault and degradation prediction before they occur. It addresses the use of automated methods to predict the degradation of physical system performance and the remaining lifetime. However, a large share of scientific contributions is toward enhancing the detection and diagnosis capabilities and a few regard

prognostics. Actually, the fundamental need of predictive intelligence tools is to monitor the degradation rather than just detecting the faults, otherwise it will be hard to optimise the asset utilisation. Early indication of failure provides more time for proper maintenance planning and scheduling. Frankly, all prognosis approaches i.e. physics-based or data-driven have currently advantages and drawbacks in different applications and operating cases, specially, in case of different and variable operating conditions and complex systems. Liu, et al. (2012) highlighted that physics-based models may not be suitable for many industrial applications where the physical parameters and fault modes may vary under different operating conditions. It is due to the difficulties to tune the derived models in situ to accommodate time-varying system dynamic and the inability to measure the internal state variables by direct measurements. Data-driven models have also difficulties to interpret their diagnosed results and to estimate the remaining lifetime, even though, they are more commonly used in rolling element bearing (REB) prognosis. Therefore, the real prognosis systems are still considered as risky systems in industry. Actually, the challenge of wear prognosis in REB is related to how much the wear progress and health degradation is understood. Wear physics in rolling contact is a complex phenomenon to be understood. Rolling contact wear is well known as a phenomenon that might involve different wear mechanisms (adhesive, abrasive, fatigue and corrosive). Furthermore, wear might be initiated and accelerated by different stress concentration mechanisms (asperity, dent, debris, etc.). In fact, the experimental results of wear evolution show several steeply-offsets that look like a stairway progress, particularly, in the instability stage of the lifetime (Harvey, et al., 2007). The estimated results of wear evolution progress, based on prognosis systems, are still far from the measured and real curve. The difference between estimated and measured results is related to a number of issues. First, the phenomenon of steep-offset progress is basically related to the nonlinear wear propagation. Therefore, the effect of wear propagation almost appears when that defect stage is completed, which is shown as steep growth in the wear curve. Second, there is interaction between different wear mechanisms i.e. fatigue wear, abrasive wear, etc. over the wear evolution progress. This interaction phenomenon might accelerate or de-accelerate the wear progress. However, the physical measurements take usually the overall effect on these wear mechanics interactions. The wear mechanics might work with each other instantaneously, sequential and/or with delays. Therefore, prediction based on these measurements might mislead the conclusions of how the wear will progress. The overall measurements will lead us also to conclude that the system health is improved. Third, the wear progress is highly dependent on operating conditions and system configurations.

Therefore, this paper provides a summary of prognosis models to illustrate how much the wear progress in REB is understood and well predicted. Then, the purpose is to develop a prognosis model which is able to predict the evolution of rolling contact wear. The proposed model tries to consider the dynamic behaviour of wear development: wear mechanics, interaction and variable operating conditions. The study utilizes five-stage model of rolling contact wear progress: running-in, steady-state, defect initiation (dentations, pits, and inclusions), defect propagation (extended pits, propagated cracks), damage growth (spalls). The system dynamics approach is utilised to deal with the interactions among different wear mechanisms and to consider their feedbacks. In the next section, a brief summary of main prognosis models and detailed discussion of model-based models are provided. Later, the proposed model is described and some preliminary results are discussed.

2 Summary of prognosis models

Several researchers have reviewed the prognosis contributions such as Engel, et al., (2000), Jardine, et al., (2006), Lee, et al., (2006), Heng, et al., (2009), Peng, et al., (2010), Jammu & Kankar, (2011), etc. There are two types of methods of prognosis: physics 'model'-based and data-driven i.e. statistical and artificial intelligence (AI). In table 1, an updated summary of approaches adopted for prognosis of rolling element bearings is represented.

Table 1. A summary of approaches adopted for prognosis of rolling element bearings

Reference	Data-driven models									Physics-based models			
	Regression analysis	Probability estimation	Principal component analysis	Support vector machine	Neural networks	Self-organizing map	Recurrent neural networks	Neuro-fuzzy	Markov modelling, Genetic algorithm	Deterministic damage	Stochastic damage	Contact stress analysis	Dynamic analysis
Begg et al., (1999), Begg et al., (2000)													X
Li et al., (1999), Li et al., (2000)							X			X			
Shao & Nezu, (2000), Mahamad, et al. (2010)					X								
Yam, et al., (2001)							X						
Wang & Vachtsevanos (2001), Khawaja, et al. (2005), Dong, et al., (2004), Gebraeel, et al., (2004), Gebraeel & Lawley, (2008)					X								
Qiu et al, (2002)													
Wang (2002), Myötyri, et al., (2006)		X									X		
Vlok, et al., (2004)		X											
Wang, et al., (2004)							X	X					
Chinnam & Baruah (2004)								X					
Orsagh, et al., (2004), Kacprzynski, et al., (2004), Marble & Morton (2006), Lybeck, et al., (2007)												X	
Yan, et al., (2004), Pham & Yang, (2010)	X												
Jantunen (2004)	X							X					
Chelidza & Cusumano (2004)													X
Xu, et al. (2005)			X					X					
Goebel, et al. (2005), Goebel, et al. (2006), Zhang, et al., (2010)										X			
Wang (2007), Liu, et al. (2009), Wang, et al., (2012), Li, et al. (2013)								X					
Huang et al., (2007)					X	X							
Dong & He, (2007), Li & Wang, (2011)								X					
Yang & Widodo (2008),Widodo et al., (2009), Widodo & Yang, (2011)		X		X									
Pan, et al., (2009)				X									
Sutrisno, et al., (2012)	X		X										

Physics-based prognostic models describe the physics of the system and failure modes based on mathematical models such as Paris' law, Forman law, fatigue spall model, contact analysis and 'stiffness based damage rule' model. Data-driven prognostic models attempt to be driven by routinely and historically collected data (condition monitoring measurements, SCADA measurements, etc.). Data-driven prognostic models cover large number of different techniques and artificial intelligence algorithms such as simple trend projection model, time series prediction model, exponential projection using artificial neural networks (ANN), data interpo-

lation using ANN, particle filtering, regression analysis and fuzzy logic, recursive Bayesian technique, hidden Markov model, hidden semi-Markov model, system identification model, etc. The survey shows that data-driven approach is more adopted into prognosis of rolling bearings than physics-based approach. Frankly, all prognosis approaches i.e. physics-based or data-driven have advantages and drawbacks in different applications and operating cases, specially, in case of different and variable operating conditions and complex systems. Moreover, the prognosis models try to control or delimit the effect of some operational variables. However, that is somehow possible in the experimental tests but not in real applications. Actually, the prediction based on simplified experimental tests i.e. ball-on-disc test is easier than tests that use rolling element bearings.

Data driven methods utilise data from past operations and current machine conditions, in order to forecast the remaining useful life. There are several reviews concerning the data-driven approaches such as Schwabacher (2005), Schwabacher & Goebel, (2006) and Camci, et al., (2012).

Statistical approach: Yan, et al., (2004) explored a method to assess the performance of assets and predict the remaining useful life. At first, a performance model is established by taking advantage of logistic regression analysis with maximum-likelihood technique. Two kinds of application situations, with or without enough historical data, are discussed in detail. Then, real-time performance is evaluated by inputting features of online data to the logistic model. Finally, the remaining life is estimated using an Auto-Regressive–Moving Average (ARMA) model based on machine performance history; the degradation predictions are also upgraded dynamically. Vlok, et al., (2004) proposed a residual life estimation method based on proportional intensity model for non-repairable systems which utilise historic failure data and corresponding diagnostic measurements i.e. vibration and lubrication levels. Yang & Widodo (2008) proposed a prognosis method using support vector machine (SVM). The proposed method is addressed to predict the upcoming state of a machine based on previous condition. The viability of the developed system is evaluated by using trending data of low methane compressor acquired from condition monitoring measurements. The statistics-based models assume that historical data is representative for the future wear progress, which is not always the case. Probabilistic-based models assume that the whole wear evolution progress is represented by a probability distribution function i.e. Weibull.

AI approach: Wang & Vachtsevanos (2001) introduced a prognostic framework based on concepts from wavelet, neural networks, and virtual sensors. Li et al., (1999) utilised recurrent neural network (RNN) approach. Yam, et al., (2001) proposed a model based on the recurrent RNN approach for the critical equipment of a power plant. Dong, et al., (2004) proposed a model that combines condition prediction for equipment in a power plant based on grey mesh GM (1,l) model and back propagation neural network (BPNN) on the basis of characteristic condition parameters extraction. Wang, et al., (2004) evaluated the performance of RNNs and neuro-fuzzy (NF) systems. Through comparison, it was found that if an NF system is properly trained, it performs better than RNNs in both forecasting accuracy and training efficiency. Chinnam & Baruah (2004) presented a neuro-fuzzy approach for performing prognostics for cutting tool monitoring. The AI-based models provide generally good predictions. However, they often suffer from the need for complex training due to the huge number of possible combinations of damage scenarios that might happen in the case of rolling contact wear.

Physics-based approach: physics-based prognostic models are based on crack length, and defect area as illustrated by Li et al., (1999), and Li et al., (2000), or relations of stiffness as shown by Qiu et al, (2002), or related to vibration and RMS values. However, the most challenging issue within physics-based prognostic is to define the loading-damage relationship

and to model it. There are models based on damage rules as linear damage rule, damage curve rule, and double-linear damage rule (Qiu et al, 2002). The drawback of these simplified functions is that they all use the constant damage factor which is hard to estimate or measure. Moreover, these functions are either linear or multi-linear functions. That means that the estimated results might seem matching with the overall measured results, however, both of them might describe different damage scenarios in behind. Therefore, the prediction based on such functions makes the prognosis a risky task. Recently, some model-based models have been utilised for the contact stress analysis to illustrate the wear evolution progress. These models provide more accurate predictions. Some models are based on contact stress analysis (Marble & Morton 2006) and some are based on system dynamics (Begg et al.,1999 and Begg et al., 2000). Chelidza & Cusumano (2004) proposed a method based on a dynamical systems approach to estimate the damage evolution. Luo et al., (2003) proposed an integrated prognostic process based on data collected from model-based simulations under nominal and degraded conditions. Interacting Multiple Model (IMM) is used to track the hidden damage. Remaining life prediction is performed by mixing model-based life predictions via time-averaged mode probabilities. Kacprzynski, et al., (2004) utilized the system-level observable features to orient and update the models responsible for tracking the material condition of a component. Defect modelling depends on how much of the physics of the defect over the lifetime are well defined. The results of these models depend also on the stress-damage function and the constant damage factor that are in use. These models assume that each wear mechanism generates stresses that in total equal to the overall measured stresses. Therefore, the wear mechanics interactions are somehow ignored. Moreover, these models assume that the stress-damage function is semi-linear and applicable for all wear evolution stages: dentation, crack initiation, crack propagation etc. Therefore, in the end, the results of these models are almost similar with the results of other models i.e. exponential damage model.

In summary, the statistical models represent the wear evolution as one function with the possibility to insert weights. The statistical models assume that past history profile represents the future failure mechanism of a specific component. However, failure mechanisms are changing with respect to failure evolution and the involvement of failure mechanisms. It means that the statistical approach is not fully valid and might not represent wear progress, especially, if the evolution stages are highly varying, as they are in the case of wear evolution stages. ANN models use specific function(s) and multiple weights. However, ANN models have drawbacks once the system conditions are rapidly fluctuating. The model-based models are still representing the wear evolution with two stages. Moreover, the damage is represented as damage factor. This really is a dramatic simplification to describe the wear evolution as a two stage stabile phenomenon, whereas it is a process by nature that is developing exponentially. Consequently this kind of approach is very far from reality and the usability can be highly criticised. In this study the idea is that prognosis models can be improved remarkably by understanding the physics of wear evolution progress and its associated measured outcomes. Actually, that will help the model-based approaches to provide better results and the data-driven approach to have better interpretations of the results. Therefore, in the next section a detailed discussion of the current physics-based models is provided. This discussion provides how far the physics of wear mechanics are considered in wear prognosis.

2 Discussion of Model-based Prognosis

Few researchers have adopted the basic Paris's formula into the application of rolling contact wear. The formula is based on deterministic fatigue crack propagation as follows:

$$\frac{da}{dN} = C_0(\Delta K)^n \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1)$$

Where 'a' is the instantaneous length of a dominant crack and 'N' represents running cycles. The parameters 'C_0' and 'n' are regarded as material-dependent constants, and are related to factors such as material properties, environment, etc. The term 'ΔK' represents the range of stress intensity factor over one loading cycle. Equation (1) states that crack growth rate in terms of length per running cycle is an exponential function of stress intensity factor range 'ΔK'. In fact, the area of bearing defect is commonly used in the analysis within industry. The defect severity of a bearing is represented by the surface area size, rather than the length of the defect. Therefore, Li et al., (1999) modified the deterministic fatigue crack propagation model based on Paris's formula to estimate the defective surface area instead of crack length, as follows:

$$\frac{dD}{dt} = C_0(D)^n \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (2)$$

Equation (2) states that the rate of defect growth is related to the instantaneous defect area 'D' under a constant operating condition. The parameters 'C_0' and 'n' are material constants that need to be determined experimentally, and often vary with factors other than the instantaneous defect size. Li et al., (2000) utilised the defective surface area as the main measure of bearing defect severity in industrial applications. The proposed model converts the measured root mean square (RMS) values (i.e. displacement, acceleration) into defect area values based on the following empirical formula as extracted by Li et al., (2000):

$$D = 3.28 + 4.56R \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3)$$

R is the root mean square (RMS) value in question and D in mm^2. The proposed model is an adaptive model. It utilises deterministic defect area propagation model with adaptive algorithm to fine tune the predicted rate of detect area propagation in a real-time manner. The adaptive model provides less error between the predicted defect area values and the estimated defect area values. However, the estimated defect area values are different in comparison to real measured defect area values obtained with a profilometer. This approach is clearly based on the crack propagation and does not provide information about the crack initiation stage which might generate a totally different damage scenario. Moreover, the crack propagation needs an initiator that indicates crack initiation. There are many operational symptoms that are similar to the crack initiation. However, many of these symptoms are related to operating conditions. Therefore, this model might assume early crack initiation and estimate the remaining lifetime, which leads to unnecessary maintenance actions. Later, Qiu et al, (2002) proposed a stiffness-based prognostic model for bearings based on vibration signal analysis and damage mechanics. The idea is to introduce the damage as a factor or ratio between the running cycles and failure lifetime cycles.

$$D = \left(\frac{N}{N_f}\right) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (4)$$

$$D = \left(\frac{N}{N_f}\right)^q \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (5)$$

$$D = \frac{N}{N_I} \times \lambda \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (6)$$

$$D = \lambda + \frac{N}{N_{II}} \times (1 - \lambda) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (7)$$

Where 'N' is the running cycles, 'N_f' is the failure lifetime (cycles), 'q' is a material and structure-dependent factor, 'N_I' is the lifetime of crack initiation phase, 'N_{II}' is the lifetime of crack propagation phase (note that $N_I + N_{II} = N_f$) and 'λ' is the damage factor at 'N_I' cycles.

Also, when 'D= 0' the system has no damage, while when 'D= 1' the system can be considered as failed. The model is based on the stiffness as a relationship between vibration spectral features and lifetime.

$$\left(\frac{S_0}{S_d}\right)^{\gamma} = \eta\left(\mathbf{1} - \mu\left(\frac{N}{N_f}\right)^{q}\right) \dots \dots (8)$$

Where 'S' denotes the signature of acceleration response. 'Ɣ, η, μ, q' are coefficients depending on the operating condition, materials and structure of the system, respectively. These damage factors have different types as constant factor (equation 4), exponential factor (equation 5) and multi-factors i.e. in equation 6 for crack initiation and in equation 7 for crack propagation. The multi factor type is used in order to provide different damage factors for the crack initiation and the crack propagation progress. It was observed that the damage curve approach (equation 5) and the double-linear damage approach (equations 6&7) are good approaches to predict the lifetime of a bearing, however, the linear damage approach (equation 4) failed to accurately reflect the evolution of a bearing damage. Moreover, it was observed that the damage initiation is the time-consuming period of bearing fatigue, while the subsequent period of crack propagation is relatively short. Therefore, it is clear that the different wear stages have quite different damage factors. Actually, the damage factor approach assumes a constant or linear behaviour for the whole damage stage although this is very far from reality. Moreover, it assumes that the degradation is only a function of loading cycles. However, the dynamic behaviour of real wear progress is highly dependent on deflection, surface roughness and its associated impact loads. These three issues are not directly related to loading cycles. It means, first that the simple loading-damage cycle relationship is not representing the real causes of the dynamic behaviour. Second, the damage-loading cycle relationship is not able to provide information about the transition in damage severity, for example, when to shift to use the damage initiation factor and when to use the damage propagation factor. In fact, it is not realistic to assume a specific number of loading cycles that would be enough to initiate a defect. The defect initiation depends on the existence of dentations, inclusions, and/or debris. Moreover, this approach ignores the damage caused by direct surface interaction i.e. adhesive and abrasive wear.

Kacprzynski, et al., (2004) utilised the Neuber's rule to convert the elastically calculated stresses from the linear finite elements model to true stress and true stain values. The model expresses the number of reversals $2N_f$ (twice of the number of cycles N_f) to failure as a function of elastic and plastic strain amplitudes. Furthermore, Marble & Morton (2006) highlighted that the traditional approaches to fatigue modelling such as Paris' law perform poorly when applied to bearings. The issue is related to the fact that bearings fail as a result of the continuous initiation and merging of thousands of small short cracks rather than the propagation of a single dominant crack. Marble & Morton (2006) proposed a model based on stress contact analysis. The analysis is based on the assumption that a damage is the projected area of the defect (S_D) divided by the cross sectional area of the element (S), as illustrated in equation 9. The end result of this model is illustrated in equation 11 which accounts for both elastic and plastic strain.

$$D = \frac{S_D}{S} \dots \dots (9)$$

$$\frac{dD}{dN} = \frac{\sigma^2 C_{tr}}{2E S_E \left(1-D\right)^2}\varepsilon_E + \frac{\sigma^2 C_{tr}}{2E S_P \left(1-D\right)^2}\varepsilon_P \dots \dots (10)$$

Where 'σ' is the is the applied local Von Mises stress, 'C_{tr}' is the triaxiality ratio, 'E' and 'S' are material constants, 'ε' is the strain, and the 'e' and 'p' subscripts which refer to elastic and plastic respectively. Equation (10) is the key relationship between applied stress and damage

accumulation per cycle. In addition to the damage caused by stress cycles, bearings also accumulate damage from direct surface interaction. The thickness of lubrication film and the roughness of the contacting surfaces control the degree of surface asperity interaction, which affects fatigue initiation in both surfaces. The standard surface interaction metric is the lambda ratio 'λ', which is defined as the central film thickness divided by the combined RMS surface roughness 'R_A', as illustrated in the following equation.

$$\lambda = \frac{film\ thickness}{\sqrt{R_{Surface\ 1}{}^2 + R_{Surface\ 2}{}^2}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(11)$$

This approach still uses the 'λ' as damage factor due to surface interactions. However, the lambda ratio is also varying over the time and during the degradation progress.

It is clear the defined loading-damage relationships (either stress-based or stain-based) are not effectively representing the wear progress over the whole lifetime. First, these relationships assume that the wear progress is following the same physics during the whole lifetime. Second, they are based on pre-defined damage factors and not as functions of time. Third, these models deal yet with individual wear mechanisms i.e. fatigue or abrasive wear. Thus, the effect of multiple wear mechanisms and their dynamic interactions is required to represent the rolling contact wear phenomenon in real industrial applications.

3 The proposed prognosis model

It became clear that the dynamic nature of wear development should be considered to reach more realistic prognosis of the rolling contact wear phenomenon. Modelling the dynamic nature of wear development seems to provide a radical modelling way compared to the current prognosis models. The later use constant damage factors and single wear mechanism approach. In the proposed approach the dynamic nature of wear development can be modelled once the multiple wear mechanisms and their interactions are considered. In order to test that, a simple model is proposed in this paper and illustrated in the following sections. However, the wear development and its dynamic progress are varying over the lifetime. This is due to the surface topological and tribological changes. They together generate different types of stress concentration mechanisms i.e. dents, asperities, cracks, defects, extended defects (damage) over the lifetime. Therefore, such changes should be considered to illustrate the real dynamic development of wear progress with respect to stress concentrations mechanisms. One way to do that is to define the wear development based on stages which have clear wear interactions and stress concentration mechanisms and depend on each other in a sequential way. Therefore, the proposed model is able to present the wear development that happens in specific time interval of the lifetime with respect to the surface topological and tribological changes. In the following subsection, the five stage model is presented and followed with detailed description of how the dynamic development of rolling contact wear has been modelled.

3.1 Wear evolution

The prognosis modelling should benefit from the advanced knowledge of rolling contact wear. In this paper, a five-stage model is utilised as a simplified description of the wear defect initiation and propagation processes. The five stages, which are illustrated in figure 1, are described as follows:
1. Running-in stage: it involves localised micro plastic flow, work hardening and shakedown.
2. Steady state stage: the response in this stage is steady state and depends on: the Hertzian stresses, formation of dark etching region and white etching bands and texture strengthening.

3. Defect initiation: it is the stage until macroscopic and self-propagating cracks appear. It starts with a crack initiating near the dented surface at the trailing edge of the original dent or material dislocation in subsurface. Contamination and dentation: The wear process starts with debris involvement which initiates dents under specific conditions. After debris leaves the surface, a dent is generated and new patterns of stresses are generated as well. However, the original shape of dent is changing due to a series of following deformations. Micro-cracking is related to the tangential forces which are concentrated at the edges of dentations.
4. Defect propagation: It is the stage from crack propagation to occurrence of flaking. The defected area might propagate in length, width and depth. The length propagation follows the same mechanism as the dent. The new trailing edge of a pit will function as the stress raiser and initiate a new pit. It plays the same role as the trailing edge of the original dent.
5. Damage growth: it is the stage from flake propagation to the occurrence of spalling. Usually, it depends on the depth propagation, existence of subsurface cracks and softening response of material at that depth.
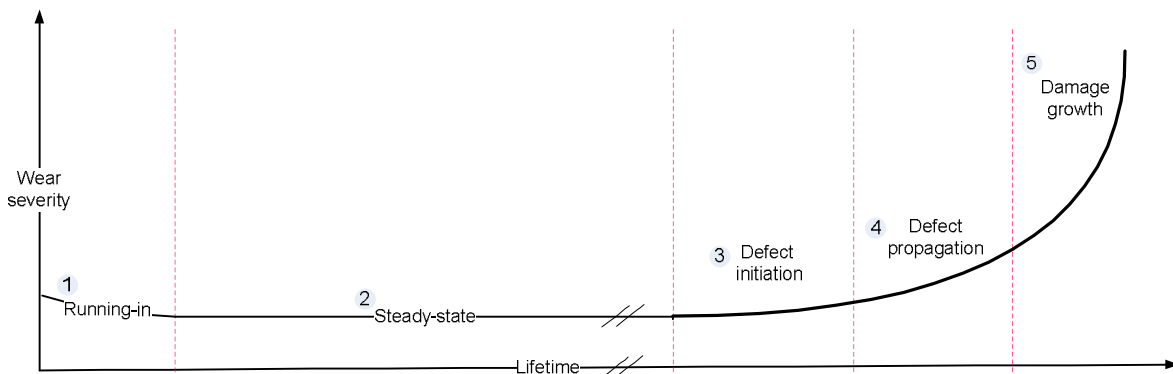

Figure 1. Evolution of rolling contact wear.

The idea is to deal with the instability stage (i.e. after the steady-state stage or defined as faulty stage) as sub-divided stages. The instability stage includes defect initiation (dentation, micro-cracking, pits, inclusions), defect propagation (extended pits, propagated cracks), and damage growth (spalls).

It should be noticed also that each stage has multiple wear mechanics and stress concentration mechanisms. There are a number of wear mechanisms that should be considered. Therefore, the model can handle multiple wear mechanisms 1,2…n. The model is illustrated in figure 1 which explains how wear mechanisms and interactions are modelled. Even though, the wear is a complex phenomenon, the modelling procedures are very simple.
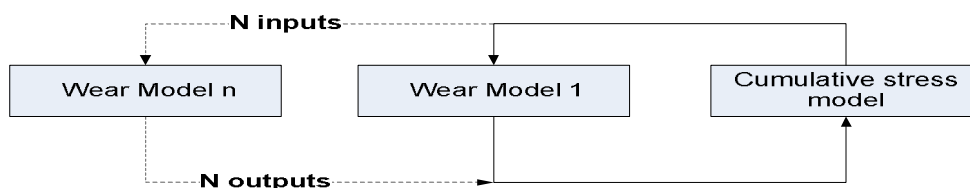

Figure 2. A model of multiple wear mechanisms.

In this paper, three wear mechanisms are considered: abrasive, adhesive, and fatigue wear. These wear mechanisms are active in each stage and deteriorate together the contact surfaces. The transition rules from one stage to the next one are based on the stress level estimations. Basically, it means that once the stress level is exceeded then a dent is generated, and the dent will produce a minor increasing in the total stresses over the dented zone. Moreover, the defect initiation progress will start once the dent asperities are enough to initiate that. If the crack is initiated either on or under the surface, the crack propagation progress will start until the first defect has completely occurred i.e. pits. The first defect (i.e. pit) will act as the dent

(stress raiser). However, the stress will be much stronger as the defect size increases and the topology gets rougher. Therefore, the damage will grow sequentially and rapidly with higher number of material removal events. The flowchart in figure 3 describes these steps and how the proposed model considers the wear stages. Second issue, the influences of these four stages are also inserted as a feedback loop into the initial stress estimation module. Note that the running-in stage is not considered in the current study.
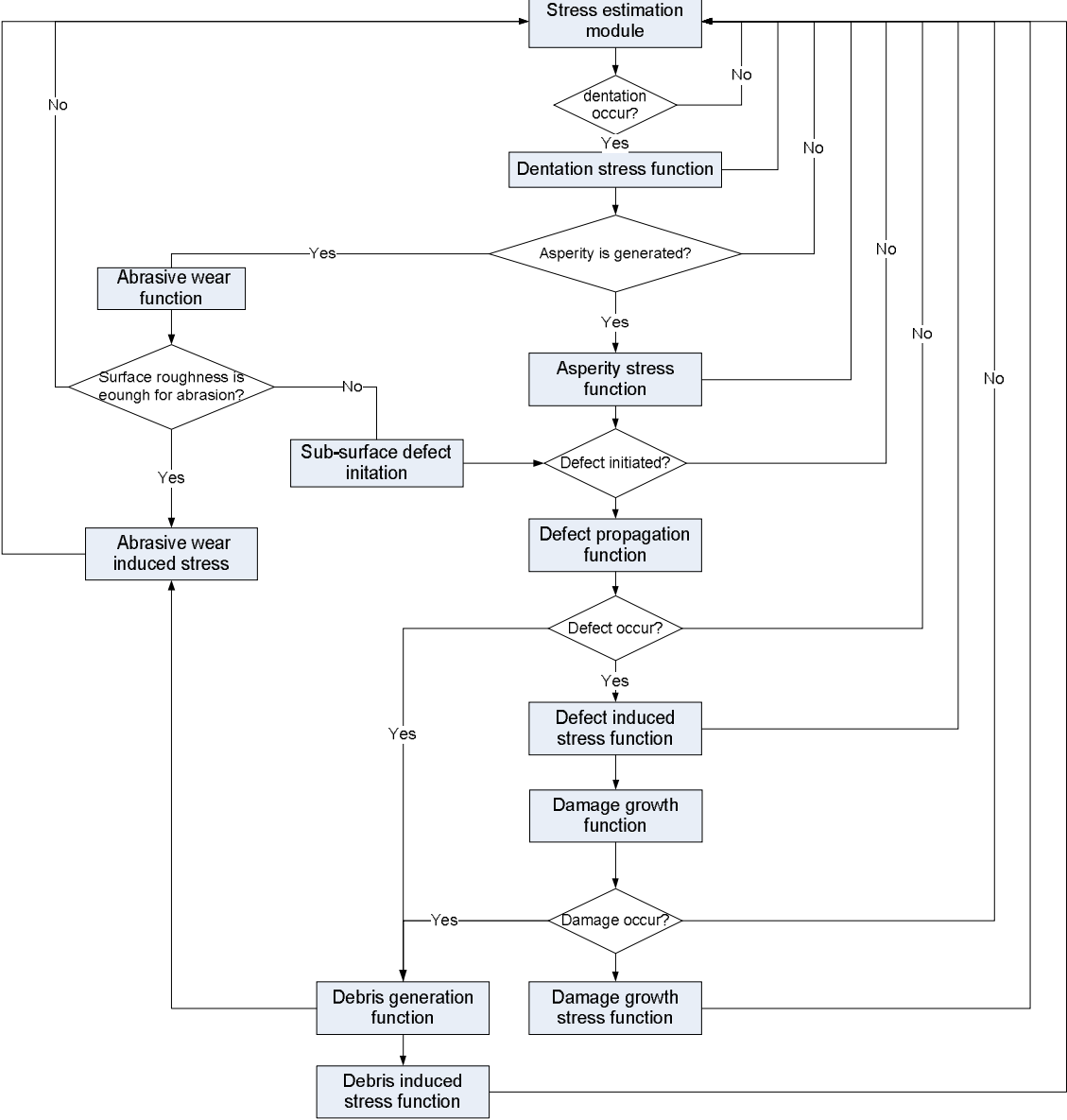

Figure 3. Flowchart of the proposed model

The flowchart requires two issues. First, a function to estimate the stresses induced by different stages of wear development i.e. dentation, asperity, crack, defect, damage. Therefore, the asperity point load model developed by Hannes & Alfredsson (2011), is applied. The hypothesis is that when the asperity enters the rolling contact, it acts as a point load. The cross-sectional shape of the asperity is assumed to follow the half cosine curve. Where the height, width and distance between asperity peak and contact centre is determined. In the same manner, the dent, defect and damage are considered as asperity, however with different shape and dimensional parameters. Based on that, the induced stresses are estimated. Second, the model requires a crack propagation function which determines the time required for a single defect

to be generated. Furthermore, these shape functions, that are used to estimate the stress induced due to dentation, asperities, defect, and damage events can also be used to estimate the impact or excitation forces and the dynamic response of wear development.

3.2 Modelling description

The basic assumption is that each wear stage has its own surface degradation characteristics, mainly, deflection and impact function parameters. The model considers the initial surface roughness as a reference function. The model utilises a normal loading function which represent the loading under steady-state stage. This function represents the future loading conditions, which is required for prognosis analysis. The model has three wear mechanisms: fatigue, adhesive, and abrasive wear. In order to model the wear mechanism, the following modules were developed:

- Stress module (Module 1): The first mechanism module specifies a level of stress concentration that is enough to generate a dent, please see module 1 in figure 4.
- Dentation module (Module 2): It means that once the stress level is exceeded then a dent is generated, please see module 2 in figure 4. The dent will produce a minor increasing in the total stresses over the dented zone. Moreover, the defect initiation progress will start due to the dent asperities.
- Abrasive and adhesive wear module (Module 3): The first wear mechanism module estimates the surface degradation due to adhesive and abrasive wear mechanics, please see module 3 in figure 4. It is actually based on the surface roughness and surface asperities. Moreover, the influence of adhesive and abrasive wear is also inserted as feedback loop to the initial stress estimation module.
- Defect initiation and propagation module (Module 4): The fatigue wear is the third wear mechanism which is considered. The dent asperities as the stress raisers might generate a high enough stress intensity factor (SIF) for crack initiations.
- The dynamic effect module (Module 5): The wear progress within steady-state, dentation, defect initiation and propagation, and damage growth is inserted into the dynamic analysis (please see modules 5 & 6 in figure 4) as impact functions. The dynamic response due to adhesive, abrasive, and fatigue wear mechanics are inserted to the overall machine dynamic module (Module 6).

The second modelling consideration is the interactions between the stages. The model considers the interaction between fatigue wear progress and adhesive/abrasive wear progress. For instance, when adhesive and abrasive wear is active, the asperity will be smoothened. Therefore that will reduce the SIF which is required for crack initiation and propagation progresses. The third modelling consideration is the wear debris. It is generated from dentations, adhesive and abrasive wear, defect completion and damage growth. The wear debris is considered as a stress raiser and inserted as feedback loop into initial stress estimation module.

3.3 Preliminary results

The wear evolution progress has been modelled using systems dynamic approach (Vensim software). This approach is able to provide feedback and interaction between the model items. The current proposed model utilises simplified stress and dynamic response formulas. The idea is to build a simplified wear evolution model for now. Therefore, the current results illustrate the wear evolution progress without scale. In figure 5, the preliminary results of the proposed model and the traditional linear-damage model are shown.
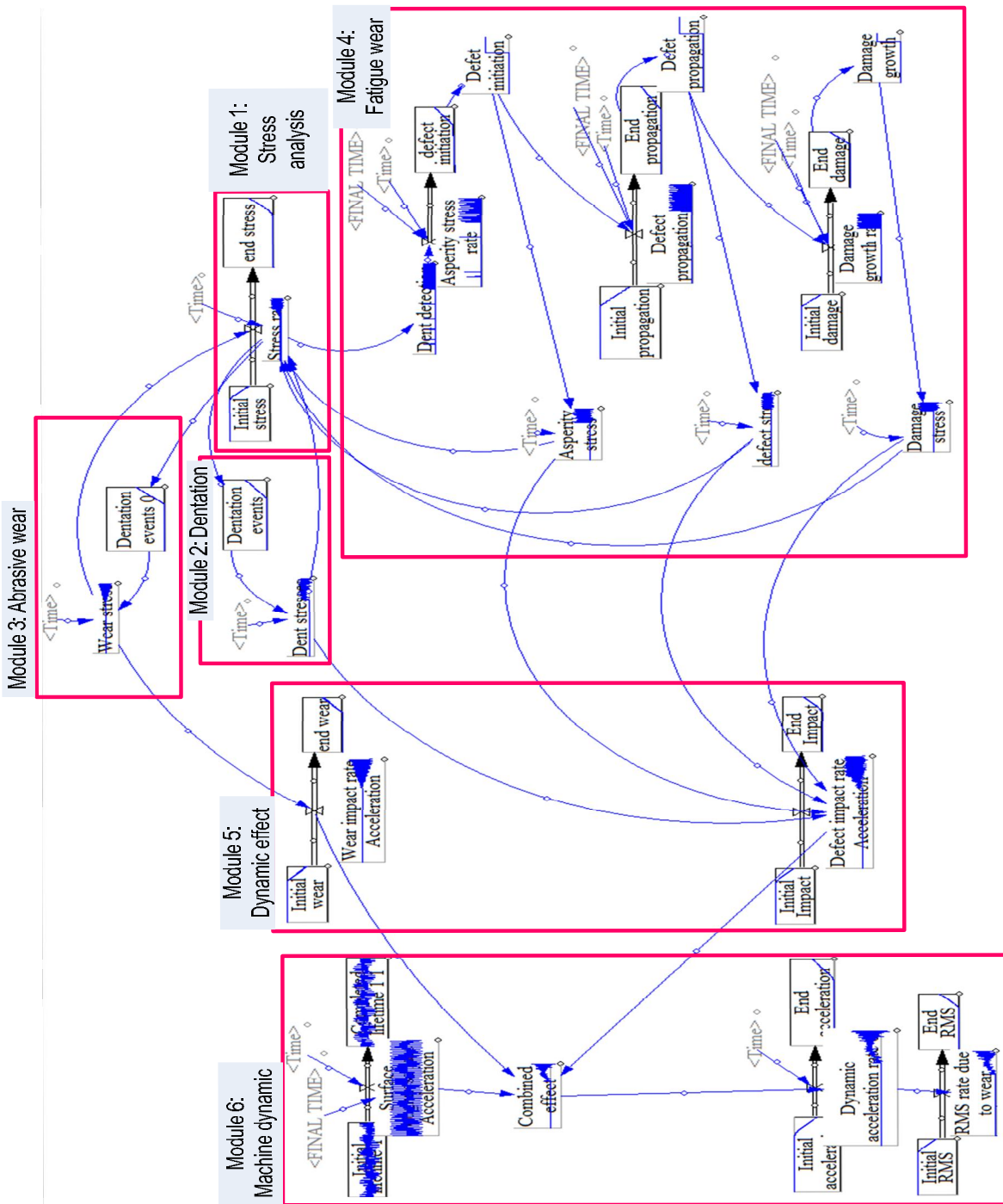
Figure 4. Modelling of wear stages and their dynamic effect.

It is clear that the wear evolution curve of the proposed model is realistic and the old linear-damage model is not. This result has also been confirmed by other researchers. Li et al., (2000) observed that the damage curve approach (equation 5) and the double-linear damage approach (equation 6&7) are good approaches to predict the lifetime of a bearing, however, the linear damage approach (equation 4) failed to accurately reflect the evolution of bearing damage. In comparison to other models, the proposed model depends on stress analysis module and it's feedback to define the loading-damage relationship, instead of using constant damage factor which is the major drawback of other models. However, in the future, the stress formulas of the new approach will be replaced by a direct data link from stress and dynamic bearing models.
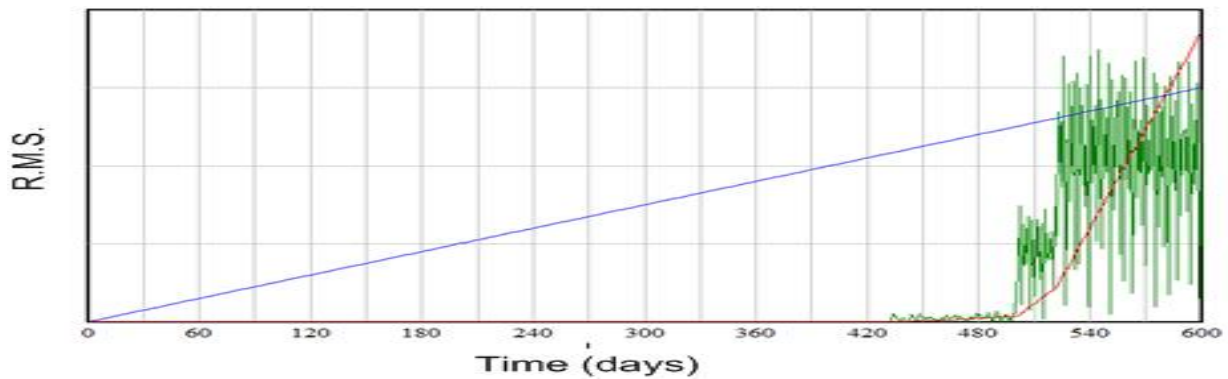
Figure 5. Comparison of RMS values of the first simplified version of the proposed model (green line) and the cumulative RMS of the proposed model (red line) and the traditional linear-damage model (blue line).

4 Conclusions

The wear predictions based on different data-driven and model-based approaches are still not reliable for rolling bearing applications. The main reason is the lack of consideration of the detailed physics of the rolling contact phenomenon. Some models ignore completely the wear physics and some others consider the physics of individual wear mechanism and at a specific stage of deterioration process. It is also worth to highlight that most of the models assume the existence of the defect and they estimate the propagation and damage following that defect initiation. It means that such models fail to link the steady-state stage and the instability stage with each other. The results of the proposed model show the dynamic development of wear progress, the behaviour of multiple wear mechanisms and their interactions. The instantaneous feedback of different wear mechanisms and their effect on surface deterioration provide more accurate results compared to the models based on 'pre-determined damage factor' for the whole lifetime. However, the model needs to be enhanced further.

5 Acknowledgements

References

Begg, C. D., Byington, C. S., & Maynard, K. P. (2000). Dynamic simulation of mechanical fault transition. *Proceedings of the 54th meeting of the society for machinery failure prevention technology* (pp. 203-212). Virginia Beach, VA.

Begg, C. D., Merdes, T., Byington, C., & Maynard, K. (1999). Dynamics Modeling for Mechanical Fault Diagnostics and Prognostics. *Mechanical system modeling for failure diagnosis and prognosis, Maintenance and reliability conference*. Gatlinburg, Tennessee.

Camci, F., Medjaher, K., Zerhouni, N., & Nectoux, P. (2012). Feature Evaluation for Effective Bearing Prognostics. *Quality and Reliability Engineering International*.

Chelidza, D., & Cusumano, J. P. (2004). A dynamical systems approach to failure prognosis. *Journal of vibration and acoustics*, *126*. American Society of Mechanical Engineers.

Chinnam, R. B., & Baruah, P. (2004). A neuro-fuzzy approach for estimating mean residual life in condition-based maintenance systems. *International Journal of Materials and Product Technology*, *20*, 166-179.

Dong, M., & He, D. (2007). A segmental hidden semi-Markov model (HSMM)-based diagnostics and prognostics framework and methodology. *Mechanical Systems and Signal Processing*, *21*, 2248-2266.

Dong, Y.-lung, Gu, W. J. I. O. N. G., Yang, K. U. N., & Zhang, W.-kun. (2004). A combining condition prediction model and its application in power plant. *Proceedings of the Third international confenrence on Machine learning and cybernetics* (pp. 26-29). Shanghai.

Engel, S. J., Gilmartin, B. J., Bongort, K., & Hess, A. (2000). Prognostics , The Real Issues Involved With Predicting Life Remaining. *IEEE Aerospace Confernece* (pp. 457-469). New York.

Gebraeel, N., Lawley, M., Liu, R., & Parmeshwaran, V. (2004). Residual Life Predictions From Vibration-Based Degradation Signals: A Neural Network Approach. *IEEE Transactions on Industrial Electronics*, *51*(3), 694-700.

Gebraeel, N. Z., & Lawley, M. A. (2008). A Neural Network Degradation Model for Computing and Updating Residual Life Distributions. *IEEE Transactions on Automation Science and Engineering*, *5*(1), 154-163.

Goebel, K., Bonanni, P., & Eklund, N. (2005). Towards an integrated reasoner for bearings prognostics. *IEEE Aerospace Conference*, 3647-3657. Ieee.

Goebel, K., Eklund, N., & Bonanni, P. (2006). Fusing Competing Prediction Algorithms for Prognostics. *IEEE Aerospace Conference*. Ieee.

Harvey, T. J., Wood, R. J. K., & Powrie, H. E. G. (2007). Electrostatic wear monitoring of rolling element bearings. *Wear*, *263*, 1492-1501.

Heng, A., Zhang, S., Tan, A. C. C., & Mathew, J. (2009). Rotating machinery prognostics: State of the art, challenges and opportunities. *Mechanical Systems and Signal Processing*, *23*(3), 724-739.

Huang, R., Xi, L., Li, X., Richard Liu, C., Qiu, H., & Lee, J. (2007). Residual life predictions for ball bearings based on self-organizing map and back propagation neural network methods. *Mechanical Systems and Signal Processing*, *21*, 193-207.

Jammu, N. S., & Kankar, P. K. (2011). A Review on Prognosis of Rolling Element Bearings. *Inrernational Journal of engineering science and technology*, *3*(10), 7497-7503.

Jantunen, E. (2004). Intelligent Monitoring and Prognosis of Degradation of Rotating Machinery. *Proceedings of the intelligent maintenance systems IMS'2004*.

Jardine, A. K. S., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, *20*(7), 1483-1510.

Kacprzynski, G. J., Sarlashkar, A., & Roemer, M. J. (2004). Predicting Remaining Life by Fusing the Physics of Failure Modeling with Diagnostics. *Journal of Metals*, *56*, 29-35.

Khawaja, T., Vachtsevanos, G., & Wu, B. (2005). Reasoning about uncertainty in prognosis: A confidence prediction neural networks approach. *IEEE Annual meeting of the North American Fuzzy information Processing society* (pp. 7-12).

Lee, J., Ni, J., Djurdjanovic, D., Qiu, H., & Liao, H. (2006). Intelligent prognostics tools and e-maintenance. *Computers in Industry*, *57*(6), 476-489.

Li, D., Wang, W., & Ismail, F. (2013). Enhanced fuzzy-filtered neural networks for material fatigue prognosis. *Applied Soft Computing*, *13*, 283-291. Elsevier B.V.

Li, D. Z., & Wang, W. (2011). An enhanced GA technique for system training and prognostics. *Advances in Engineering Software*, *42*, 452-462.

Li, Y., Billington, S., Zhang, C., Kurfess, T., Danyluk, S., & Liang, S. (1999). Adaptive prognostics for rolling element bearing condition. *Mechanical Systems and Signal Processing*, *13*, 103-113.

Li, Y., Kurfess, T., & Liang, Y. (2000). Stochastic prognostics for rolling element bearings. *Mechanical Systems and Signal Processing*, *14*(5), 747-762.

Liu, Jie, Wang, W., & Golnaraghi, F. (2009). A multi-step predictor with a variable input pattern for system state forecasting. *Mechanical Systems and Signal Processing*, *23*, 1586-1599.

Liu, J., Wang, W., Ma, F., Yang, Y. B., & Yang, C. S. (2012). A data-model-fusion prognostic framework for dynamic system state forecasting. *Engineering Applications of Artificial Intelligence*, *25*, 814-823.

Luo, J., Bixby, A., Pattipati, K., Qiao, L., Kawamoto, M., & Chigusa, S. (2003). An Interacting Multiple Model Approach to Model-based Prognostics. *System Security and Assurance* (Vol. 1, pp. 189-194).

Lybeck, N., Marble, S., & Morton, B. (2007). Validating Prognostic Algorithms: A Case Study Using Comprehensive Bearing Fault Data. *2007 IEEE Aerospace Conference*. Ieee.

Mahamad, A. K., Saon, S., & Hiyama, T. (2010). Predicting remaining useful life of rotating machinery based artificial neural network. *Computers & Mathematics with Applications*, *60*, 1078-1087. Elsevier Ltd.

Marble, S., & Morton, B. P. (2006). Predicting the Remaining Life of Propulsion System Bearings. *Proceedings of the 2006 IEEE Aerospace Conference*. Big sky, MT: IEEE.

Myötyri, E., Pulkkinen, U., & Simola, K. (2006). Application of stochastic filtering for lifetime prediction. *Reliability Engineering & System Safety*, *91*(2), 200-208.

Orsagh, R., Roemer, M., Sheldon, J., & Klenke, C. J. (2004). A comperhensive prognostics approach for predicting gas turbine engine bearing life. *Proceedings of IGTI TurboExpo*. 14-17, June, Vienna, Austria.

Pan, Y., Chen, J., & Guo, L. (2009). Robust bearing performance degradation assessment method based on improved wavelet packet–support vector data description. *Mechanical Systems and Signal Processing*, *23*, 669-681.

Peng, Y., Dong, M., & Zuo, M. J. (2010). Current status of machine prognostics in condition-based maintenance: a review. *The International Journal of Advanced Manufacturing Technology*, *50*(1-4), 297-313.

Pham, H. T., & Yang, B.-S. (2010). Estimation and forecasting of machine health condition using AR-MA/GARCH model. *Mechanical Systems and Signal Processing*, *24*, 546-558. Elsevier.

Qiu, J., Zhang, C., Seth, B. B., & Liang, S. Y. (2002). Damage Mechanics Approach for Bearing Lifetime Prognostics. *Mechanical Systems and Signal Processing*, *16*, 817-829.

Ray, A., & Tangirala, S. (1996). Stochastic modeling of fatigue crack dynamics for on-line failure prognostics. *IEEE Transactions on Control Systems Technology*, *4*, 443-451.

Schwabacher, M. A. (2005). A Survey of Data-Driven Prognostics, (September), 1-5.

Schwabacher, M., & Goebel, K. (2006). A Survey of Artificial Intelligence for Prognostics, 107-114.

Shao, Y., & Nezu, K. (2000). Prognosis of remaining bearing life using neural networks. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, *214*, 217-230.

Sutrisno, E., Oh, H., Vasan, A. S. S., & Pecht, M. (2012). Estimation of remaining useful life of ball bearings using data driven methodologies. *IEEE Conference on Prognostics and Health Management*. Ieee.

Vlok, P.-J., Wnek, M., & Zygmunt, M. (2004). Utilising statistical residual life estimates of bearings to quantify the influence of preventive maintenance actions. *Mechanical Systems and Signal Processing*, *18*, 833-847.

Wang, P., & Vachtsevanos, G. (2001). Fault prognosis using dynamic wavelet neural networks. *AI EDAM-Artifical intelligence for Engineering Design Analysis and Manufacturing* (Vol. 15, pp. 349-365).

Wang, Wenbin. (2002). A model to predict the residual life of rolling element bearings given monitored condition information to date. *Journal of Management mathematics*, *13*, 3-16.

Wang, W. Q., Golnaraghi, M. F., & Ismail, F. (2004). Prognosis of machine health condition using neuro-fuzzy systems. *Mechanical Systems and Signal Processing*, *18*, 813-831.

Wang, Wilson. (2007). An adaptive predictor for dynamic system forecasting. *Mechanical Systems and Signal Processing*, *21*, 809-823.

Wang, Wilson, Li, D. Z., & Vrbanek, J. (2012). An evolving neuro-fuzzy technique for system state forecasting. *Neurocomputing*, *87*, 111-119.

Widodo, A., Kim, E. Y., Son, J.-duk, Yang, B.-suk, Tan, A. C. C., Gu, D.-sik, Choi, B.-keun, et al. (2009). Fault diagnosis of low speed bearing based on relevance vector machine and support vector machine. *Expert Systems With Applications*, *36*, 7252-7261. Elsevier Ltd.

Widodo, A., & Yang, B.-S. (2011). Machine health prognostics using survival probability and support vector machine. *Expert Systems with Applications*, *38*, 8430-8437. Elsevier Ltd.

Xu, R., Liang, S. Y., & Haynes, L. (2005). An integrated approach to bearing fault diagnostics and prognostics. *Proceedings of American Control Conference* (pp. 2750-2755). June 8-10, 2005. Portland, OR, USA: Ieee.

Yam, R. C. M., Tse, P. W., Li, L., & Tu, P. (2001). Intelligent Predictive Decision Support System for Condition-Based Maintenance. *The International Journal of Advanced Manufacturing Technology*, *17*, 383-391.

Yan, J., Koç, M., & Lee, J. (2004). A prognostic algorithm for machine performance assessment and its application. *Production Planning & Control*, *15*(8), 796-801.

Yang, B.-S., & Widodo, A. (2008). Support Vector Machine for Machine Fault Diagnosis and Prognosis. *Journal of System Design and Dynamics*, *2*(1), 12-23.

Zhang, B., Sconyers, C., Orchard, M., Patrick, R., & Vachtsevanos, G. (2010). Fault Progression Modeling: An Application to Bearing Diagnosis and Prognosis. *American Control Conference* (pp. 6993-6998). June 30-July 02, Baltimore, MD, USA.

Towards a Smart Spare Part

Ralf Gitzel*, Guido Sand

ABB Corporate Research

Darko Anicic, Rico Knapper, Jochen Martin, Thomas Setzer, Valentin Zacharias

FZI Karlsruhe

Catherina Burghart

University of Applied Sciences Karlsruhe

Michael Beigl, Till Riedel

Karlsruhe Institute of Technology

Henrik Oppermann

USU Software AG

*Corresponding author: Ralf Gitzel
e-mail:ralf.gitzel@de.abb.com

Abstract

In many industries today service business is driven by cost pressure but also by high expectations regarding the timeliness and quality of the solution. Thus, there are two ways to stay competitive as a service provider. The first option is to increase operational efficiency in order to reduce cost. The second option is to develop new, value-creating services in order to increase revenue. We propose that up-to-date information about spare parts accessible to all stakeholders at all stages of the part life cycle will enable both strategies. Based on this premise, we describe an interdisciplinary vision for Smart Spare Parts which act as intelligent participants in a cyber-physical system together with mobile devices, ERP systems and warehouses. The virtual representation of the part can be used to make efficient decisions regarding storage, transportation and installation in order to reduce cost or enable new services.

Key words: Spare Part, Cyber-Physical System, Logistics, Sensors, Industry 4.0.

1 Introduction

Despite its low visibility to the general public, maintenance is one of the key businesses in today's world (Biedermann 2007). In many industries today service business is driven by cost pressure which is being passed on to 3rd party providers of maintenance. Despite this focus on cost customers nevertheless have high expectations regarding the timeliness and quality of the

solution. These drivers suggest two major strategies to stay competitive. The first is to reduce cost without sacrificing quality (i.e. improved operational efficiency). The second way is to develop new service products to establish unique selling points thereby increasing revenue. In this paper, we describe an interdisciplinary vision for a Smart Spare Part which will enable both strategies by adapting the ideas proposed in the context of Industry 4.0. Our goal is to provide an accurate and up-to-date data representation of a real-world part which is accessible to the different stakeholders throughout the stages of the spare part life cycle. In order to achieve this, the smart spare part acts as an intelligent participant in a cyber-physical system which also includes mobile devices, Enterprise Resource Planning (ERP) systems and warehouses. The virtual representation of the part can be used to make optimal and efficient decisions in its storage, transportation and installation. It will also enable new business models and service offerings which are not possible at today's level of data accuracy.

The paper starts with an overview of the problems in spare parts handling and today's solution to those. Based on these, we will describe our proposed solution for the smart spare part as part of a cyber-physical system. We will also show which existing concepts exist, how they can be used for our vision as well as the white spots that will need to be addressed. The vision is illustrated with two real-world use case scenarios that were developed based on interviews with service business managers. The paper ends with a conclusion and information about the next steps to reach the vision of the smart spare part.

2 Spare Part Challenges

As it has been mentioned in the introduction, there are two major strategies to stay competitive in the industrial service landscape – reduce cost or innovate by devising new service concepts. There is no ready patent solution to do the latter but there is a lot of experience in cost reduction. Since customers will react negatively to any reduction in quality, the best approach to reduce cost is to increase operational efficiency (Aberdeen Group 2012).

Spare parts play a key role in improving operational efficiency as they are a central element of most maintenance activities. Each phase of the spare parts life cycles faces challenges that influence cost and/or part availability. The savings potential resulting from these challenges is quite high, e.g. studies see one of 5-50% in spare parts logistics alone (Männel 2001, Mexis 2004). For this paper, based on a series of expert interviews with both service people and logistics experts, we have identified the following key challenges:

- *Shelf Life:* Even when not in use, parts age and possibly deteriorate. Poor transportation and storage conditions (e.g. wrong temperature ranges, high air humidity, or concussions) might increase this effect. Also, some parts require special maintenance while in storage (e.g. motor shafts have to be turned manually in fixed intervals to avoid damage). Poor conditions can reduce the quality of a part or even make parts unusable. This can lead to customer dissatisfaction, warranty issues or increased time to repairs. In the typical scenario today, storage conditions are monitored (transport not as much). However, the "condition history" of the part is recorded at the warehouse site and not passed on when the part moves around the global supply chain. In other words, there is a history for each warehouse but not for each part.

- *Mismatch between Records and Reality:* A worst case scenario for spare parts is non-availability at the time of service, especially when the records indicate that the part should exist. If there is a high level of part variants and versions, a great number of parts has to be kept in stock and properly identified. While this problem can be addressed today through rigorous processes, these processes come at a trade-off as they reduce service agility and incur higher overhead cost.

- *Installation Mistakes:* Improper installation can have a major impact on the long-term success of a maintenance activity and reduce the life time of the new part/replacement equipment. Typical mistakes are the use of the wrong parts (e.g. gaskets, screws, upgrade kits etc.), skipped steps in the installation process or poor quality of execution (e.g. poor alignment of motor shafts). Today, a final test (which takes non-negligible time) has to be performed to verify the installation process. If manuals or special calibration tools are needed, they have to be taken from different stores than the actual parts. Again, a possibly relevant part history is not associated with the part directly. In other words, the information and tools needed for a proper installation are not inherent in the part today but are separate entities, which might be unavailable, mixed up and require time to be obtained.

- *Lack of Installed Base Information:* Typically, information about a spare part or spare unit is only known in the early phases of the life cycle (e.g. due to warranty issues). Still, many professionals express the benefit of installed base information as a basis for service business (Gitzel 2013). If the details about a customer's installation are known, the proper parts can be brought by the service engineer and thus problems can be resolved more often without a second visit. Furthermore, if equipment is to be recovered and refurbished (which is not uncommon in some kinds of legacy equipment) a detailed record of the part's history and thus current quality would be helpful to reduce cost. Also, such end-of-life histories could be used to improve the design of future parts. Today such information is collected manually and is often quite incomplete, which means that it has little positive impact.

Addressing these issues can help industrial service providers, especially those which are also manufacturers of parts and equipment to reduce their cost and increase customer satisfaction. In the next section we discuss a vision for a smart spare part which helps to solve these problems in the future.

3 The Smart Spare Part Concept

When looking at these challenges and their (in our view unsatisfying) solutions from the perspective of an IT specialist, a possible root cause for many of the challenges is the lack of complete, up-to-date information. Usually, we do not know if there were problems with a part, what the exact configuration of the customer's plant is, where to find the proper tools etc. Figure 1 shows this problem – there are different, incomplete and possibly out-dated models of the real-world part, which are not accessible via the part itself but are found in location-focused IT systems.
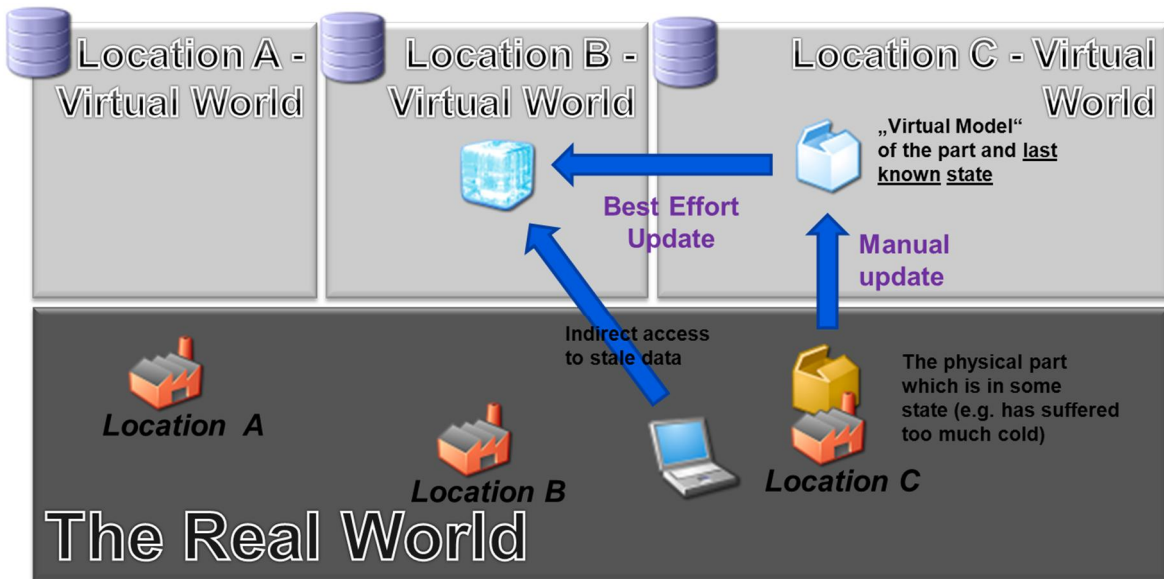
Figure 1: The Information Concept Today

The Smart Spare Part concept proposed by us to address this issue is an implementation of a Cyber Physical System (CPS) which uses dynamic coupling of hard- and software to realize adaptive, distributed processes in the real world. The system utilizes interfaces to various existing systems such as environmental condition surveillance systems, maintenance management systems, logistical planning software, semantic product memory, process and product models as well as intelligent products which include integrated sensors and RFID-tags.

The *key element* of the proposed concept is the Smart Spare Part, which is a "self-aware", intelligent product containing sensors and a connection to the virtual world. This connection allows maintaining a complete, up-to-date virtual image of the part which also includes links to other relevant information such as manuals or customer installed base information. With the smart spare part, today's approach will be transformed into the vision shown in Figure 2.
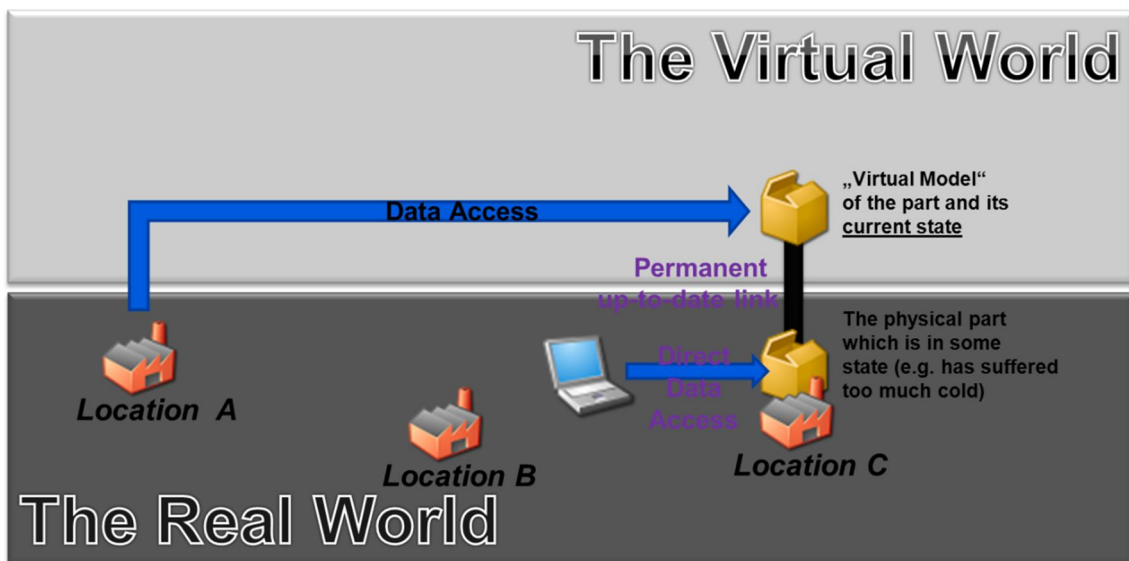

Figure 2: Smart Spare Part Concept

The Smart Spare Part will record transportation and storage conditions, its location and current state, updating its virtual model in its "*virtual product memory*". As an autonomous component in the CPS, it will intelligently recognize relevant events and abnormal conditions to update the model. This will enable adaptive and semi-formal processes around the part which result in higher operational efficiency. In particular, it will automatically sign in and out of warehouses and provide decision support during on-the-shelf maintenance, selection and installation.

We will discuss the details of the envisioned technical architecture later in the paper, however, it should be mentioned that there is a wide range of possible implementations of the Smart Spare Part concept. Thus, the part might actually be intelligent itself or use computational power found elsewhere in the CPS. Possibly, time-critical computations might be run in or near the part, while complex, yet less urgent analyses might take place elsewhere in the system. Communication with the end user might take place via displays, mobile devices or even augmented reality. In the simplest case, the part is given a so-called Quick Response (QR) code which is used to link it up to the relevant information in established systems. This means that there are many *intermediate steps* to the full vision which are more down to earth but still incorporate the spirit of the concept.

Data analysis will play a crucial role in the Smart Spare Part system. While it would already be helpful to be able to define and recognize undesired events and conditions during the supply chain, an advanced system could even go further. Often, the exact boundaries of an undesirable event are not known. For example, it might be unclear which temperature exactly is the limit for a certain spare part during the time it has been stored. An intelligent system can use recorded data to learn about the impact of the various environmental factors on the quality and life-time of a part. A good basis for such a semantic-analytical layer in the system would be based on methods such as Complex Event Processing (CEP) (Luckham 02), ontological modelling (cf. Spyns et al 2002), Stream Reasoning (Anicic et al 2010, Anicic et al 2011) and data analysis models in order to recognize patterns.

On the other hand, the system will not be completely autonomous but will allow human actors to intervene at various points of the processes. For example, irregular situations might be brought to the attention of a warehouse supervisor who can make decisions based on the recommendations given by the system.

The envisioned system will address the issues mentioned in Section 2 in the following way:

- *Maximization of Shelf Life and Avoidance of Transportation Damage:* Intelligent parts with sensors are able to maintain and use a virtual product memory to recognize and assess irregular events and conditions in the supply chain. Mobile devices or other interfaces can inform a technician about these issues and support the decision making process about parts usability.
- *Presentation of up-to-date and accurate parts information for internal and external stakeholders:* Intelligence, sensors and interconnectivity will allow the Smart Spare Part to provide various stakeholders with context-relevant information such as the part version, manuals, part history and the customer's system configuration.
- *Support through relevant information in all phases of the life cycle:* The stakeholders will not be flooded with irrelevant information but instead will be provided with relevant and aggregated subsets they need for their tasks at hand.
- *Installed Base Transparency:* The Smart Parts will record installed base information when possible and use their connection to the CPS to update the installed base information in the enterprise. It will also give the access to relevant subsets needed for a proper service job.

4. Related Work

The vision of the Smart Spare Part is admittedly a bold one but there is a strong technological foundation already which can be used to realize the vision in the near future, possibly as a series of gradual improvements. In fact, we feel that it sometimes requires such a bold vision to create a motivation for innovation. Assuming the reader of this paper to be more interested in maintenance than computer science, we only provide a high-level overview of the underlying technologies in relatively simple terms.

According to a study by the Aberdeen Group, the main challenge in spare parts logistics is the insufficient integration of technological infrastructures (58%). Furthermore, 52% of the study participants criticize the "silo-thinking" of the various service units (Aberdeen Group 2012). The relevant technological basis used today is quite heterogeneous depending on industry and company. Generally speaking, the supply chain is supported by semi-centralized (ERP) systems. Information in the systems is updated more or less manually and the systems rarely cross organizational borders.

Many of our ideas are inspired by recent work in the logistics area, where Radio Frequency Identification (RFID) technology is starting to play a major role, e.g. in the context of the RAN project. However, these approaches do not actively monitor condition and environmental influences in order to determine possible deterioration, nor is there any concept of supporting version problems of parts or installation guidelines. Even approaches to spare parts logistics focus primarily on optimization based on existing enterprise data (Gitzel et al 2012). While RFID tags and QR codes facilitate data collection, spare parts today are not able to perform the required updates themselves. For this reason, problems during delivery and storage cannot be automatically recognized. Neither can one be sure that the information is up-to-date.

In contrast, a *cyber-physical system* (CPS) is made up of dynamically connected, self-coordinating components (Geisberger and Broy 2012). What this means is that there are many intelligent devices which use wireless communication to build networks. These devices could be intelligent parts, warehouses and other non-human elements of a spare parts supply chain. Especially wireless sensor nodes have already been used in an industrial context but not for a spare part concept (cf. Krishnamurthy et. Al. 2005, Maaike et al., 2008). Due to the unique problems of the industrial domain (see e.g. Fantana and Riedel 2009) many of the current solutions can be directly re-used for the Smart Spare approach.

Data transfer and analysis is a major element of our concept. Therefore it requires suitable formats, which are both machine readable and semantically rich. Work within on de-centralized collection of operational states in order to minimize resource consumption done in the RESCOM project (Loskyll et. al 2012) covers similar topics as our vision. Also early work on smart items in the logistics domain, e.g. in the CoBIs project (Decker et al. 2007), has evaluated the surveillance of storage conditions for generic smart items. Prevíous work, however, does not consider the specific lifecycle of spare parts.

5 Technological Basis for a Smart Spare Part

As we have mentioned in the previous section, there is a strong technological base even today to realize a Smart Spare Part. In this section, we describe a possible vision for the Smart Spare Part using cutting edge technologies to solve the various challenges associated with the concept. This section is therefore divided into challenges, which are briefly explained before

technological solutions are discussed. Again, the aim is to make the ideas accessible to a wider audience and not specialists in those technologies.

As already explained in its overall concept, the actual Smart Spare Parts will be elements in CPS. The parts will be context-adaptive and will act autonomously. Figure 3 shows the overall technological architecture which we will discuss in this section.
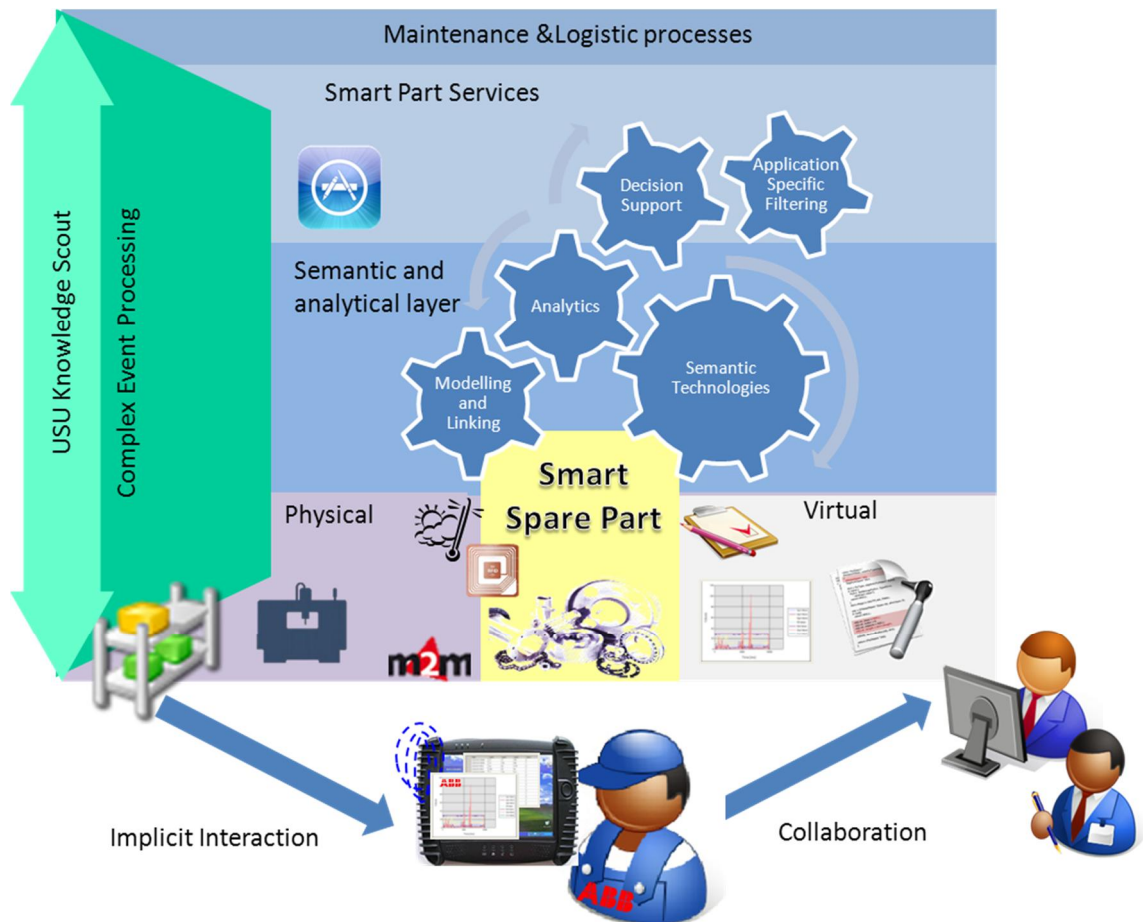

Figure 3: Technological Architecture

5.1 Physical and Virtual Layers

The physical and virtual layers lie at the bottom of the layer stack in Figure 3. They represent the physical elements (such as the spare parts) as well as virtual documents associated with them. The strong connection between the physical and the virtual is realized through a CPS.

Smart Parts have to be capable of recognizing their environment in order to understand problematic situations on the physical layer. There are however several challenges to accomplish this. First of all, cheap and non-interfering sensors have to be found or developed which can be put on the parts. The second question is whether these sensors should be re-usable, built-in but turned off during the installation, built-in and running permanently, or just disposable. For early stages of the paradigm, reusable sensors which are temporarily attached to a part are probably the best option. Further existing and retrofitted sensors in the environments or in an automation system can be semantically linked to sensor via localization techniques. Instead of proprietary or domain specific communication protocols we propose light-weight, loosely coupled Web services to exchange configuration and measurement data

between RFID, mobile and fixed sensing and automation systems (Jammes und Smit, 2005; Riedel et. al 2010) to support the wide spectrum of scenarios involving smart spare parts.

The required sensor capabilities for local and environmental sensors are determined by a particular spare part product, and good candidates are, for example, sensors for temperature, humidity and vibration. There are several technologies which might be suitable for this purpose (see the previous section) but as stated before, their applicability to an industrial environment has yet to be verified and their interoperability has to be ensured.

5.2 Semantic and Analytical Layer

While the physical layer generates new data and the virtual layer stores it, this data is yet in a raw form which for machine algorithms is hard to interpret. In order to add *meaning* to the raw values, a semantic layer is needed. This layer also enables analytical algorithms to process the data. The W3C, the entity responsible for Web-related standards such as HTML, offers a series of well-accepted languages for semantic modelling (e.g. the Web Ontology Language (OWL) (Horrocks et al 2003) and the Resource Description Framework (RDF) (W3C 2004)). These languages can be used to create models which enable drawing conclusions from the collected data through reasoning algorithms.

One challenge for the reasoning is that in the system, large amounts of real-time data will be generated and must be handled and combined with semantic knowledge bases. Conventional data analysis algorithms are too slow for semantic processing of rapidly changing data. However, modern technologies to tackle this problem exist in the form of Complex Event Processing (CEP) (Luckham 02) and Stream Reasoning (SR) (cf. Anicic et al 2010, 2011). The core idea of CEP is to filter, aggregate and correlate real-time data in order to recognize relevant key events which are indicated by a specific combination of measurement results. For example, CEP might recognize a combination of transport conditions which will damage the part and alert the driver about them. This can also be used as part of a self-check or to explore the exact boundaries of adverse conditions. There are several useful tools for both CEP and SR which have in realized already (cf. Anicic et al 2010, 2011, InDiNet 2013).

There are different scenarios where to locate this layer. It could be part of the cloud or placed on individuals parts. The former concept is probably the more realistic one for the current technological and economical capabilities, however the semantic processing and reasoning on devices with constrained capabilities is recently also getting attention in research and industry (Grimm et al 2012).

5.3 Smart Part Services Layer

Since our vision is based on a CPS, we need a suitably flexible communication architecture. The best choice seems to be a service-based concept with the ability to register new elements which implement a service interface and drop out existing elements. However, in such an environment, there must be a powerful search mechanism to locate services and a semantic metadata concept which allows a service description. Web Services are a well-known tool which can be used to implement such an architecture. A service-based layer will allow system access through any device that can interface to this technology, e.g. tablet PCs or smart phones.

6. Use Cases

So far we have described the general concept of the Smart Spare Part as well as the potential technological foundation. In order to show the value of the proposed approach, we show two practical examples which have been developed after interviews with experts working in the respective fields.

6.1 Flowmeters

The flowmeter market is very mature and saturated. Even in the brownfield area, there is a massive price battle. As a result, the feeling prevails that only by providing highly efficient service the market share can be maintained. A Smart Spare Part would provide the right tool set to meet this goal.

Unique Challenges: A key problem in the flowmeter market is obsolescence. Many installed meters are no longer available from their vendors and thus have to be replaced with newer models. However, such a replacement is rarely straightforward and requires an upgrade kit. If the proper kit is not taken to the customer site, the upgrade cannot be performed on the first visit.

Smart Spare Solution: As mentioned before, the Smart Spare Part provides *installed base transparancy* by collection and storing information about the customer's assets. Using information about product versions owned by the customer, smart flowmeters can automatically order upgrade kits when they themselves are ordered for a particular customer. During installation, the part will provide *relevant information* that helps the technician to apply the upgrade kit properly.

Since the parts understand the complexity of the installed base and the effects of obsolescence, they can use this information to plan their migration between warehouses. Such an automated parts migration can enable time-efficient delivery of parts to the customers. Finally, the parts maximize their shelf life by complaining about wet storage conditions.

6.2 Low Voltage Motors

Low voltage motors are a common-place piece of equipment and thus it is easy for customers to switch loyalty. Also, they are produced and sold in larger quantities to improvement, so improvements to the spare unit business have a high savings potential. For these reasons, they are an interesting use case for the Smart Spare Part.

Unique Challenges: Low voltage motors are products which need maintenance even while in the warehouse, i.e. their shafts have to be turned periodically. They can suffer damage during transportation, e.g. through jolts and extreme temperatures below zero. If damage during transportation is not noticed, replacement units might fail quickly after installation. Finally, installation of motors requires some care, e.g. misalignment can lead to damage quickly.

Smart Spare Solution: The sensor and analytics capabilities of the smart spare parts (in this case spare motors) *maximize shelf life* by ensuring that the motor is properly maintained. Since the maintenance schedule is tied directly to the motor, even complex journeys through the supply chain will not result in missed maintenance activity. Similarly, *transportation incidents* will be recorded and can be used to assess whether a motor should be scrapped in order to avoid warranty issues and loss of customer confidence. During installation the motor will provide information as to whether the motor is correctly installed, e.g. by checking the alignment.

7. Conclusions

In this paper we have presented a vision for a Smart Spare Part which addresses several key challenges in today's spare parts logistics and use in service. We have further illustrated those challenges with use cases from two different domains. Our proposed concept in return raises a series of technical challenges which are identified in this paper and contrasted with the state of the art. While our vision is quite radical in some respects, it can be seen that its foundations

already exist today and with the roadmap laid out, work can commence on the foundation of a Smart Spare Part infrastructure.

References

Aberdeen Group (2012): "Analyst Insight - Convergence 2012 – People and Parts Linked Together to Solve Customer Issues." http://www.aberdeen.com/Aberdeen-Library/8257/AI-service-parts-operations.aspx

D. Anicic, P. Fodor, S. Rudolph, R. Stühmer, N. Stojanovic und R. Studer (2010): "A Rule-Based Language for Complex Event Processing and Reasoning," In: RR 2010: Proceedings of the Fourth International Conference on Web Reasoning and Rule Systems, Italy

D. Anicic, P. Fodor, S. Rudolph, N. Stojanovic (2011): "EP-SPARQL: A Unified Language for Event Processing and Stream Reasoning," In: WWW 2011: Proceedings of the Twentieth International World Wide Web Conference, India.

H. Biedermann (Hrsg.) (2007): „Wertschöpfendes Instandhaltungs- und Produktionsmanagement - Erfolgreich durch Innovationen in Management und Technologie", TÜVMedia, 2007

M. Botts und A. Robin (2007): "OpenGIS sensor model language (SensorML) implementation specification". OpenGIS Implementation Specification OGC (2007): 07–000.

Christian Decker, Till Riedel, Michael Beigl, L M S De Souza, P Spiess, J Muller, S Haller (2007): Collaborative business items, 3rd IET International Conference on Intelligent Environments IE 07(531 CP), p. 40-47,

C. Emmanouilidis (2009): "A Wireless Sensing Development Platform for Ubiquitous Condition Monitoring." In: Proceedings of the 22nd International Congress on Condition Monitoring and Diagnostic, Engineering Management.

N. Fantana, und T. Riedel (2009): "Servicing industrial machinery: Challenges using wireless identification and networked sensing systems." In: Networked Sensing Systems (INSS), 2009 Sixth International Conference on, 1-4.

Stephan Grimm, Michael Watzke, Thomas Hubauer, Falco Cescolini (2012): "Embedded EL+ Reasoning on Programmable Logic Controllers", In: International Semantic Web Conference (ISWC), pp. 66-81, 2012

E. Geisberger und Broy (2012): „Cyber-Physical Systems—Wissenschaftliche Herausforderungen bei der Entwicklung". Cyber-Physical Systems (2012), S. 17–31.

R. Gitzel, I. Harjunkoski und C. Pinto (2012): "Stock Pooling Optimization" In: ABB Review 4/2012, pp. 30.

R. Gitzel (2013): "Round Table Discussion - What is the Impact of Uncertainty and Lack of Information on Spare Parts Logistics?" In: "Optimizing the International Spare Parts Management in the Machinery Industry", Berlin, 24-25.1.2013

I. Horrocks, P. F. Patel-Schneider, F. Van Harmelen (2003): "From SHIQ and RDF to OWL: The making of a web ontology language." In: *Web Semantics, 1*(1), pp. 7-26

InDiNet (2013): http://www.software-cluster.com/de/forschung/projekte/verbundprojekte/indinet

F. Jammes und H. Smit (2005): "Service-oriented paradigms in industrial automation," In: IEEE Transactions on Industrial Informatics, vol. 1, 2005, pp. 62ff.

L. Krishnamurthy, R. Adler, P. Buonadonna, J. Chhabra, M. Flanigan, N. Kushalnagar, L. Nachman, und M. Yarvis M. (2005): "Design and deployment of industrial sensor networks: experiences from a semiconductor plant and the north sea." In: Proceedings of the SenSys '05. ACM, New York, NY, USA, 64-75

M. Loskyll, I. Heck, J. Schlick, M. Schwarz (2012): Context-Based Orchestration for Control of Resource-Efficient Manufacturing Processes. Future Internet, Vol. 4, Nr. 3, S. 737-761.

David Luckham(2002): The Power of Events: An Introduction to Complex Event Processing in Distributed Enterprise Systems. Addison-Wesley, Reading, MA, USA.

W. Männel (Hrsg.) (2001): „Tagungsband der Fachtagung Instandhaltung." Verlag der GAB, Lauf an der Pregnitz

N. D. Mexis (2004): „Die Philosophie der Instandhaltung.", Institut für Analytik und Schwachstellenforschung, Mannheim, 2004.

RAN Projekt: http://www.autoran.de/

T. Riedel, N. Fantana, A. Genaid, D. Yordanov, H. Schmidtke, M. Beigl (2010), "Using Web Service Gateways and Code Generation for Sustainable IoT System Development", Internet of Things 2010 – Second International Conference for Academia and Industry (IOT2010)

Spyns, P., Meersman, R., & Jarrar, M. (2002): "Data modelling versus ontology engineering." In: *SIGMOD Record, 31*(4), pp. 12-17, 2002.

VDI/VDEh (2010): Einleitungsrede des 31. VDI / VDEh Forums Instandhaltung 2010 "Effizienz im Anlagenmanagement"

W3C (2004): „Resource Description Framework (RDF): Concepts and Abstract Syntax", online at: http://www.w3.org/TR/2004/REC-rdf-concepts-20040210/

Economic lifetime of a drilling machine:

A case study on mining industry

Hussan Al-Chalabi[a,b,]*, Jan Lundberg[a] and Adam Jonsson[c]

[a] Division of Operation, Maintenance and Acoustics
Luleå University of Technology
SE-971 87 Lulea
Sweden
[b] Mechanical engineering Department
College of Engineering
University of Mosul
41002 Mosul
Iraq
[c] Division of Mathematic Science
Luleå University of Technology
SE-971 87 Lulea
Sweden
*Corresponding author: Hussan Al-Chalabi
e-mail: hussan.hamodi@ltu.se
e-mail: Jan.Lundberg@ltu.se
e-mail: adam.jonsson@ltu.se

Abstract

Underground mines use many different types of machinery during the drift mining processes of drilling, charging, blasting, loading, scaling and bolting. Drilling machines play a critical role in the mineral extraction process and thus are important economically. However, as the machines age, their efficiency and effectiveness decrease, negatively affecting productivity and profitability and increasing total cost. Hence, the economic replacement lifetime of the machine is a key performance indicator. This paper introduces an optimisation model that gives the optimal lifetime for a drilling machine. A case study has been done at an underground Swedish mine to identify the economic replacement time of a drilling machine. It considers the purchase price, maintenance and operation costs, and the machine's second-hand value. Findings show that the economic replacement lifetime of a drilling machine in this mine is 96 months. The proposed model can be used for other underground mining machines.

Key words: Drilling machine, Optimal equipment lifetime, Optimization model.

1 Introduction

Mines are a source of energy resources and minerals. Thus mines play a key role in the economic growth of industrialised countries. Many different machines are essential in the

mineral extracting process; one example is the drilling machine. Economic competition and customer demand have pushed companies to achieve higher production rates through greater mechanisation and automation. This has lead to high investments in equipment (Duffuaa et al., 1998). The trend towards larger and more expensive equipment in underground mining to achieve cost effectiveness raises the question of replacement. When should a company replace the existing equipment to maximise production and minimise cost? Because drilling machines are a key element of production, they are important economically. A significant cost issue is the machine's maintenance cost. At long-term profitability, the Maintenance can play a key role for a firm, where it can have major impact on cost (Baglee and Knowles, 2010). Up to 40% of the total production cost of the heavy industries represents by maintenance cost (Lee and Wang, 1999). A study by the Swedish mining industry shows that the cost of maintenance in a highly mechanized mine can be 40-60 % of the operating cost (Danielson, 1987). Thus, the important factors behind these costs needs to be measured for their performance, like; measuring value created by the maintenance, justifying investment and revising resource allocations (Parida and Kumar, 2006). These factors are related to the cost of mining equipment and its economic lifetime.

The growing interest in modelling the economic lifetime of capital equipment has dramatically increased during recent decades. The optimal economic replacement of productive machines is a fundamental question faced by researchers, economic engineers and management engineers. Researchers concerned with cost optimisation are especially interested in the optimum replacement time of production equipment.

Many researchers have studied optimal procedures for replacing old equipment with new. Some have used the theory of dynamic programing considering technological changes under infinite and finite horizon (Bellman, 1955; Bethuyne, 1998; Elton and Gruber, 1976; Hritonenko and Yatsenko, 2008). Another study optimised the lifetime of capital equipment using integral models (Yatsenko and Hritonenko, 2005); the study designed a general investigation framework for optimal control of the integral models. Many researchers have studied the optimal lifetime of capital equipment through economic theory by using vintage capital models, represented mathematically by non-linear Volterra integral equations with unknown limits of integration, (Boucekkine et al., 1997; Cooley et al., 1997; Hritonenko and Yatsenko, 2003; Hritonenko, 2005). (Hartman and Murphy, 2006) presented a dynamic programming approach to the finite-horizon equipment replacement problem with stationary cost. Their model was introduced to study the relationship between the infinite-horizon solution (continuously replace equipment at the end of its economic lifetime) and the finite-horizon solution. (Kärri, 2007) studied the optimal replacement time of old machine. He used an optimization model which minimizes the machine cost; the model has been built for capacity expansion and replacement situation. The costs of old machine were modelled with simple linear functions and all costs that he used in his study are real costs without inflation. He also used another optimization model which maximizes profit. (Hritonenko and Yatsenko, 2009) constructed a computational algorithm to solve a nonlinear integral equation. The solution is important for finding the optimal policy of equipment replacement under technological advances. Other researchers such as (Galar et al., 2012) used different cost models to define the efficiency of the operation of an industrial installation in a finite time horizon. They develop a methodology for the calculation of operation costs in industrial facilities.

The optimum replacement age of equipment is defined as that time at which the total cost is at its minimum value (Jardine and Tsang, 2006). In this case study the economic lifetime of drilling machine is defined as the optimal age which minimises the total adjusted cost value.

The term "total adjusted cost value" is defined as the summation of the machine purchase price, operation cost, maintenance cost and machine second-hand value. The machine second-hand value is the value of the machine in case the company wants to sell the machine at any time during the machine's planned lifetime. In this study, the most influential factors in the drilling machine's economic lifetime have been considered; cost data were collected for four years.

A previous literature review found that researchers have focused on estimating the optimal lifetime of equipment considering technological changes by using integral models, theories of dynamic programing, vintage capital models and algorithms to solve a nonlinear integral equations; it is sometimes hard for users to implement these models. Moreover, these models sometimes require specific types of data that, as in our case study, are simply not available. Thus, the aim of this study is to present a practical optimisation model to more easily estimate the economic lifetime of drilling machine, using available data from the mining company.

The rest of the study is as follows. Section 2 describes the drilling machine, while Section 3 discusses data collection. Methodology and model development are presented in Section 4; results and a discussion appear in Section 5; Section 6 offers conclusions and Section 7 offers future work.

2 The Drilling Machine

All drilling machines for mining applications are composed of similar operational design units: cabin, boom, rock drill, feeder, service platform, front jacks, hydraulic pump, rear jack, electric cabinet, hose reeling unit, cable reeling unit, diesel engine, hydraulic oil reservoir, operator panel and water tank. A typical drilling machine is shown in Figure1 (Atlas, 2010).
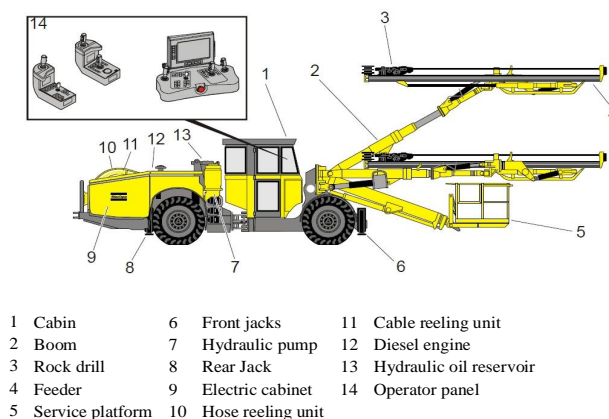

1	Cabin	6	Front jacks	11	Cable reeling unit
2	Boom	7	Hydraulic pump	12	Diesel engine
3	Rock drill	8	Rear Jack	13	Hydraulic oil reservoir
4	Feeder	9	Electric cabinet	14	Operator panel
5	Service platform	10	Hose reeling unit		

Figure 1. Drilling machine (Source: Atlas Copco Rock Drills AB)

Drilling machines manufactured by different companies have different technical characteristics, e.g. capacity and power. Based on the operation manuals, field observations and maintenance reports from the collaborating mine, in this study the drilling machine is considered a system divided into several major subsystems connected in a series configuration. If any subsystem fails, the operator will stop the machine to maintain it. Thus,

all machine subsystems work simultaneously to achieve the desired function. Figure 2 is a block diagram of drilling machine subsystems.
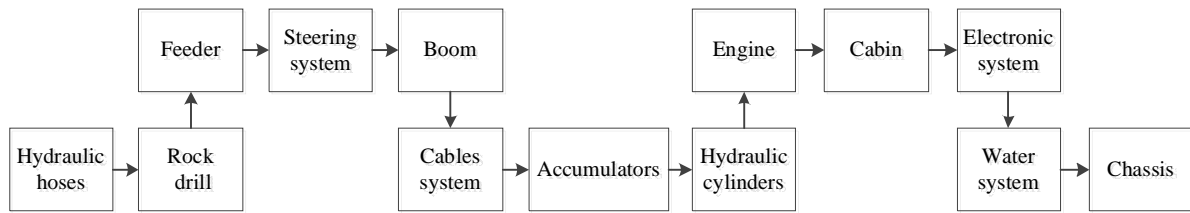

Figure 2. Block diagram of drilling machine subsystems

3 Data collection

The cost data used in this study were collected over four years in the Maximo computerised maintenance management system (CMMS). The cost data contain corrective and preventive maintenance costs and time to repair. The corrective and preventive maintenance cost contains spare part and labour (repair man) cost. In CMMS, the cost data are recorded based on calendar time. Since drilling is not a continuous process, the operation cost is estimated by considering the utilisation of the machine. All costs data that used in this study are real costs without inflation.

4 Methodology and model development

In this study, the notation for maintenance and operation costs as well as the machine purchase price with other quantities used in the optimisation problem is given in Table 1.

Table 1. Definition of model variables

Variable	Definition
cu	Currency unit
pp	Purchase price (cu)
rT	Replacement time (month)
MC	Maintenance cost (cu)
CMC	Corrective maintenance cost (cu)
PMC	Preventive maintenance cost (cu)
SPC	Spear part cost (cu)
LC	Labour cost (cu)
OC	Operation cost (cu)
$SHV(t)$	Second-hand value (cu)
Dr	Depreciation rate
BV_1	Booking value at first day of operation (cu)
SV	Scrap value (cu)
TAC_i	Total adjusted cost (cu)

The maintenance costs (corrective and preventive) for each operation month were calculated as follows:

$$MC = CMC + PMC \qquad (1)$$

$$CMC = SPC + LC \qquad (2)$$

$$PMC = SPC + LC \qquad (3)$$

Determination of the utilisation of the drilling machine was based on the estimation of the operation cost because drilling is not a continuous process in the collaborating mine.

The company planned to use the machine for ten years. For that reason, extrapolation has been done for maintenance and operation cost data. Figures 3 and 4 illustrate the expected maintenance and operation costs data extrapolation.
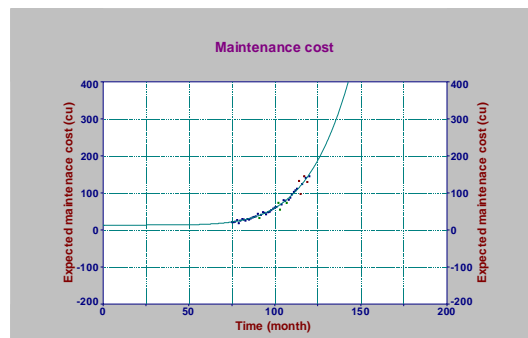

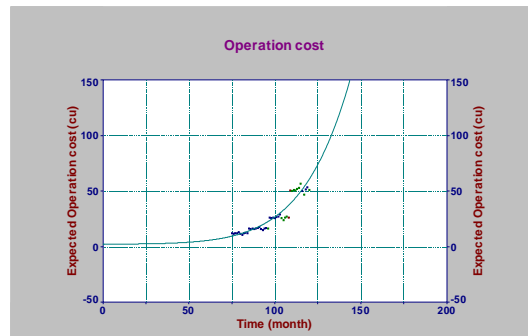**Figure 3. Expected maintenance cost**

Figure 4. Expected operation cost

In Figures 3 and 4, dots represent the real data for maintenance and operation costs. Curve fitting is done by using Table curve 2D software to show the behaviour of the machine in term of these costs before and after the time of collected data. The figures show that the maintenance and operation costs increase over time. Possibly, the number of failures increases with time and/or the machine consumes more energy due to machine degradation.

A declining balance depreciation model was used to model the second-hand value of the machine after each month of operation. The second-hand value of the machine was estimated from the following formula (Luderer et al., 2010):

$$SHV(t) = BV_1 \times (1 - Dr)^t \qquad (4)$$

where (t) represents time (month), $t=1, 2, 3... 120$.

The depreciation rate that allows for full depreciation by the end of the planned lifetime of the machine was modelled by the following formula (Luderer et al., 2010):

$$Dr = 1 - \left[\left\{ \frac{SV}{BV_1} \right\}^{\frac{1}{L}} \right] \qquad (5)$$

where (L) represents the planned lifetime of the machine (in this case 120 months). The machine's second-hand value was modelled by the following formula:

$$SHV(t) = (pp - a) \times (1 - Dr)^t \qquad (6)$$

Where a represents the machine's depreciation in value on the first day of use. It is assumed that the machine's total lost value will be 10% on the first day of use. Hence, the machine's second-hand value at the end of the first day of operation is (pp-a) $= 0.9 \times pp$.

We have chosen the declining balance depreciation model because it is suitable for representing the depreciation of industry equipment, especially repairable systems. The declining balance depreciation model assumes that more depreciation occurs at the beginning of the equipment's planned lifetime, less at the end. The equipment is more productive when it is new and its productivity declines continuously due to equipment degradation. Therefore, in the early years of its planned lifetime, it will generate more revenue than in later years. In accountancy, depreciation refers to two aspects of the same concept. The first is the decrease in the equipment's value. The second is the allocation of the cost of the equipment to periods in which it is used. The scrap value is an estimate of the value of the equipment at the time it is sold or disposed of; in this study, 50 cu was assumed as the scrap value. Due to the secrecy policy of the company, all cost data were encoded and expressed as currency unit cu.

Figure 5 shows the drilling machine's second-hand value using the declining balance depreciation model.
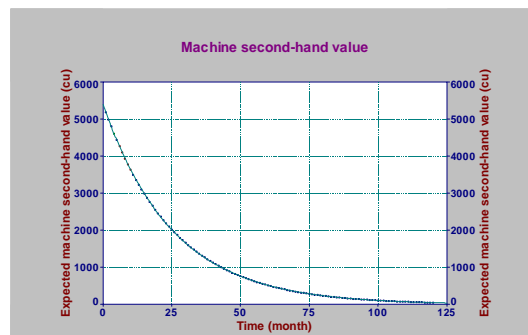

Figure 5. Expected machine second-hand value

Figure 5 shows that the machine's second-hand value decreased with time until it reached scrap value at the end of its planned lifetime.

The next step in the calculations is to compute the total adjusted cost TAC_i during a period i of operation using the following formula:

$$TAC_i = pp + \left[\sum_{k=1}^{rT} \left(MC_k + OC_k \right) \right] - SHV\left(rT\right) \tag{7}$$

where $i = 1, 2, 3, ..., N+1$. $N+1$ represents the number of operation periods.

For example, TAC_1 represents the total adjusted cost of the first period of operation and TAC_2 represents the total adjusted cost of the second period of operation.

The optimisation model assumes that the replacement machines have the same performance and cost as the old machines. The number of replacements during the optimisation time horizon is determined by the following formula:

$$N = \frac{\text{Optimization time horizon}}{\text{Machine replacement time}} = \frac{T}{rT} \tag{8}$$

Figure 6 illustrates the expected total adjusted cost of the machine over the machine's planned lifetime.
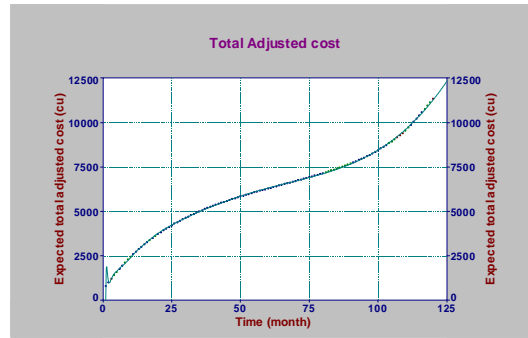

Figure 6. Expected total adjusted cost

Figure 6 shows that the total adjusted cost increased with time for two reasons: first, maintenance and operation costs increased over time; second, the machine's second-hand value decreased over time.

To show the behaviour of the optimisation curve after the optimal replacement time, we assumed that the machine would survive for a finite horizon of 360 months; see Figure 7. The total adjusted cost for each operation period of the optimisation time horizon was computed by using the total adjusted cost function. This function is the fit of the calculated total adjusted cost over the machine's planned lifetime (120 months). Table Curve 2D software was used to find the total adjusted cost function which can be used for any time horizon. Equation 8 expresses the total adjusted cost function used here:

$$\begin{aligned} TAC(t) = a + b \times \ln(t) + c \times \left[\ln(t)\right]^2 + d \times \left[\ln(t)\right]^3 + e \times \left[\ln(t)\right]^4 + f \times \left[\ln(t)\right]^5 \\ + g \times \left[\ln(t)\right]^6 + h \times \left[\ln(t)\right]^7 + i \times \left[\ln(t)\right]^8 + j \times \left[\ln(t)\right]^9 \end{aligned} \tag{9}$$

where *a= 814.0, b= 13834.3, c= -56718.9, d= 95747.0, e= -86169.8, f= 45829.6, g= -14863.2, h = 2890.3, i= -309.9, and j= 14.1.*

The optimal replacement time (*rT*) which minimises the total adjusted cost value can be calculated by the following formula:

$$Min\left(TAC_{value\ rT}\right) = Min\left[\left\{pp + \left[\sum_{k=1}^{rT}\left(MC_k + OC_k\right)\right] - SHV\left(rT\right)\right\} \times N\right] \tag{10}$$

5 Result and discussion

Microsoft Excel™ software was used to enable variation of the *rT* of Eq. (10) for a period of 360 months, to identify the optimum replacement lifetime of a drilling machine that minimises *TAC_{value rT}*. Fig.7 shows *TAC_{value rT}* versus different replacement time *rT*. As is evident, the lowest possible *TAC_{value rT}* can be achieved by replacing the machine every 96 months (8 years). Hence, a decision to replace before or after 96 months incurs greater cost for the company.
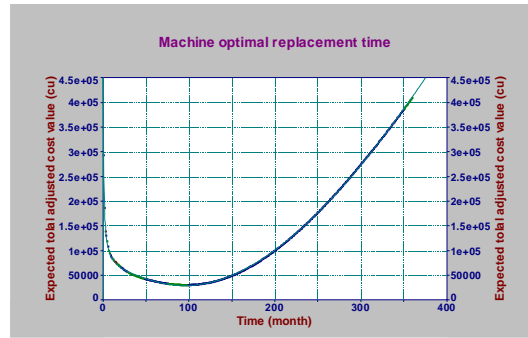

Figure 7. Optimal replacement time

The losses will increase if the lifetime of the machine exceeds 96 operating months for two reasons:

1. The maintenance and operation cost increase when the operation time increases due to machine degradation;

2. The machine's second-hand value will decrease until it reaches scrap value at the end of its planned lifetime which is 120 months.

6 Conclusions

We derive the following conclusions from the present study:

1. This study gives a basic approach to determining the optimum economic lifetime of a drilling machine, which facilitates the management in making investment decision making.

2. When using the purchase price, operation and maintenance costs, and second-hand value, the optimum lifetime of the drilling machine is the minimum sum of the associated total adjusted cost value.

3. We recommend replacing the machine between 90-102 months if the company only considers the cost.

4. This model helps engineers and decision-makers decide when it is best economically to replace an old machine with a new one. Thus, it can be extended to more general applications in mining industry.

7 Future works

Further research is needed to extend the developed model by performing a sensitivity analysis to identify the effect of purchase price, operation and maintenance costs on the optimal replacement time of the drilling machine on mining industry.

References

Duffuaa, S. O., Raouf, A., and Campbell, J. D. (1998) 'Planning and control of maintenance systems: modeling and analysis' 1st edition, Wiley Publisher.

Baglee, D., and Knowles, M. (2010) 'Maintenance strategy development within SMEs: the development of an integrated approach' *Control and Cybernetics*, Vol. 39, NO. 1, pp. 275-303.

Lee, J., and Wang, B. (1999) 'Computer-aided Maintenance: methodologies and practices' Vol. 5, Kluwer Academic Publisher.

Danielson, B. (1987) 'A Study of Maintenance Problems in Swedish Mines, Study Report', *Idhammar Konsult AB* (in Swedish).

Parida, A and Kumar, U. (2006) 'Maintenance Performance Measurement (MPM): Issues and Challenges', *Journal of Quality in Maintenance Engineering*, Volume 12, No. 3, pp. 239-251

Bellman, R. (1955) 'Equipment replacement policy', *Journal of Society for Industrial and Applied Mathematics*, Vol. 3, No. 3, pp. 133-136.

Bethuyne, G. (1998) 'Optimal Replacement Under Variable Intensity of Utilization and Technological Progress', *The Engineering Economist: A Journal Devoted to the Problems of Capital Investment*, Vol. 43, No. 2, pp. 85-105.

Elton, E.J., Gruber, M.J. (1976) 'On the Optimality of an Equal Life Policy for Equipment Subject to Technological Improvement', *Operational Research Quarterly*, Vol. 27, No. 1, pp. 93-99.

Hritonenko, N., Yatsenko, Y. (2008) 'The dynamics of asset lifetime under technological change', *Journal of the Operations Research Letters*, Vol. 36, pp. 565-568.

Yatsenko, Y., Hritonenko, N. (2005) 'Optimization of the lifetime of capital equipment using integral models', *Journal of industrial and management optimization*, Vol. 1, No. 4, pp. 415-432.

Boucekkine, R., Germain, M., Licandro, O. (1997) 'Replacement Echoes in the Vintage Capital Growth Model', *Journal of economic theory*, Vol. 74, No. 962265, pp. 333-348.

Cooley, T.F., Greenwood, J., Yorukoglu, M. (1997) 'The replacement problem', *Journal of Monetary Economics*, Vol. 40, pp. 457-499.

Hritonenko, N., Yatsenko, Y. (2003) 'Applied Mathematical Modeling Of Engineering Problems', *Kluwer Academic Publishers*.

Hritonenko, N. (2005) 'Optimization Analysis of a Nonlinear Integral Model with Applications to Economics', *Nonlinear Studies*, Vol, 12, No. 1, pp, 59-71.

Hartman, J.C., Murphy, A. (2006) 'Finite-horizon equipment replacement analysis', *IIE Transactions*, Vol. 38, No. 5, pp. 409-419.

Kärri, T. (2007) 'Timing of Capacity Change: Models for Capital Intensive Industry', Lappeenrannan teknillinen yliopisto/Lappeenranta University of Technology.

Hritonenko, N., Yatsenko, Y. (2009) 'Integral equation of optimal replacement: Analysis and algorithms', *Journal of Applied Mathematical Modelling*, Vol. 33, pp. 2737-2747.

Galar, D., Kumar, U., Sandborn, Pand Morant, A. (2012) 'O&M efficiency model: A dependability approach', *Journal of Physics: Conference Series,* No. 1, Vol. 364.

Jardine, A. and Tsang, A. (2006) 'Maintenance, Replacement, and Reliability Theory and Application' Taylor & Francis Group.

Atlas Copco Rock Drills AB (2010), 'Atlas Copco Boomer L1C, L2C Mk 7B Operator's instructions, Manual edn', Atlas Copco Rock Drills AB, Sweden.

Luderer, B., Nollau, V., Vetters, K. (2010), 'Mathematical formulas for economists'. *Springerverlag Berlin Heidelberg*.

Driving performance improvement through the concept of Maintenance Business Model

Maria Holgado*, Marco Macchi and Luca Fumagalli

Department of Management, Economics and Industrial Engineering
Politecnico di Milano
20133 Milan, Italy
*Corresponding author: Maria Holgado
e-mail: maria.holgado@polimi.it; marco.macchi@polimi.it; luca1.fumagalli@polimi.it

Abstract

Maintenance function within manufacturing companies should be seen as a source of added-value for the whole company's performance and goals. Indeed, improvements of maintenance performance have an effect also on the whole company's performance. This integrated view is supported by the concept of Maintenance Business Model (MBM), and the proposed framework including MBM as an intermediate link between the formulation and the execution of maintenance strategy. The MBM can be used as a means for analyzing and improving maintenance management activities in order to provide the highest value to the stakeholders of maintenance function, being both internal (e.g. production process, quality) and external (e.g. final customer, regulatory bodies..).

Keywords: maintenance performance, maintenance concepts, maintenance business model.

1 Introduction

Perception of maintenance in a manufacturing company has changed in the last years, from considering it as a "necessary evil" to "an important support function for production and manufacturing" (Parida and Kumar, 2006). Furthermore, it has gone even further and some authors reflect on maintenance not only as a support function but as a source for creating added value to companies (Liyanage and Kumar, 2003; Marais and Saleh, 2009). In this vision, maintenance performance contributes to the whole company's performance. Indeed, an integrated view of maintenance together with other company's functions can be reached only by a complete maintenance performance measurement system which considers not only metrics within the maintenance function but also metrics for its contribution to the whole company's performance. Thus, the maintenance performance measurement system should be rooted in a maintenance management system which shares that integrated view. Several maintenance management frameworks and models have been defined in literature without this integrated approach, although there are some recent attempts for attaining a holistic view of companies' performance including maintenance (Narayan, 2012).

In the last years, there is also a raising concept in business literature frequently associated and mentioned together with business strategy: the business model (BM) concept. As considered by Richardson (2008), the BM drives the execution of the strategy. A simple definition of BM

considers it as the way a company does business. By analogy, the BM concept could be also applied to single business functions within companies. Therefore, regarding the analogy with maintenance function, we define the concept of Maintenance Business Model (MBM) as the logic that permits the right execution of maintenance strategy. If maintenance strategy is aligned with business strategy, then the MBM is also coherent with the business goals.

The execution of the strategy, although guided by the BM, is then realized by business processes. The same applies to the maintenance function by analogy: maintenance processes are seen as the realization of maintenance strategy and they are guided and, to some extent limited, by the choices taken in the MBM.

MBM concept was discussed in the past (Garetti et al., 2007; Fumagalli et al., 2008; Gomez Fernández et al., 2008), although neglecting business literature compliancy. Further on, their focus on the MBM concept was closely related to the changes that technological advances bring to maintenance organizations, without deepening on the MBM concept itself. Therefore, this paper introduces novelties grounding on the business theory (section 2). After a quick review of maintenance concepts (section 3), it then presents the MBM concept, together with its relations to maintenance strategy and processes (section 4): the purpose is to create a maintenance management framework that follows the analogy with business literature, and can be used as a basis for the definition of a maintenance performance system. As relevant element of the framework, MBM concept is discussed in its components (section 5), thus providing a categorization of key maintenance decisional areas, presented as a conceptual map in order to express the business logic that should guide maintenance processes: indeed, the MBM is fostered to be the relevant layer to execute the maintenance strategy by driving improvement of maintenance processes and of maintenance performance, compared to business goals. The proposed framework advances in the direction suggested by Parida and Kumar (2006) who identified a gap between maintenance planning and execution, and stated the need of mapping maintenance processes.

2 Review on business model concept and frameworks

Several authors have made recently a review of publications on the BM concept (as examples, Al-Debei and Avison, 2010; Bask et al., 2010; Zott et al., 2011; George and Bock, 2011). These reviews reveal that BM concept is widely used although no agreement has been reached yet regarding its definition or its role within companies. A lot of the fuzziness about business models stems from the fact that when different authors write about business models they do not necessarily mean the same thing (Linder and Cantrell, 2000). In particular, the analysis of publications carried out by Zott et al. (2011) suggested for this concept some common themes, such as (i) the BM as a new unit of analysis, (ii) a holistic perspective on how firms do business, (iii) an emphasis on activities, and (iv) an acknowledgement of the importance of value creation.

Among the broad range of definitions found in literature (see collections of BM definitions in Al-Debei and Avison (2010) and Zott et al. (2011)), some have been selected due to their approach/focus in order to be the basis on which building the application to industrial maintenance of this concept (see Table 1).

Table 1. Selected definitions of business model.

Author/s, Year	Definition
Chesbrough and Rosenbloom, 2002	The BM is the heuristic logic that connects technical potential with the realization of economic value.
Hedman and Kalling, 2003	BM is a term often used to describe the key components of a given business.
Richardson, 2008	The BM is a conceptual framework that helps to link the firm's strategy, or theory of how to compete, to its activities, or execution of the strategy.
Casadesus-Masanell and Ricart, 2010	A BM is… a reflection of the firm's realized strategy.
Osterwalder and Pigneur, 2010	A BM describes the rationale of how an organization creates, delivers and captures value.

There is an open debate regarding BM's place and role in the firm (Osterwalder et al., 2005), specially concerning its boundaries and interconnections with other business aspects, such as business strategy and business processes (Bask et al., 2010; Al-Debei and Avison, 2010). Bask et al. (2010) consider that strategy, BMs, and processes are closely linked, focusing on the same challenges within the firm, although on different levels. This differentiation in different levels is mentioned by some other authors, who consider that a BM serves as a link or interface between the company's strategy and its activities or business processes (Amit and Zott, 2001; Osterwalder et al., 2005; Richardson, 2008) and, by consequence, it is seen as a conceptual tool of alignment, in particular by considering business strategy, BM and business processes as a harmonized package (Al-Debei and Avison, 2011).

Nevertheless, the BM is seen as a multi-purpose concept (Al-Debei and Avison, 2010), thus having diverse utilities within a company. Osterwalder et al. (2005) outline the managerial roles of the BM concept, identifying five categories of functions where it may have contribution: (i) understanding and sharing, as well as (ii) analyzing and (iii) managing the business logic; (iv) fostering prospects and innovation; (v) patenting of BMs or processes. Other authors delineate the BM contribution to company's development by considering the BM as a source of innovation (Zott and Amit, 2007; Teece, 2010), as the representation of the execution of the strategy to gain competitive advantage (Richardson, 2008) and a powerful tool for improving execution when it is used as a basis for employee communication and motivation (Magretta, 2002). Another interesting perspective is given by Casadesus-Masanell and Ricart (2010) as they stated that "business models are made of concrete choices and the consequences of these choices… different designs have different specific logics of operation and create different value for their stakeholders", thus, underlining the relevant links between the BM concept and stakeholders.

Another subject of debate regarding BM concept is its composition (i.e. which are the elements comprised in a BM). Authors proposed diverse frameworks including a variety of components within the BM (see, as an example, the reviews made by Morris et al. (2005) and Richardson (2008) on BM components). Among other proposals, Osterwalder and Pigneur (2010)'s canvas covers the dominant components discussed in literature, although presenting some limitations such as a focus on solely economic value and a restricted inclusion of stakeholders, comprising just customers and immediate partners (Holgado et al., 2013). The components enclosed within the canvas are: value proposition, customer segments, channels, customer relationships, key resources, key activities, key partnerships, revenue streams and cost structure. The value proposition is the most cited component in literature, therefore, it

may be the central element around which the BM can be built (Richardson, 2008). Osterwalder and Pigneur (2010)'s canvas can be considered the most popular business model specification framework (Resta, 2012). It has been already used in several applications, such as to describe new service business for agricultural machinery manufacturers (Corti et al., 2013); to support the development of product service systems (PSS) in aeronautics scope (Wallin et al., 2013); to map the case of a Machine Tool Manufacturer (Barquet et al., 2012). According to its diffusion within industry related work, it is considered as a main reference to keep a practical approach in the conceptualization of business models.

This brief review of the BM concept brings out some interesting ideas that are taken into consideration for its application to industrial maintenance, such as:

- the BM as an unit of analysis, endowed with a holistic perspective of business logic which provides alignment between strategy and processes;
- the emphasis on value as a driving concept for the BM: business logic is described from a viewpoint of how value is created, delivered and captured;
- the BM as a conceptual map illustrating the key components of a business, as a guide to influence the way operations (i.e. processes) are executed;
- the BM as a source of innovation, for analyzing the existent business logic and nurturing potential changes and innovations;
- the BM canvas for enabling concrete application of the BM concept (the canvas from Osterwalder and Pigneur (2010) is a relevant inspiration for our work).

3 Literature review on maintenance concepts

3.1 Maintenance value and maintenance stakeholders

The traditional view of maintenance as just an expense for the company is changing due to the introduction of the concept of value in maintenance (Naughton and Tiernan, 2012). This has recently raised, so a clear definition of maintenance value is not still commonly agreed in literature. Some authors understand it as just economic value (Marais and Saleh, 2009), connected to productivity and profitability (Alsyouf, 2007), while others advocate to give also environmental and social perspective to the concept (Liyanage and Kumar, 2003; Rosqvist et al., 2009), including environmental friendliness, health and safety, skillful personnel as potential benefits. Not so many concrete implementations of the concept of maintenance value have been proposed till now although some remarkable contributions have been done towards the integration of the value concept in maintenance function and activities. As an example, in their value-driven maintenance planning approach, Rosqvist et al. (2009) introduce the value tree as a reflection of the fundamental objectives of company and plant managers into maintenance objectives. However, the value of maintenance goes beyond the contribution to company and plant managers' objectives as can be foreseen from the wide typology of value discussed above. Maintenance may have a say in other company internal processes, such as production process, or in the fulfillment of external stakeholders' requirements, for example regulatory bodies (Söderholm et al., 2007). Nevertheless, the literature does focus frequently just on the cost of maintenance but not on its value; this could occur due to the difficulty on quantifying the benefits of maintenance (Marais and Saleh, 2009).

3.2 Maintenance management frameworks and models

There is a myriad of contributions regarding how to manage the maintenance function in an industrial system which are named as frameworks, systems, processes or models. We will use then those terms interchangeably along the article to refer to any type of contribution aiming at better organizing maintenance management. Lopez Campos and Crespo Marquez (2009) made a review, classification and analysis of 20 maintenance management models published from 1990 to 2007. Their classification into declarative and process-oriented models reflected a tendency towards process orientation, as the majority of models shown information flows, inputs and outputs definition or a closed loop sequence. Moreover, their analysis of contributions revealed, among others, the following gaps: (i) although all models included the definition of maintenance objectives, they were not always connected to business goals; (ii) most contributions neglected a clear reference to principles of responsibility, authority and good communication; (iii) another topic that was often omitted was resources management, receiving however more attention in earlier publications rather than in later ones; (iv) an identified emerging trend was the focus on the concept of continuous improvement, though only few models presented an application/implementation methodology stimulating continuous improvement. The strategic view of maintenance function, that is, its connection to business strategy and by consequence its alignment with business goals, has obtained more relevance in manufacturing industry due to the major concern on equipment availability, environment and safety as well as the emerging operational strategies (for example, lean manufacturing) and changes brought by new technologies to operations and maintenance practices (Murthy et al., 2002; Al-Turki, 2011). In this regard, Al-Turki (2011) proposes a framework for maintenance strategic planning which would enable the alignment of strategic goals between the company and maintenance, including a mindful approach to maintenance stakeholders' needs while setting maintenance objectives. The emphasis on the contribution of maintenance to the fulfillment of stakeholders' needs was first introduced in the maintenance management model proposed by Söderholm et al. (2007). The focus on stakeholders' needs is also guiding the framework developed by Lopez Campos and Crespo Marquez (2011) which is, moreover, aligned to the quality management standard ISO 9001:2008 and the normative PASS 55:2008. Information and communication technologies (ICT) are a relevant resource for maintenance management. For instance, Pintelon and Gelders (1992) previewed the use of expert systems related to maintenance management activities; indeed, ICT have then both pushed and enabled changes in maintenance function. The role of technology for maintenance has been highlighted by several authors (Jardine et al., 2006; Lee et al., 2006) and has brought into light the concept of e-maintenance (Levrat et al., 2008). Information technology has been recognized as one of the pillars supporting maintenance management by Crespo Marquez and Gupta (2006). They propose three pillars which are: (1) Information Technology (concerning condition monitoring techniques, information systems, e-maintenance, etc.); (2) Maintenance Engineering (including procedures, techniques, RCM, TPM, maintenance policies, optimization models, etc.); (3) Organizational (related to knowledge management, internal and external relationships, operators involvement, incentives systems, etc.). They state that all three pillars are important but they cannot stand alone without the others. The connection among pillars would create some dependencies between choices in each of them. The adoption of new technologies and its connection with the organization of maintenance management has been discussed also by (Garetti et al., 2007), who identify new technologies as a relevant lever for leading changes in the organizational support. Garetti et al. (2007) are the first authors mentioning the concept of maintenance business model to refer to *the way in which maintenance management is organized*. The purpose stated for the maintenance business models was defined as "to put in

evidence the relationship between technical inputs and the management outputs that can be achieved". Regarding manufacturing industry, they identified two organizational drivers – type of company's site and type of company – for analyzing the effects of novel available technologies on maintenance management choices and four super-classes of maintenance business models based on those drivers: site-maintenance and centralized-maintenance, regarding the manufacturing plants, and maintenance artisan, machinery vendor acting as service provider or pure service provider in case of companies making maintenance as a business.

3.3 Maintenance performance measurement

The main sense of designing maintenance management models is to continuously improve maintenance performance (Lopez Campos and Crespo Marquez, 2009). New proposals of maintenance management models or a combination of existing models could be an interesting source of inspiration for the development of maintenance performance measurement systems. Macchi and Fumagalli (2013) review a series of maintenance management models in order to better define the process areas related to organizational, managerial and technological capabilities to be evaluated in their maturity assessment of maintenance processes. Cholasuke (2004) understands key measures in maintenance as related to the successful implementation of a maintenance framework. Indeed, maintenance performance goals and measurement help companies and plant managers to drive continuous improvement in plant and maintenance performance with respect to business and maintenance objectives, as well as to realize a benchmarking of their performance within industry (Rosqvist et al., 2009). According to Simões et al. (2011), companies which tend to perceive maintenance as a strategic competitive resource would use consistently the maintenance performance measures in an integrated information system and broader benchmarking practices.

4 Proposal of a maintenance management framework motivated by business literature

Some authors suggest that maintenance management involves two main aspects: the formulation and the execution of the strategy (Murthy et al., 2002; Crespo Márquez et al., 2009). We claim that there is a missing linkage between formulation and execution of the strategy and, based on the evidences from business literature (shown in section 2), a three-layer framework is proposed for maintenance management which adds an additional dimension as the central point (see Fig. 1). This proposal is based on an analogy with business literature, where the BM is presented to link strategy and its execution; thus, being an instrument of alignment between strategy and business processes and describing the key components and choices taken with respect to those components, within the business logic.

The maintenance strategy layer concerns the strategic decisions for managing the maintenance function and aligning it with business goals. The definition of strategic goals and objectives for maintenance function are key aspects which concerns maintenance strategy.

The strategic decisions taken within maintenance strategy then drive choices to be made on the key components of maintenance function at the MBM layer. Those choices within the BM would have operational consequences which, reflecting the maintenance strategy goals, lead maintenance processes to perform activities in a way that is coherent with both maintenance objectives and business goals.
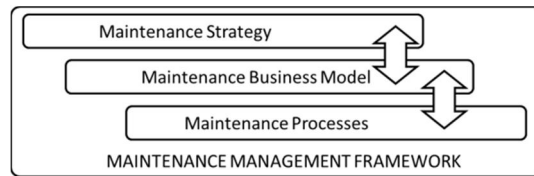
Figure 1. The proposed maintenance management framework

5 The concept of Maintenance Business Model

The concept of maintenance business model is not new, it was first mentioned by Garetti et al. (2007) as the way in which maintenance management is organized. They stated that the MBM is strongly influenced by company's features and context, such as its business (vendor or user of industrial equipment) and its geographical dispersion (mono-site or multi-site). Later, Fumagalli et al. (2008) defined the MBM as a set of interrelated elements present in the maintenance organization and in the technological systems used to support maintenance operations, giving a technology-oriented perspective to the concept with a specific focus on the exploitation of new ICT systems for condition based maintenance. Finally, Gomez Fernandez et al. (2008) included the viewpoint of value into the MBM concept, specifically the value created by Maintenance Service Provider companies to their clients. Here, the concept is revisited and enhanced with a stronger background on business literature. The MBM describes the rationale of how maintenance function creates and delivers value to its stakeholders and how the value is captured by maintenance function itself. The main components within the MBM, inspired by the business literature, are: value proposition, stakeholder groups, stakeholder relationships, communication channels, key resources, key activities, key partnerships, cost structure, value capture streams. These components are introduced in Figure 2, graphically reported within a MBM canvas similarly to the BM canvas proposed by Osterwalder and Pigneur (2010). The BM canvas is chosen as main reference for this study, since it has been recognized both as reference in the scientific community and as intuitive model for industrial application.

Figure 2. The MBM canvas (elements reinterpreted from the BM canvas)

The MBM canvas is herein described, giving also some potential categorizations which could guide the choices for each company's context. The definition of MBM components are often derived from the analogue definition given by Osterwalder and Pigneur (2010) for business model components, reinterpreting the concepts according to maintenance function perspective. In this concern, it is worth to make some remarks: (i) the understanding of each category, within a component, could depend strongly on the type of company, industrial sector as well as other context variables, for example geographical dispersion (mono-site or multi-site), etc; (ii) business / maintenance strategies can lead to different perception on the priority / importance of different categories.

5.1 Value proposition

The value proposition concerns the bundle of activities and services performed by maintenance function which creates value for its stakeholders. The type of value created varies from one stakeholder type to another, according to their different needs and requirements. For example, the company itself would require maintenance function to contribute to its business goals and to gain more competitive advantages, in terms of higher product quality or flexibility and availability of production equipment. Value can be categorized also according to its nature as tangible (e.g. quality, availability) or intangible (e.g. know-how, brand, status) or according to the triple bottom line viewpoint (Elkington, 1997) as economic (e.g. contribution to profit or productivity), environmental (e.g. energy efficiency) or social (e.g. health and safety). Some potential characteristics of the value provided by maintenance function could be the following: technological update/upgrade (related to the use of new technologies); asset life cycle (related to the extension of asset life or the improvement of asset performance); product quality; production availability or flexibility: process design (related to feedback regarding technical features of production process); brand or status (related to company's image, e.g. environmental damages caused by a failure could negatively affect brand image or good working conditions within the plant could positively create a satisfaction within workers); cost reduction (related to direct and indirect costs of maintenance activities); and risk reduction (related to decrease of risk of failure but also prevention or mitigation of its effects).

5.2 Stakeholder groups

Stakeholders can be seen as "any group or individual who can affect or is affected by the achievement of the organization's objectives" (Freeman, 1984) or as "individual or group that has an interest in any decision or activity of an organization" (ISO, 2010). The role of maintenance as a function inside a company has an effect on the definition of maintenance stakeholders, so it is important to consider its potential relations with other business functions. Thus, derived by the definitions from general literature, maintenance stakeholders may be seen as *any individual, group or business function that has interest or influence in maintenance decisions or activities or that can be affected by the execution of maintenance processes*. Understanding stakeholders' interests and requirements is an important issue in order to define adequate value propositions which provide them with their expected value. Therefore, the categorization of maintenance stakeholder groups would be useful for studying their requirements and establishing, in case, the prioritization of actions to be taken. The categorization herein proposed consists of two drivers. A first driver related to their relations respect company's boundaries, i.e. internal vs. external (maintenance function could be used also as a boundary, considering as internal stakeholders only those within the maintenance process as suggested by Söderholm et al. (2007)). A second driver related to the way in which stakeholders and maintenance function interacts with each other (i.e. direct vs. indirect).

Depending on the company context, some stakeholders could be seen as indirect or direct from the maintenance function viewpoint, for example the final customer which in some cases would need to interact with maintenance department (Crespo Marquez and Gupta, 2006).

5.3 Stakeholder relationships

This component concerns the relationships that maintenance function creates with its internal and external stakeholders and how these relationships are maintained. This component of the MBM would apply just to direct stakeholders to whom maintenance function establishes an immediate relationship, independently on being internal or external. Strong and dynamic relationships are the foundation of any successful business endeavor (Allee, 2008) and are important for value creation (Windahl and Lakemond, 2006). Thus, the relationships that maintenance function sets up with its direct stakeholders could be crucial for reaching a successful performance and increasing the value provided by maintenance's value propositions. The relationships could be categorized by the role that the stakeholders play as a part involved in the release of the value proposition, for example they could offer assistance, consultancy, information, collaboration, coordination, etc. The relationships could be supported by procedures and methods or not, e.g. so being provided in an informal way.

5.4 Communication channels

Unlike the previous component, communication channels are established with direct and indirect stakeholders, although it may have different purposes depending on the stakeholder type. Communication channels are the interfaces between maintenance and its stakeholders created in order to deliver the value propositions. These interfaces may be supported by available technologies in terms of information systems or platforms where information regarding maintenance performance or equipment health can be shared among several stakeholders. Nevertheless, the interfaces may permit two-way communications, serving to send information from maintenance to its stakeholders and viceversa. Thus, they could also be the means for receiving requests or work orders from maintenance stakeholders.

5.5 Key resources

The key resources of the maintenance function are the essential assets required to create and deliver value to the maintenance stakeholders. They are necessary to perform the activities or services offered through the value propositions as well as to establish relationships and communicate with maintenance stakeholders. Resources pertain to different types and can be categorized in many ways. The classification herein proposed includes four categories of resources: financial, human, physical and support resources. *Financial resources* for maintenance function are mainly identified as maintenance budget. In some cases, it could also concern the life cycle budget of the equipment under maintenance which is categorized according to two concepts: CAPEX (capital expenditures) and OPEX (operational expenditures). *Human resources* comprise the maintenance personnel as well as their skills and competences. The classification can be done according to different taxonomies. Maintenance personnel may be appointed with different responsibilities and duties, hence they could also be classified according to their organizational role, at an operational/technical, engineering/supervision or managerial level. *Physical resources* encompass a wide variety of technical and technological resources, spread from ICT components for maintenance management as a whole, to instruments, tools and MRO (Maintenance, Repair, Operations) materials for maintenance execution. Support resources concerns the set of methodologies, procedures and techniques needed to support decision making and carry out maintenance

activities at different management levels, i.e., at strategic, tactical and operational levels. Maintenance optimization models, maintenance methodologies and techniques are included within this type of resources.

5.6 Key activities

The key activities of the maintenance function are the main activities or processes performed in order to create and deliver value to maintenance stakeholders. Maintenance is defined as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (EN 13306). In a broader sense, it comprises decisions at all levels of organization regarding acquiring and maintaining a high level of reliability, availability and value of assets (Al-Turki, 2011) and decisions along all life cycle of assets, i.e., not only during operations phase but also in design and end of life phases (Takata et al, 2004; Levrat et al, 2008). Thus, maintenance activities can be categorized in three levels: strategic, tactical and operational. *Strategic activities* are usually associated with long-term planning and could assume two different perspectives regarding the development of maintenance function (related to the alignment between business and maintenance objectives) and the life cycle management approach (concerning the contribution of maintenance to asset life cycle phases). The alignment with business goal would be done respect to maintenance activities, processes, internal and external resources, as well as maintenance organisation. Asset life cycle costing and operational availability analysis are activities were maintenance would contribute in order to support capital asset decisions. *Tactical activities* consider a mid-term horizon, comprising all the activities carried on to engineer and plan maintenance during the asset operations phase; such as maintenance budgeting, planning and control cycle, supervised (or not) through maintenance engineering. Herein, the activities deals with failure and criticality analysis, development of plans to avoid potential failures and performance losses, technical and economic performance control, continuous performance improvement as maintenance spending in the budget can be also dedicated to such activities. Support activities are those related to the supplier and contractual management, regarding maintenance services and/or materials. *Operational activities* concern a short-term horizon and encompass a huge variety of activities perfomed by maintenance personnel for delivering field service, ranging from MRO replacements, human sense inspections, to real time monitoring, diagnostics and prognostics based on availability of technical/technological tools. Short term planning and and work order management are two relevant operational activities. Finally, it is worth observing that the different types of activities can be at different technology intensity, depending on the "tools" available at hand of maintenance personnel.

5.7 Key partnerships

The key partnerships for maintenance function are those formed with the main third parties which provide services and/or resources required to create and deliver value to maintenance stakeholders. They entail a supplement to the key resources of maintenance function which may be, in some cases, fundamental in order to perform the activities or services involved in maintenance's value propositions. The key partners pertain to different types and can be categorized in many ways. The categorization herein proposed includes four categories: Maintenance Service Providers, Original Equipment Manufacturers, Consulting companies, MRO materials suppliers. *Maintenance service providers* (MSPs) are third parties providing specialized skills and competences to maintenance function. They may offer operational/technical, engineering/supervision or managerial capabilities, for example: maintenance planning and control, maintenance engineering, engineering support for plant

revamping and retrofitting, spare parts engineering, diagnostics and prognostics, field maintenance service with different specialties (mechanical and electric maintenance, etc.). *Original Equipment Manufacturers* (OEMs) are manufacturers of durable goods providing additional services linked to their products, e.g. technical assistance supporting operation and maintenance of their equipment, for example: spare parts management, maintenance planning, field maintenance service, diagnostics and prognostics, tele-maintenance service,... *Consulting companies* would provide support to rethink the maintenance activities in the company, in different matters such as: maintenance engineering, maintenance planning, business process re-engineering and maintenance re-organization, empowerment of maintenance personnel,... Last but not least, *MRO materials suppliers* would provide different classes of maintenance materials (i.e. strategic, generic and specific materials, and consumables) as well as related repair services.

5.8 Cost structure

Cost structure is the categorization of cost entries to be included as costs of maintenance activities. The categorization can be done in several ways. A simple manner of classification of costs is the following: fixed costs versus variable costs. In all cases, the maintenance organizational structure would strongly influence the cost structure; thus, being very related to concrete context of any maintenance function within the company and company's organizational structure.

5.9 Value capture streams

This component concerns the value generated to maintenance function from the creation and delivery of value to its stakeholders. The value that maintenance function perceives from the activities and/or services shaping its value propositions may come from different sources, i.e., from different value capture streams. As a first and main stream, maintenance stakeholders would provide maintenance with some feedback from the activities and/or services performed which can be quantitative, such as incentives, but also qualitative, such as satisfaction or recognition. Another stream could be maintenance function itself. According to Parida and Kumar (2006) maintenance performance measures are used for measuring the value created by maintenance. These measures could not only serve as a means to communicate the achievement or the state of achievement of maintenance goals and/or the fulfillment of stakeholders' needs to the stakeholders but also as feedback to maintenance function regarding its own performance. This would be used to evaluate internally maintenance performance and guide actions in order to improve and increase the maintenance processes and the value created to maintenance stakeholders.

6 Conclusions

Manufacturing companies are looking to the different sources of added-value for the whole company's performance and goals. The research herein presented support to view maintenance function as one of these sources, grounding on the idea that maintenance performance have an effect also on the whole company's performance. In order to support this integrated vision the concept of Maintenance Business Model (MBM) has been discussed. The MBM has been considered as an intermediate link between the formulation and the execution of maintenance strategy and a proper MBM Canvas has been proposed as synthetic description of MBM. Besides the Canvas, description of the single components of the MBM,

reinterpreted from the BM canvas (Osterwalder and Pigneur, 2010), have been provided, revealing how the MBM concept fits with actual industrial practice and scientific literature. Future works will deal with further developing the robustness of the MBM concept, further deepening literature analysis and testing the concept in industry. Thanks to empirical research developed in the scope of "Technologies and Services for Maintenance" (www.tesem.net) of School of Management of Politecnico di Milano, potential use of MBM as reference tool for analysis has been already explored by the authors and is going to be further refined and analysed by empirical case studies to achieve a consolidated procedure of use of the MBM Canvas.

7 Acknowledgements

References

Al-Debei, M.M. and Avison, D. (2010) 'Developing a unified framework of the business model concept', *European Journal of Information Systems*, Vol. 19, pp. 359–376.

Allee V. (2008) 'Value network analysis and value conversion of tangible and intangible assets', *Journal of Intellectual Capital*, Vol. 9, No. 1, pp. 5-24.

Alsyouf, I. (2007) 'The role of maintenance in improving companies' productivity and profitability', *International Journal of Production Economics*, Vol. 105, pp. 70-78.

Al-Turki, U. (2011) 'A framework for strategic planning in maintenance', *Journal of Quality in Maintenance Engineering*, Vol. 17, No. 2, pp. 150-162.

Amit, R. and Zott, C. (2001) 'Value creation in e-business', *Strategic Management Journal*, Vol. 22, pp. 493–520.

Bask, A.H., Tinnilä, M. and Rajahonka, M. (2010) 'Matching service strategies, business models and modular business processes', *Business Process Management Journal*, Vol. 16, No. 1, pp. 153-180.

Barquet, A. P. B., Cunha, V. P., Oliveira, M. G., and Rozenfeld, H. (2012) 'Business Models for Product-Service Systems (PSS): An Exploratory Study in a Machine Tool Manufacturer'. In *Sustainable Manufacturing*, pp. 189-194. Springer Berlin Heidelberg.

Casadesus-Masanell, R. and Ricart, J.E. (2010) 'From Strategy to Business Models and onto Tactics', *Long Range Planning*, Vol. 43, No. 2-3, pp. 195-215.

Chesbrough, H. and Rosenbloom, R. S. (2002) 'The role of the business model in capturing value from innovation: evidence from Xerox Corporation's technology spin-off companies', *Industrial and Corporate Change*, Vol. 11, Issue 3, pp. 529-555.

Cholasuke C, Bhardwa R and Antony J. (2004) 'The status of maintenance management in UK manufacturing organisations: Results from a pilot survey', *Journal of Quality in Maintenance Engineering*, Vol. 10, No. 1, pp. 5.

Corti, D., Holgado Granados, M., Macchi, M. and Canetta, L. (2013) 'Service-oriented business models for agricultural machinery manufacturers: looking forward to improving sustainability', *IEEE International Technology Management Conference and 19th ICE Conference*, 24-26 June 2013, the Hague, The Netherlands.

Crespo Márquez, A., Moreu de León P., Gómez Fernández J., Parra Márquez C., López Campos M. (2009) 'The maintenance management framework: A practical view to maintenance management', *Journal of Quality in Maintenance Engineering*, Vol. 15, No. 2, pp. 167-178.

Crespo Márquez, A and Gupta, J.N.D. (2006) 'Contemporary maintenance management: process, framework and supporting pillars', *Omega*, Vol. 34, pp. 313-326.

Elkington, J. (1997), *Cannibals with Forks. The triple bottom line of 21 st century business*. Oxford, UK: Capstone Publishing Ltd.

EN 13306:2001. (2001). Maintenance Terminology. European Standard. CEN (European Committee for Standardization), Brussels.

Freeman, R.E. (1984), *Strategic Management: A Stakeholder Approach*. Boston: Pitman.

Fumagalli, L., Garetti, M., Macchi, M. (2008) 'Investigating Business Models when adopting new ICT systems for condition based maintenance: a case study analysis', pp. 209-219, *Fifteenth International Working Seminar on Production Economics.* , Innsbruck, Austria.

Garetti, M., Macchi, M., Fumagalli, L., Terzi, S. (2007) 'Investigating the organizational business models of maintenance when adopting self diagnosing and self healing ICT systems in multi-site contexts', *Proceedings of IFAC Conference on Cost Effective Automation in Networked Product Development and Manufacturing*, Monterrey, Mexico

George, G., Bock, A.J. (2011) 'The Business Model in Practice and its Implications for Entrepreneurship Research', *Entrepreneurship, theory and practice*, January, pp. 1042-2587.

Gomez Fernandez, J.F., Fumagalli, L., Macchi, M, Crespo Marquez, A. (2008) 'A score card approach to investigate the IT in the Maintenance Business Models', *MITIP 2008, Prague, Czech Republic*, .

Hedman, J., Kalling, T. (2003) 'The business model concept: theoretical underpinnings and empirical illustrations', *European Journal of Information Systems*, Vol.12, pp. 49–59.

Holgado, M., Donatella, C., Macchi, M., Rana, P., Short, S. and Evans, S. (2013) 'Business Modelling for Sustainable Manufacturing'. *Competitive Manufacturing for Innovative Products and Services: Proceedings of the APMS 2012 Conference, Advances in Production Management Systems*, Emmanouilidis, C., Taisch, M., and Kiritsis, D. (editors).

ISO 26000 (2010), Guidance on social responsibility.

Jardine, A., Lin, D. and Banjevic, D. (2006) 'A review on machinery diagnostics and prognostics implementing condition-based maintenance', *Mechanical Systems and Signal Processing*, Vol. 20, pp. 1483-1510.

Lee, J., Ni, J., Djurdjanovic, D., Qiu, H. and Liao, H. (2006) 'Intelligent prognostics tools and e-maintenance', *Computers in Industry*, Vol, 57, pp. 476–489.

Levrat, E., Iung, B. and Crespo Marquez, A. (2008) 'E-maintenance: review and conceptual framework', *Production Planning and Control*, Vol. 19, No. 4, pp. 408-429.

Linder, J. and Cantrell, S. (2000) *Changing Business Models: Surveying the Landscape*, Accenture Institute for Strategic Change.

Liyanage, J.P. and Kumar, U. (2003) 'Towards a value-based view on operations and maintenance performance management', *Journal of Quality in Maintenance Engineering*, Vol. 9, No. 4, pp. 333-350.

López Campos, M. and Crespo Márquez, A. (2009) 'Review, classification and comparative analysis of maintenance management models', *Journal of Automation, Mobile Robotics and Intelligent Systems*, Vol. 3, No. 3, pp. 110-115.

Lopez Campos. M and Crespo Marquez, A. (2011) 'Modelling a Maintenance Management Framework Based on PAS 55 Standard', *Quality and Reliability Engineering International*, Vol. 27, pp. 805-820.

Macchi, M and Fumagalli, L. (2013) 'A maintenance maturity assessment method for the manufacturing industry', Journal of Quality in Maintenance Engineering, Vol. 19, No. 3.

Magretta, J.(2002) 'Why business models matter', *Harvard Business Review*, Vol.80, No. 5,pp.86–92.

Marais, K.B., Saleh, J.H. (2009) 'Beyon its cost, the value of maintenance : an analytical framework for capturing its net present value', *Reliability Engineering and System Safety*, Vol, 94, pp. 644-657.

Morris, M, Schindehutte, M and Allen, J. (2005) 'The entrepreneur's business model: toward a unified perspective', *Journal of Business Research*, Vol. 58, No. 6, pp.726-735.

Murthy, D.N.P., Atrens, A and Eccleston, J.A. (2002) 'Strategic maintenance management', *Journal of Quality in Maintenance Engineering*, Vol. 8, No. 4, pp. 287-305.

Narayan, V. (2012) 'Business performance and maintenance: How are safety, quality, reliability, productivity and maintenance related?', *Journal of Quality in Maintenance Engineering*, Vol. 18, No. 2, pp. 183-195.

Naughton, M.D. and Tiernan, P. (2012) 'Individualising maintenance management: a proposed framework and case study', *Journal of Quality in Maintenance Engineering*, Vol. 18, No. 3, pp. 267-281.

Osterwalder, A., Pigneur, Y., Tucci, C.L. (2005) 'Clarifying business models: origins, present, and future of the concept', *Communications of the AIS*. Vol.15, May 2005.

Osterwalder, A. and Pigneur, Y. (2010) *Business Model Generation – A Handbook for Visionaries, Game Changers, and Challengers*, John Wiley & Sons, Inc., New Jersey.

Pintelon, L.M. and Gelders, L.F. (1992) 'Maintenance management decision making', *European Journal of Operational Research*; Vol. 58, No. 3, pp. 301-317.

Parida, A., Kumar, U. (2006) 'Maintenance performance measurement (MPM): issues and challenges', *Journal of Quality in Maintenance Engineering*, Vol. 12, No. 3, pp. 239-251.

Resta, B. (2012). *Designing and configuring the value creation network for servitization: a product-service provider's perspective*. Doctoral Thesis, University of Bergamo, Italy.Richardson, J. (2008) 'The business model: an integrative framework for strategy execution', *Strategic Change*, Vol. 17, pp. 133–144.

Rosqvist, T., Laaksoa, K. and Reunanen, M. (2009) 'Value-driven maintenance planning for a production plant', *Reliability Engineering and System Safety*, Vol. 94, pp. 97–110.

Simões, J.M., Gomes, C.F., Yasin, M.M. (2011) 'A literature review of maintenance performance Measurement A conceptual framework and directions for future research', *Journal of Quality in Maintenance Engineering,* Vol. 17, No. 2, pp. 116-137.

Söderholm, P., Holmgren, M. and Klefsjö, B. (2007) 'A process view of maintenance and its stakeholders', *Journal of Quality in Maintenance Engineering,* Vol. 13, No. 1, pp. 19–32.

Takata, S., Kimura, F., van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ce-glarek, D. and Lee, J. (2004) 'Maintenance: changing role in life cycle management', *Annals of the CIRP*, Vol. 53, No. 2, pp. 643–656.

Teece, D. (2010) 'Business models, business strategy and innovation', *Long Range Planning*, Vol. 43, No. 2/3,pp. 172–194.

Tsang, A.H.C. (2002) 'Strategic dimensions of maintenance management', *Journal of Quality in Maintenance Engineering*, Vol. 8, No. 1, pp. 7 – 39.

Wallin, J., Koteshwar C., Thompson, A. (2013) 'Developing PSS concepts from traditional product sales situation: the use of business model canvas', *Product-Service Integration for Sustainable Solutions*. Springer Berlin Heidelberg, pp. 263-274.Windahl C. and Lakemond N. (2006) 'Developing integrated solutions: The importance of relationships within the network', Industrial Marketing Management, Vol. 35, pp. 806–818.

Zott, C., Amit, R. (2007) 'Business Model Design and the Performance of Entrepreneurial Firms', *Organization Science*, Vol. 18, No. 2, March–April 2007, pp. 181–199.

Zott, C., Amit, R. and Massa, L. (2011) 'The Business Model: Recent Developments and Future Research', *Journal of Management*, Vol. 37, No. 4, pp. 1019-1042.

Effect of maintenance cost on trucks performance and reliability:

a case study of ConCost Construction Company

Ahmed E Haroun[1]*, Elkhawad A Elfaki[2] and El Mahdi A. M. Beshir[3]

1: *Department of Systems Engineering*
King Fahd Uuniversity of Petroleum & Minerals
Dhahran 31261
Kingdom of Saudi Arabia
2: Department of Mechanical Engineering
Sudan University of Science & Technology
P.O. Box 407,East Demis
Khartoum, Sudan
3: Al-Rajhi Corporation Workshop
P. O. Box 50 – Al khobar 31952
Kingdom of Saudi Arabia
*Corresponding author: Ahmed E Haroun
e-mail: aharoun@kfupm.edu.sa
e-mail: khawad2002@yahoo.com
e-mail: mahdisinada@yahoo.com

Abstract

In this paper the costs to maintain and operate a fleet of trucks were derived from deploying two sourcing strategies (in-house or *subcontracting)* to deliver roads' construction materials. Since each of the two strategies has merits under specific circumstances, the paper aims to find the effects of maintenance cost on both performance (*availability*) and *reliability* through the analysis of a case study; whereby cost data and information are collected from a real life project. The paper aims to find the effects of maintenance cost on performance and reliability, respectively, as an alternative method to the classical probability based methods i.e., the relationships between maintenance cost and performance/reliability. Excel software is used to facilitate the presentation and analysis of the data, i.e., which strategy outperform the other in terms of performance and reliability, and, ultimately, provide guidelines for selecting the appropriate materials delivery strategy. The paper found that in-house maintenance should be selected for its improved, both, performance (improve availability by 10%) and reliability (increase MTBF by 31 hours).

Key words: Maintenance cost, Subcontracting, Performance/availability, Reliability**,** Mean Time Between
Failures (MTBF)

Key Practical Implications -. The traditional in-house maintenance approach is challenged by out-sourcing, as a recognized competing option, world-wide, which is not widely practiced in Sudan.   Many construction firms are faced by the process of selecting an appropriate (best) operation and maintenance strategy. ConCost Construction, the case of this study, is striving to select a strategy that minimizes its cost, while optimizing performance and reliability of its trucks' fleet. The decision criteria presented in this paper provides a useful management tool to select between out-sourcing and in-house operation and maintenance. The study seeks to

find a relationship between operation/maintenance costs and performance/reliability parameters. Although the criteria is intended to be applied to a trucks' fleet case in a construction firm, but it can be extended to the management of maintenance activities in other industries that need special skills of qualified personnel.

Originality/value - Much of previous and current research on outsourcing focuses on managing outsourcing projects and evaluating ex post decisions' consequences (e.g. output measurability) more than addressing the effect of cost on those output measures. Hence, the paper is relevant in this respect and intended to find a relationship between cost, performance and reliability, and hence provide a contribution to the practice of maintenance management.

1 Introduction

The purpose of maintenance is to extend equipment lifetime, or at least the mean time to the next failure. Maintenance incurs expenditures and it may not be economical to perform it too frequently, however, it has effects on equipment performance and reliability. Unfortunately, the increasing complexity of manufacturing technologies have increased maintenance related costs (Parida and Kumar, 2006). In manufacturing organizations, maintenance related costs are estimated to be 25 percent of the overall operating cost (Cross, 1988a; Komonen, 2002). In some industries, such as petrochemical, electrical power, and mining, maintenance related costs might surpass operational cost (Raouf, 1993; De Groote, 1995; Eti et al., 2005; Parida and Kumar, 2006). U.S. industry spent over $300 billion on plant maintenance and operations, approximately, 80% of it was to correct the chronic failure of machines systems (Heinz and Geitner 2005).

Therefore, a relationship between the maintenance expenditure/cost and the two equipment behavior parameters (i.e., performance and reliability) must be explored. Past attempts were made to approximate a balance between costly consequences that results from little maintenance (low performance and reliability) and expenditures incurred by maintenance activities may not be economical to perform it too frequently. However, no practical example was found to find a relationship between maintenance costs and the two parameters.

Maintenance performance and equipment reliability are critical for companies to survive in open boarders of a competitive world. Consequently, maintenance performance measurement has received a paramount attention from researchers and practitioners in recent years. With the advent of techniques like preventive maintenance and condition monitoring, the maintenance cost perception changed to: "It can be planned and controlled." (Partia and Kumar, 2006).

The use of classical statistical techniques has proven to be an effective tool for performance and reliability analysis of manufacturing and service equipment. However, scholars strive to present efficient alternatives to these classical probability based methods, e.g., to find the effects of maintenance cost on performance and reliability, respectively. Ram and Singh, as cited by Mangey (2013) handled the availability, cost and MTTF of a system that consists of two independent systems under preemptive repeat repair and resume repair policies. Through a mathematical model they have got improved results of reliability characteristics. In the model they applied copula in failure as well as in repair. Surveying the literature "On system reliability approaches" Mangey (2013) realized that traditional maintenance scheduling in conditioned based maintenance (CBM) is based on the threshold setting on forecasted failure probability, or remaining useful life for individual components. This approach may not optimize the system, because individual components are associated with each other and mutually dependent. So, scholars, as he cited, believe that designing a comprehensive tool that optimizes availability and cost of whole system is crucial to fully benefit from CBM. He also cited Painton and Campbell (1995) who presented an optimization model that maximizes system reliability or availability

(performance) subject to cost constraint in the presence of uncertainty of the components' failure. Consequently other optimization methods were developed to perform analyses that select the best combination of component reliability improvements that meet or exceed the performance goals at the lowest cost.

Ultimately, remarkable cost savings and profitability can be achieved through combining assets (i.e., machinery) reliability, safety, availability, and maintainability. However, effective and efficient machinery maintenance can be achieved through expertise acquired in troubleshooting and failure analysis that built-in asset's design. Planned maintenance schemes must be set, consequently, to keep equipment in good operating condition and, hence, avoiding unexpected failures. Integration of condition-based devices enhance the preventive maintenance plans that elevates disruptive breakdowns of critical equipment (Haroun et al., 2012).

Besides many, the characteristics of performance measures include reliability and validity (Al-Turki and Duffuaa, 2003), so, operational performance measurement systems act like early-warning systems. Parida, A. and Kumar, U. (2006) added other important factors behind demands on maintenance performance measures, such as, measuring value created by the maintenance; revising resource allocations; health, safety and environment issues; adapting to new trends in operation and maintenance strategy; etc.

Corporations nowadays tend to contract out more manufacturing and service activities than they did two decades ago, in order to reduce cost, hence stay competitive and agile in a dynamic market (Tsang, 2002). Moreover, he thinks maintenance is an indispensable support function in business with significant investment in physical assets and plays an important role in achieving organizational goals. This option is defended by the traditional in-sourcing which is defined as the management process of performing a service by the in-house staff. Through outsourcing, the organization can devote its scarce resources to developing its core competencies in a bid to sustain competitive advantages (Hui, 2004). Once an activity has been identified as non-core, the conventional wisdom is to outsource it to external parties through some contractual arrangements (Fuller, 2002). However, it would be too simplistic a decision to outsource every activity that is classified as non-core, because these non-core activities may contribute to the successful implementation of the corporate strategy to different extents (Haroun et al., 2012).

So, outsourcing is often seen as a critical business capability that enhances a company's overall profitability. It allows to leverage resources and capabilities by concentrating on core competencies that create value for the company's customers, with non-value added activities being outsourced. Outsourcing is thought as a contributer to reduction in operational cost and capital investment while improving product and service quality (Haroun et al., 2012). However, Marttonen, Salla and Timo Kärri (2012) found that the relative proliferation of outsourcing of industrial maintenance has increased the need for elaborate research in maintenance cost and profitability. They believe that quantifying the profitability of outsourcing has proven difficult; so there are very few practical tools for firms decision-makers to use in actual outsourcing cases. Nevertheless, they think that it is better "to have even an approximate estimation of the profitability of outsourcing, than to proceed without any profitability assessment".

Nevertheless, as surveyed by Hui (2002), a number of scholars (Brown, 2002; Copeland, 2001; Crocker, 1999; James, 2000; Van der Werf, 2000) found that, while outsourcing is gaining popularity, the number of reported cases of failure is also increasing. Very often, expectations of the client organization are not fully met. A study of the failure cases has revealed that some of the outsourcing should have been administered from a strategic perspective. In some situations, there should have been more input from the client organization. So, outsourcing is not however risk free, i.e., vulnerability to supplier self interest, such as the raising of prices (Yoon and

Naadimuthu, 1994, Quinn and Hilmer, 1994, McFarlan and Nolan, 1995, Kakabadse and Kakabadse, 2002, Leavy, 2001, Doganis, 2001, as quoted by Al-Kaabi et al., 2007)

1.1 *Problem definition: The Case Study*

ConCost Construction Company, where the research is conducted (the "Case Study"), works mainly in roads and bridges construction and maintenance. In-house maintenance of its earth moving equipment and machinery necessitates the existence of a central workshop plus small field and mobile ones.

ConCost company had a fleet size of 192 units of earth moving equipment (Trucks, Dozers, Excavators, Scrapers, …, etc). Out of which 57 are trucks (tippers) of IVECO 16 m^3 type. Only 18 of those trucks were operational, i.e. 68% were out of service. So, the company, represented by the project's Resident Engineer (Project Manager) decided to subcontract (rent) some trucks to fulfill the bidding contract[1], however, it is faced by performance and reliability concerns, so a decision-making situation exists: is it more productive to have its own fleet and hence maintains it (spend/invest some money) or has to continue in renting (subcontracting) and thus the maintenance is part of the deal, in order to secure a reasonable equipment performance level (availability and reliability). However, the company is well aware of the fact that relying on out-sourcing will encourage cannibalization of the existing out-of-service equipment and hence, destroy the company's assets and lose their book value.

So, the decision criteria is based on the effect of maintenance cost on performance and reliability. Searching the literature, it is found that there is no current research has indicated, a clear-cut, measurable relationship between the effect of cost on these parameters in a much simpler way compared to classical statistical methods. However, it is well known that production affects return on investment, while, performance and reliability affects production. The researchers intended to simplify and, hence, understand these phenomena by taking a case study to find out the effects of maintenance cost on performance and reliability, respectively (Figure 1).

1.2 *Research objective*

The aim of the research is to develop a means to find the effect (relationship) of maintenance cost on availability and reliability. In fact, the research was conducted to help ConCost Construction Company to take a decision on whether to have its own trucks fleet (and hence maintains it) or renting one including the maintenance service as part of the outsourcing contract. Ultimately, the decision will be extended to its whole earth moving equipment fleet (Dozers, Excavators, Scrapers, …, etc) that perform other typical construction applications (haul road maintenance, road construction, ditching, loose fill spreading and land forming, maintenance of hard packed roads with embedded rock, heavy fill spreading, ripping–scarifying of asphalt or concrete, ……., etc.).

1.3 *Design/methodology/approach*
– This research uses a case study approach whereby cost data and information are collected from a case study, then presented and analyzed. Performance and reliability measures and excel software were used for presentation and analysis of the data. Although the data sample is quite small, however, a further thorough study with elaborative analyses is recommended to be undertaken. Two of the authors were consultants to the study, while the third one was the technical manager of the company from where he collected the data and contributed considerably in the whole undertaken study.

---

[1] The company signed a contract (project, the case of this study) with one of the states government to build roads and maintain the existing one inside its capital and other locations in the state.

1.4 *Scope (limitations) of the study*

Fifty seven trucks (IVECO 16 m^3) were selected as the study subject and examined, holistically (Appendix A). A very small sample of that population (only 3 trucks) out of the operational ones (18 are operational, i.e., 32%) from two locations (Khartoum and Khuwi stations) were selected, randomly, to conduct a thorough study. The tippers are a part of the existing 192 earth moving equipment that perform different functions. Although, the sample is so small (the study could be considered as a pilot one), but we expect the result will open an avenue for an extended study based on a bigger sample.
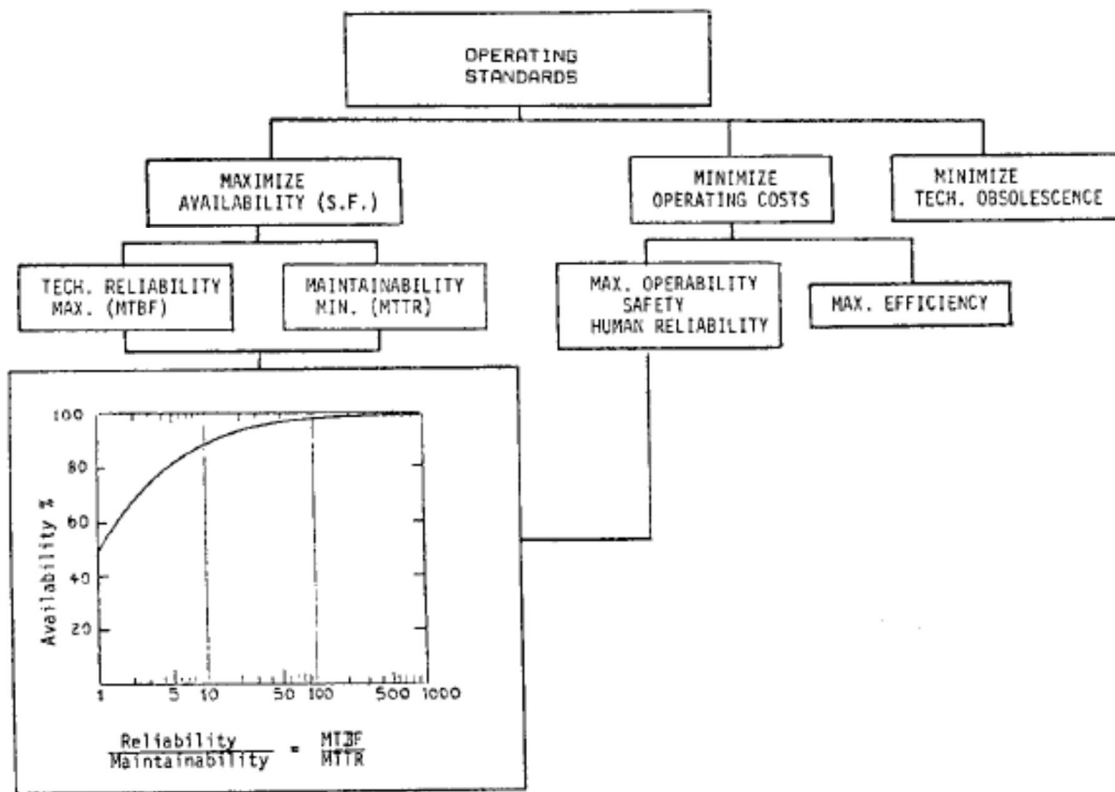
Figure 1: Possible goals of process machinery management (the total picture)

(Source: *Heinz et al. Machinery Component Maintenance and Repair, 2005*)

2 Performance measurement

Successful maintenance organizations regularly measure their performance through various means. Performance analyses contribute to maintenance efficiency and are essential to reveal the peculiarities in operational behavior of assets and, hence, developing timely realistic plans for future maintenance. Various applicable performance indices (measures) exist in the maintenance discipline, i.e., availability and reliability (Dhillon, 2002). Neely *et al. (1995)* as quoted by Partia and Kumar (2006) defined performance measurement as the process of quantifying the efficiency and effectiveness of action, i.e., a set of metrics used to quantify the efficiency and effectiveness of actions. For roads construction industry, the maintenance costs of the earth

moving equipment are a significant component of the operational cost. In addition, breakdowns and downtime have an impact on the overall company's cost, as well as contracts' deadlines and associated loss of credibility and financial penalties.

"Availability" is the actual time that the machine or system is capable of production as a percent of total planned production time. Availability rate should not be confused with overall availability. The latter is calculated using total calendar time as the divisor, not planned production time.

"Reliability" is one of the widely applicable used performance measures. It is the probability that an item will perform its stated mission satisfactorily for the given time period when used under the specified conditions. It is an important factor in maintenance because lower equipment reliability means higher need for maintenance. The basic requirement of plant performance is equipment reliability because factors such as product quality, profitability, and production capacity hinge on this crucial factor alone. Over the years various studies have been conducted to determine the root cause of poor equipment reliability. *The mean time between failures*, MTBF (average time between failures of a repairable item) indicator is widely used to measure the reliability of equipment and machines (Hangzhou and Pham, 2006). An item is considered as good candidate for preventive maintenance has to follow a normal distribution, while keeping low occurrence interval variability as shown in Figure 2 below (Ushakov, 1994), where it is clear that there is relationship between MTBF and candidate preventive maintenance items.

Figure 2: Normal distribution of mean time between failures
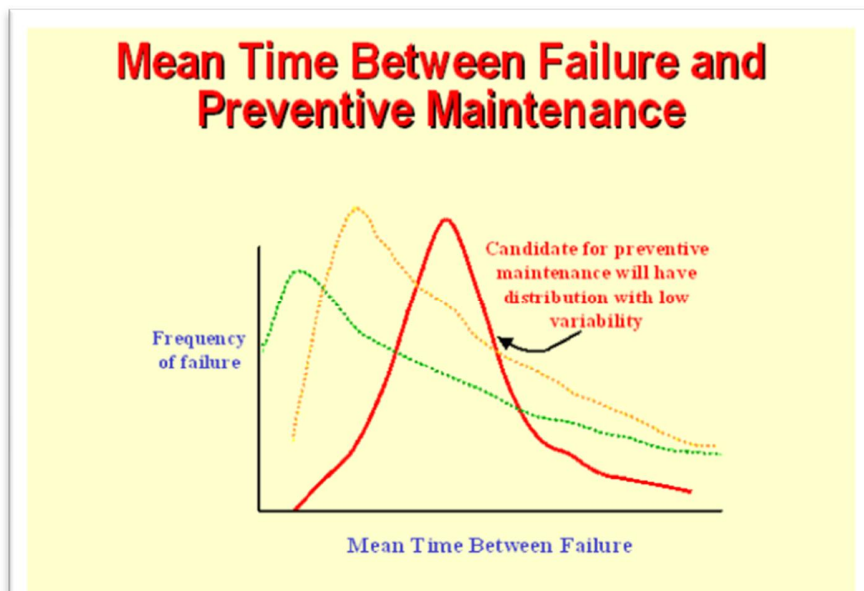
(Source: *Handbook of Reliability Engineering, 1994*)

Failure rate (FR %): reciprocal of MTBF

(FR %) = $\dfrac{\text{Number of failure}}{\text{Number of units tested}}$ …………………...…………….………(1)

Failure per operation hours, FR (n) = $\dfrac{\text{Number of failure}}{\text{Operating time}}$ …………..………. (2)

MTBF = $\dfrac{1}{\text{FR (n)}}$ …………………………………………….………….. (3)

3 Rehabilitation & Repairing Program

It is known that any time delay (postponement) in preventive and predictive maintenance activities generate negative effects on efficiency, availability and reliability of the equipment, e.g., in spot maintenance of a leaking centrifugal pump and consequently reducing operating cost. ConCost construction passed through bad times (more than 68% of its loader -tipper brand- were out of service). The operational ones were not enough to meet the contract deadline, so subcontracting was the available option. But still the company has to rehabilitate its existing valuable and expensive assets (earth moving equipment).

The execution stage had classified the functions to be performed on the equipment into:

* Repairing: equipment out of service but maintainable.
* Rehabilitating: equipment worked with low efficiency needed to upgrade their efficiency.

3.1 *Data Collection*

This study is based on a previous study (Table 1: Haroun et al., 2012). Haroun's et al (2012) concluded that maintaining own equipment (in-house), even through a loan, is quite economical than out-sourcing. This research paper explores the maintenance performance after that decision (in-house maintenance) was put in action, while, still, some of the out-sourced trucks were in service.

Table (1) shows the renting costs, for a year, associated with the project activity stages.

Table (1): The cost distributed through project activity stages

ITEM	Quarter				TOTAL TIPPERS RENT FOR A YEAR
	1st	2nd	3rd	4th	
Relative Work Load[2]	100%	70%	40%	10%	
Cost of 3 Months	1,118,627.8	783,039.44	447,451.11	111,862.77	**2,460,981.1**

(Source: Haroun's et al, 2012)

Considering the above total of SDG 2,460,981.10 (Sudanese Pound[3]) in a year.

The previous study (Haroun et al. 2012) was based on the company's top management request. A consultant of two (later being part of the paper authors) had advised the company to recruit a competent engineer, to act as a technical manager. The recruit, being the third paper's authors, started his job by collecting the cost data and information of the case project from financial and administration managers, the procurement and purchasing department, and through direct observations and the project management records. The other two authors were acted as consultants to the study.

Data of 192 earth moving equipment was collected and sorted in 5 tables (Appendices A-C2). Fifty seven trucks (IVECO 16 m^3) were examined, holistically. Out of the 57 trucks (tippers) only 18 were operational, although working with both low efficiency and availability (68% were out of service). Only, a sample of three, out of the 57 tippers, was selected randomly and elaborately examined (Number 5, 10 and 16, Tables B1-C2).

---

[2] Considering the highest earth moving activity (full load) at the first quarter, and taking that as the comparison base for the following three quarters.

[3] 1 US$ =SDG 2.0 at the time of the study

The data is tabulated into five tables (Appendices A-C2) as follows:

Worked and standby (Reserve) hours collected from operation and transportation department (Appendix B1/B2).

Repair hours and wait for repair hours collected from workshops department. (Appendix B1/B2)
Possible working hours and hours available for work (Appendix B1/B2)

The researchers have chosen three trucks randomly (5, 10 and 16) with the same working conditions as research sample/subjects (Appendix C1/C2)

3.2 *The In-house Program Execution*

Finance was secured (797,255 SDG) to deal with spare parts and components from four earth moving equipment dealers :

1-	Tital company (Komatsu dealer)	SDG 137,000
2-	Abarsi company (Iveco truck dealer)	430,000
3-	Finance with buffer stock to spare parts flow	
	Sutrac Company (CAT dealer)	90, 000
4-	Cash Finance for tanker (Hino ZY)	140,255
	TOTAL FINANCING	SDG 797,255

To the above figure we have to add SDG 475680 as workshop materials and labor operation and maintenance costs (SDG 39,640.00 per month), so a total of 797,255 + 457,680 = SDG1,254,935 constitutes the in-house costs (*Haroun's et al, 2012*), compared to SDG 2,460,981.10 as a rent cost.

4 Program Evaluation

4.1 Data Analysis

Before evaluating the program success, the status quo situation (before the repairs and rehabilitations were executed) showed that the overall rate of breakdown (all earth moving equipment) was 42.16% in December 2006, reduced to 28.46% by the end of October 2007, and ended-up with 14.94% by the end of December 2007 (Appendix A). Considering the selected sample (57 units/trucks) we found that the breakdowns rate was 68.42 % in December 2006 (post-execution period) reduced to 45.61% by the end of December 2007, noticing that the first stage of the in-house plan was carried out in October 2007. Consequently, the objective of in-house repairing and rehabilitating the equipment was achieved (improved performance). The results of that stage encouraged top management to proceed for the second stage. Unfortunately, the second stage was not fully executed due to mal- financing.

The following table reveals the effect of the first stage of the maintenance on the sample of the three trucks:

Table 2: The average of availability, reliability Value of T for the 3 selected trucks:

PARAMETERS	June 2006	October 2007	T- VALUE
Availability	57%	67%	10%
Reliability (MTBF)	33 hours	64 hours	31 hours

Referred to the data in table 2, it is found that the effect of maintenance on availability (67%) and reliability, as noted from T-Value (T =10%) is quite significant. The 67% is taken, in October 2007, as an average of the three selected trucks (5, 10 and 16), which was used to be 57% in June 2006.

The table also showed that the reliability increased from 33 to 64 hours, in the same period, representing a significant difference of 31 that represents 94%.

4.2 *Conclusions*

The findings obtained from the analysis, within the limit of the research sample, showed an increase of availability (performance) from 57% to 67% in 17 months, i.e., by 10 per cent (4 hours in a 40-hours week), showing a significant difference between the two measurement indices of availability; meanwhile, increasing the MTBF (reliability) from 33 to 64 hours, i.e., by 31 hours (that is equivalent to 94 per cent) in the same period. So, it is evident that investing in in-house maintenance (repairing and rehabilitation) is quite rewarding. Comparing this result with subcontracting experience, we find that we improved the quality of the maintenance (increased availability) while reducing the time between reporting the equipment mal function or failure to the sub-contractor and replacement of the defective equipment.

The whole study also showed that the asset value[4] (book value), after maintenance and rehabilitation, increased by the end of the project (trade in value) by 41.5%.

We concluded that, true cost saving and profitability can only be achieved by combining equipment/machinery performance and reliability into a cost relationship model. The model could be extended to include the effect of cost on equipment/machinery and maintainability.

5 Acknowledgement

References

Al-Turki, U. and Duffuaa, S. (2003), Performance measures for academic departments, *International Journal of Educational Management,* Vol. 17, No. 7, pp. 330-338

Caterpillar (2003), Caterpillar Performance Handbook, 34th ed., Caterpillar, Peoria, IL.

Dasgupa, Parthia (2004), Economic: A very short introduction, Oxford university.

Dhillon, B.S. (2002), Engineering Maintenance: a modern approach, U.S.A., New York, CRC Press LLC. ISBN: 1-58716-142-7

Fuller, N. (2002). Beyond the core. *Supply Management*, 7(20), 39.

Gross, John M. (2002), Fundamental of Preventive Maintenance, U.S.A., New York.

---

[4] This remark is not part of this study (paper).

Hangzhou Wang and Hoag Pham (2006), Reliability and optimal maintenance, Springer-Verlag London Limited.

Haroun, Ahmed E., Elfaki, Elkhawad A., Beshir El Mahdi A. M. "Feasibility of Adopting In-And-Out-Sourcing: a case study of PetroCost for Engineering Investment and Construction Co. Ltd.", *Journal of Quality in Maintenance Engineering*, V18 (1), 2012, pp. 4-15.

Heinz P. Bloch, Fred K. Geitner (2005), Machinery Component Maintenance and Repair: Practical Machinery Management for Process Plant, U.K., Oxford, third edition, volume 3, Elsevie.

Higgins, Lindley R., Keith Mobley, Rick Smith (2002), Maintenance Engineering Handbook, six edition, U.S.A., Mc Graw-Hill.

Hui, Y. Y. Encon & Tsang, H. C. Albert (2004). Sourcing strategies of facilities management. *Journal of Quality in Maintenance Engineering*, 10(2).

Igor A. Ushakov (1994) Handbook of reliability engineering, John Wiley & Sons, Inc. , New York.

Joseph Frein, Editor (1980), Handbook of Construction Management and Organization, second edition, U.S.A., Educational Publishing Inc.

Mangey Ram (2013) On system reliability approaches: a brief survey. *Int J Syst Assur Eng Manag* 4(2):101–117

Marttonen, Salla and Timo Kärri (2012) "A conceptual model for assessing the profitability of a maintenance outsourcing decision" *17th International Working Seminar on Production Economics*, 20-24 February, Vol. 2, p. 429-443, Innsbruck, Austria.

Parida, A. and Kumar, U. (2006), Maintenance performance measurement (MPM): issues and challenges, *Journal of Quality in Maintenance Engineering*, Vol. 12 (3).

Rick Smith, Keith Mobley (2003), Industrial Machinery Repair: Best Maintenance Practices Pocket Guide, U.S.A., Elsevier Science.

Simo˜es, J.M., Gomes, C.F., and Yasin, M.M. (2011), A literature review of maintenance performance measurement: A conceptual framework and directions for future research. *Journal of Quality in Maintenance Engineering,* Vol. 17 (2), pp. 116-137.

Tsang, A. (2002). Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, 8(1), 7-39.

Ushakov, Igor A. (1994), Handbook of reliability engineering, John Wiley & Sons, Inc. , New York.

ConCost Construction Company Machinery & Equipment Inventory: Equipment Efficiency Reports

Appendix A   **Period***:*   ***May-October 2006***

No	Type of equipment	Quantity	Working Condition 31/12/06			Maintenance Activities - Period: 1/1/2007 - 31/10/2007						Observed Condition - 31/12/2007			
			Operational	Breakdown	Break-Down Rate(%)	Rehabilitation	Repaired Breakdowns	Rehabilitation Rate	Op-nal	Breakdown	Break-Down Rate	Rehabilitation	Repaired break-Down	Rehabilitation Rate (%)	Break-down Rate (%)
1	DOZER	8	5	3	37.50	3	1	37.50%	6	2	25.00%	3	1	75.00	12.50
2	GRADER	12	3	9	75.00	5	5	41.67%	8	4	33.33%	3	2	66.67	16.67
3	LOADER	12	4	8	66.67	7	4	58.33%	8	4	33.33%	1	1	66.67	25.00
4	COMPACTOR	17	11	6	35.29	5	2	29.41%	13	4	23.53%	3	2	47.06%	11.76%
5	TANKER	20	9	11	55.00	5	5	25.00%	9	6	30.00%	2	2	35.00%	20.00%
6	TIPPER	57	18	39	68.42	25	8	43.86%	26	31	54.39%	5	5	52.63%	45.61%
7	EXCAVATOR	2	2	0	0.00	1	0	50.00%	2	0	0.00%	1	0	100.00%	0.00%
8	SCRAPER	2	0	2	100.00	0	0	0.00%	0	2	100.00%	1	1	50.00%	50.000%
9	ROCK DISTR	1	1	0	0.00%	1	0	100.00%	1	0	0.00%	0	0	100.00%	0.00%
10	COMPRESOR	3	2	1	33.33%	1	0	33.33%	2	1	33.33%	1	1	66.67%	0.00%
11	SERVICE TRUCK	5	1	4	80.00%	1	2	20.00%	3	2	40.00%	1	0	40.00%	40.00%
12	MC DISTR	3	2	1	33.33%	1	0	33.33%	2	1	33.33%	1	1	66.67%	0.00%
13	CARS	40	24	16	40.00%	8	3	20.00%	27	13	32.50%	4	6	30.00%	17.50%
14	TRAILER	6	5	1	16.67%	3	0	50.00%	5	1	16.67%	2	1	83.33%	0.00%
15	FINISHER	3	2	1	33.33%	2	1	66.67%	3	0	0.00%	1	0	100.00%	0.00%
16	FORKLIFT	1	1	0	0.00%	0	0	0.00%	1	0	0.00%	1	0	100.00%	0.00%
	Average				42.16%			38.07%			28.46%			67.48%	14.94%

RESULTS
1. *The attainment rate on repairing breakdowns is 60%*
2. *The attainment rate on rehabilitations is 57%*

Appendix B1 — Equipment Efficiency Report — Period: *May-October 2006*

No.	Unit	Type	Equipment Location	Unit Number	A Possible working hours	B Available working hours	C Actual worked hours	D Reserve hours	E Wait for repair hours	F Repair hours	G Availability % $\frac{C}{A-D-E}$	H Utilization % $\frac{C}{B}$	I Number of failures	J Rehabilitation (MTBF) hours	Comments
1			1	12.-08	260	217	156	14	3	39	64%	72%	4	40	
2			2	12.-09	260	217	0	0	212	0	0%	0%	0	0	BDs**
3			2	12.-10	260	217	0	0	0	0	0%	0%	0	0	OOS***
4			2	12.-11	260	217	0	0	212	0	0%	0%	0	0	BDs
5			3	12.-12	260	217	158	17	5	33	66%	73%	3	48	
6			3	12.-13	260	217	0	0	0	0	0%	0%	0	0	BDs
7			2	12.-14	260	217	123	46	5	38	59%	57%	4	32	
8			2	12.-15	260	217	0	0	0	0	0%	0%	0	0	TR****
9			2	12.-16	260	217	0	0	212	0	0%	0%	0	0	BDs
10	TIPPER	IVECO 16 m³	2	12.-17	260	217	108	3	11	90	44%	50%	7	15	
11			2	12.-18	260	217	0	0	212	0	0%	0%	0	0	BDs
12			2	12.-19	260	217	111	17	9	75	48%	51%	5	22	
13			4	12.-20	260	217	0	0	212	0	0%	0%	0	0	BDs
14			3	12.-21	260	217	188	19	0	6	78%	87%	2	94	
15			2	12.-22	260	217	64	6	15	128	27%	29%	8	8	
16			2	12.-23	260	217	146	12	7	48	60%	67%	4	36	
17			1	12.-24	260	217	0	0	212	0	0%	0%	0	0	BDs
18			2	12.-25	260	217	0	0	212	0	0%	0%	0	0	BDs
19			3	12.-26	260	217	194	16	0	3	79%	89%	1	194	
20			3	12.-27	260	217	0	0	0	0	0%	0%	0	0	OOS
21			2	12.-28	260	217	0	0	212	0	0%	0%	0	0	BDs
22			2	12.-29	260	217	168	19	4	22	71%	77%	2	76	
23			4	12.-30	260	217	36	0	13	173	15%	17%	9	4	
24			2	12.-31	260	217	153	14	6	39	64%	71%	4	39	

* SMR = Service Meter Reading
**BD = Breakdown
***OOS = out-of-service
****TR = Transferred

Locations: 1 = Obaid Station   2 = Khuwi Station   3 = Khartoum Station   4 = Ginaid Station

Appendix B2   Equipment Efficiency Report   Period: *May-October 2007*

No.	Unit	Type	Location	Unit	*SMR	A Possible working hours	B Hours available for work	C Worked hours	D Standby hours	E Wait for read air hours	F Red air hour	G Availability % $\frac{C}{A-D-E}$	H Utilization % $\frac{C}{B}$	I No. of failure	J Reliability (MTBF) hours	Comments
1			1	12.-08		260	217	164	19	12	34	72%	76%	1	164	
2			2	12.-09		260	217	0	0	217	0	0%	0%	0	0	B Down
3			2	12.-10		260	217	0	0	217	0	0%	0%	0	0	OOS
4			2	12.-11		260	217	0	0	217	0	0%	0%	0	0	B Down
5			3	12.-12		260	217	168	11	12	38	71%	77%	2	84	
6			3	12.-13		260	217	0	0	217	0	0%	0%	0	0	B Down
7			2	12.-14		260	217	154	28	4	35	68%	71%	5	31	
8			2	12.-15		260	217	0	0	217	0	0%	0%	0	0	TR
9	TIPPER	IVECO 16 m³	2	12.-16		260	217	0	0	217	0	0%	0%	0	0	B Down
10			2	12.-17		260	217	149	12	13	56	63%	69%	3	50	
11			2	12.-18		260	217	158	0	13	59	64%	73%	4	0	
12			2	12.-19		260	217	136	13	14	68	58%	63%	3	45	
13			4	12.-20		260	217	0	0	217	0	0%	0%	0	0	B Down
14			3	12.-21		260	217	176	21	0	20	74%	81%	3	59	
15			2	12.-22		260	217	172	14	7	31	72%	79%	4	43	
16			2	12.-23		260	217	174	0	0	43	67%	80%	3	58	
17			1	12.-24		260	217	0	0	217	0	0%	0%	0	0	
18			2	12.-25		260	217	145	27	4	45	63%	67%	4	0	B Down
19			3	12.-26		260	217	186	8	11	23	77%	86%	3	62	
20			3	12.-27		260	217	0	0	217	0	0%	0%	0	0	OOS
21			2	12.-28		260	217	0	0	217	0	0%	0%	0	0	B Down
22			2	12.-29		260	217	169	11	0	37	68%	78%	2	85	
23			4	12.-30		260	217	114	0	26	103	49%	53%	5	23	
24			2	12.-31		260	217	181	0	4	36	71%	83%	2	91	

Appendix C1 — Equipment Efficiency Report — Period: *May-October 2007*

No.	Unit	Type	Location	Unit Number	May 2007			June 2007			July 2007			August 2007			September 2007			October 2007			Avg. Of days/month			Avg. Of hours/month		
					W	B.D	S	W	B.D	S	W	B.D	S	W	B.D	S	W	B.D	S	W	B.D	S	W	B.D	S	W	B.D	S
1			1*	12.-08	9	9	0	22	2	0	22	4	0	20	4	2	14	5	8	21	5	0	18	5	2	156	42	17
2			2	12.-09	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
3			2	12.-10	Out of Service																		0	0	0	0	0	0
4			2	12.-11	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
5			3	12.-12	10	5	3	17	7	0	19	7	0	22	2	2	18	2	7	23	3	0	18	4	2	158	38	21
6			3	12.-13	Out of Service																		0	0	0	0	0	0
7			2	12.-14	9	1	8	24	0	0	26	0	0	13	11	2	10	8	9	3	10	13	14	5	6	123	43	55
8			2	12.-15	Transferred to Petro Delta																		0	0	0	0	0	0
9			2	12.-16	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
10	TIPPER	IVECO 16 m³	2	12.-17	18	0	0	23	1	0	13	13	0	21	3	2	0	27	0	0	26	0	13	12	0	108	101	3
11			2	12.-18	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
12			2	12.-19	10	4	4	22	2	0	11	15	0	1	25	0	11	9	7	22	3	1	13	10	2	111	84	21
13			4	12.-20	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
14			3	12.-21	14	0	4	24	0	0	26	0	0	24	2	0	17	1	9	25	1	0	22	1	3	188	6	23
15			2	12.-22	14	0	4	21	3	0	9	17	0	0	26	0	0	27	0	0	26	0	7	17	1	64	143	7
16			2	12.-23	18	0	0	22	2	0	18	8	0	15	10	1	10	10	7	8	8	0	17	6	2	146	55	14
17			1	12.-24	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
18			2	12.-25	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
19			3	12.-26	18	0	0	22	2	0	26	0	0	24	0	2	18	0	9	26	0	0	22	0	2	194	3	19
20			3	12.-27	Out of Service																		0	0	0	0	0	0
21			2	12.-28	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
22			2	12.-29	15	2	1	22	2	0	25	1	0	24	1	1	8	8	11	22	4	0	19	3	3	168	26	23
23			4	12.-30	12	6	0	12	12	0	1	25	0	0	26	0	0	27	0	0	26	0	4	20	0	36	176	0
24			2	12.-31	11	6	1	22	2	0	20	6	0	20	6	0	18	0	9	15	11	0	18	5	2	153	45	17

Appendix C2 | **Equipment Efficiency Report** | **Period:** *May-October 2007*

No.	Unit	Type	Location	Unit No.	May 2007 W	B.D	S	June 2007 W	B.D	S	July 2007 W	B.D	S	August 2007 W	B.D	S	September 2007 W	B.D	S	October 2007 W	B.D	S	Avg. Of days/month W	B.D	S	Avg. Of hours/month W	B.D	S
1	TIPPER	IVECO 16 m³	1	12.-08	9	9	0	22	2	0	22	4	0	20	4	2	14	5	8	21	5	0	18	5	2	156	42	17
2			2	12.-09	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
3			2	12.-10	Out of Service																		0	0	0	0	0	0
4			2	12.-11	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
5			3	12.-12	10	5	3	17	7	0	19	7	0	22	2	2	18	2	7	23	3	0	18	4	2	158	38	21
6			3	12.-13	Out of Service																		0	0	0	0	0	0
7			2	12.-14	9	1	8	24	0	0	26	0	0	13	11	2	10	8	9	3	10	13	14	5	6	123	43	55
8			2	12.-15	Transferred to petro Delta																		0	0	0	0	0	0
9			2	12.-16	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
10			2	12.-17	18	0	0	23	1	0	13	13	0	21	3	2	0	27	0	0	26	0	13	12	0	108	101	3
11			2	12.-18	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
12			2	12.-19	10	4	4	22	2	0	11	15	0	1	25	0	11	9	7	22	3	1	13	10	2	111	84	21
13			4	12.-20	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
14			3	12.-21	14	0	4	24	0	0	26	0	0	24	2	0	17	1	9	25	1	0	22	1	3	188	6	23
15			2	12.-22	14	0	4	21	3	0	9	17	0	0	26	0	0	27	0	0	26	0	7	17	1	64	143	7
16			2	12.-23	18	0	0	22	2	0	18	8	0	15	10	1	10	10	7	18	8	0	17	6	2	146	55	14
17			1	12.-24	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
18			2	12.-25	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
19			3	12.-26	18	0	0	22	2	0	26	0	0	24	0	2	18	0	9	26	0	0	22	0	2	194	3	19
20			3	12.-27	Out of Service																		0	0	0	0	0	0
21			2	12.-28	0	18	0	0	24	0	0	26	0	0	26	0	0	27	0	0	26	0	0	25	0	0	212	0
22			2	12.-29	15	2	1	22	2	0	25	1	0	24	1	1	8	8	11	22	4	0	19	3	3	168	26	23
23			4	12.-30	12	6	0	12	12	0	1	25	0	0	26	0	0	27	0	0	26	0	4	20	0	36	176	0
24			2	12.-31	11	6	1	22	2	0	20	6	0	20	6	0	18	0	9	15	11	0	18	5	2	153	45	17

W = Worked Hours *B.D. = Breakdown Hours* *S = Standby Hours*

Creating a life-cycle model for industrial maintenance networks

Harri Kivimäki*, Tiina Sinkkonen, Salla Marttonen and Timo Kärri

Department of Innovation Management
Lappeenranta University of Technology
P.O.Box 20
FIN-53851 Lappeenranta
Finland
*Corresponding author: Harri Kivimäki
e-mail: harri.kivimaki@lut.fi
e-mail: tiina.sinkkonen@lut.fi
e-mail: salla.marttonen@lut.fi
e-mail: timo.karri@lut.fi

Abstract

Our objective in this article is to create a general life-cycle model for maintenance decision making in different industries at the item level. The need for network-level tools will increase, as inter-organizational collaboration is emphasized more and more. Previous life-cycle models have mostly viewed the matter from the perspective of just one company, but our model takes the different members of maintenance networks into account. We have also integrated value thinking with life-cycle accounting, as it is crucial for companies to perceive which elements increase the value of each member in their network. The value-based life-cycle model introduced in this article can be used in maintenance contract negotiations and in monitoring the life-cycle costs and profits of both past and planned maintenance. In addition, it can be designed how additional value can be reached through future maintenance and how this value can be equitably shared between the network partners.

Key words: Value, life cycle, maintenance, networks, model

1 Introduction

The importance of industrial maintenance has been emphasized during the last decades: it is no longer a mere cost item, but one of the mainstays of business. Market conditions have worsened lately, investments in production assets have decreased, and companies have focused more on their core functions. These changes have caused increasing restructuring, especially outsourcing, of maintenance in industrial companies. The main benefits pursued through outsourcing include for example cost savings, resource optimization, increased safety, and superior quality. However, despite the possible benefits of maintenance outsourcing, there are also some risks that can be increased when buying services from an outside service provider: for example losing the know-how of your personnel, facing general resistance to change, or high dependency on the service provider (Gómez et al., 2008; Kumar and Markeset, 2007).

The high number of maintenance outsourcings has been followed by increased inter-organizational collaboration and new collaborative networks as regards industrial maintenance. Thus there is a growing need for network-level tools to support decision making and maintenance management. In addition, to promote advantageous collaboration, it is crucial for companies to know the preferences of their network partners: companies may think they know what elements in maintenance services are the most important for their partners, but they can be wrong. Thus this information on the most important value-creating elements should be made explicit to advance win-win situations in networks.

We address the above-mentioned issues by introducing a novel tool for maintenance networks. Our objective is to create a general life-cycle model to support decision making in company networks as regards item-level maintenance. The research questions of the paper are the following:

- What kind of structure is needed for a life-cycle model that takes the perspectives of different maintenance network members into account?

- How can the concept of value be integrated into the life-cycle model?

- How can the results generated by the model be used in decision making?

Models of this kind have not been introduced in the academic literature before. Previous models (e.g. Jun and Kim, 2007; Waghmode and Sahasrabudhe, 2012) have mostly concerned the perspective of a single company. In our model the inspection is done from the perspectives of different members of a maintenance network: a maintenance customer (who buys maintenance services), a service provider (who provides maintenance services for the customer), and an equipment provider (who supplies equipment and some related maintenance services for the customer). The groundwork for the model has been done mostly with qualitative data (Sinkkonen et al., 2013B; Tynninen et al., 2012). Thus we consider it important that the model introduced in this paper can be tested with quantitative data, in other words with actual and estimated costs and profits. The model guides the user in decreasing the costs (see e.g. Idhammar, 2009) and increasing the profits (see e.g. Gokiene, 2010; Knights et al., 2004) of maintenance services during the life cycle of the item at issue. The model is suitable for different kinds of production equipment, as well as for various industries.

After this introductory section, the theoretical framework for the model is discussed in section 2. Next, section 3 introduces the research design, including the modeling process and the research context. Section 4 addresses the value-based life-cycle model for maintenance networks, and explicates how the model has been validated in cooperation with the mining industry. The article finishes with conclusions in section 5.

2 Recent studies on life-cycle models in maintenance

Life-cycle costing (LCC) hails from the 1960s when the United States Army started to use it to estimate their acquisition costs. This method has typically been used in construction industry and government investments. However, it is still not very familiar in the field of industrial companies (Korpi and Ala-Risku, 2008). Conventionally LCC has been seen as a tool for calculating the investment costs of the whole life-cycle period of an item. During the last years, different kinds of life-cycle models (LCM) have been developed for companies to plan the future and organize their operations in the long term, meaning better transparency of

costs, activities, and their interaction (Lindholm and Suomala, 2007; Blanchard and Fabrycky, 1998).

Table 1 presents seven recent academic studies which discuss maintenance costs and LCMs. Most of the models still focus on different kinds of new or replacement investments (e.g. Navarro-Galera and Ortúzar Maturana, 2011), being usually very case-specific and thus suitable only for the item in question (Hochschorner and Noring, 2011). However, there is also an increased interest towards models connecting maintenance costs and life-cycle thinking (see e.g. Jun and Kim, 2007; Waghmode and Sahasrabudhe, 2012; Lad and Kulkarni, 2012). It should be noted that there are still very few models integrating value thinking with maintenance costs (Wang and Xu, 2009). Also the life-cycle profits (LCP), e.g. minimizing downtime and failures, are mainly neglected in the previous models.

Table 1. List of the LCC articles reviewed for this paper

Authors	Year	Title of the article	Substance of the article
Jun & Kim	2007	Life cycle cost modeling for railway vehicle	- A model that uses net present value - Maintenance costs are one of the three cost categories
Wang & Xu	2009	SVLC: Service value life cycle model	- An LCM for consumer services - Main focus is on the quality of the services
Navarro-Galera & Ortúzar Maturana	2011	Innovating in defence policy through spending efficiency: The life cycle costing model	- An LCM for defense costs and economic growth - Empirical study
Kayrbekova et al.	2011	Activity-based life cycle cost analysis as an alternative to conventional LCC in engineering design	- Activity-based life cycle cost analysis as an alternative to conventional LCC
Hochschorner & Noring	2011	Practitioners´ use of life cycle costing with environmental costs - a Swedish study	- Using LCC as a part of decision making - Interview study
Waghmode & Sahasrabudhe	2012	Modelling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems	- Modeling maintenance costs with LCC - Case study
Lad & Kulkarni	2012	Optimal maintenance schedule decisions for machine tools considering the user's cost structure	- LCC and present value are used for optimal maintenance schedule decisions

Figure 1 presents the theoretical framework for our value-based LCM. The model consists of long-term value calculations and controlling criteria, which take into account the benefits and costs of all the network members (a customer, an equipment provider, and a maintenance company). All too often, the customer evaluates the maintenance services only from the cost point of view (Barringer, 2003; Dorf, 2004; Idhammar 2009; Knights et al., 2004).

When discussing the maintenance services required by a single item, there are three main options: the customer produces the services by itself (option I), the customer and the equipment provider produce the services together (option II), or an independent maintenance service company acts as an integrator and produces the services (option III). In practice, the solution is usually a combination of these options, which is not necessarily the most optimal way of creating value. Each member of the maintenance network examines the life-cycle profits and costs from their own viewpoint. From the customer's point of view, the main issue

is planning and simulating the life cycle of the item while considering the changing market situation (variations in demand) and risks (item criticality to the production process). Thus, creating added value to the customer calls for maintenance profits during the item life cycle to be higher than the required costs. On the other hand, from the equipment provider's point of view, selling maintenance services should create added value.
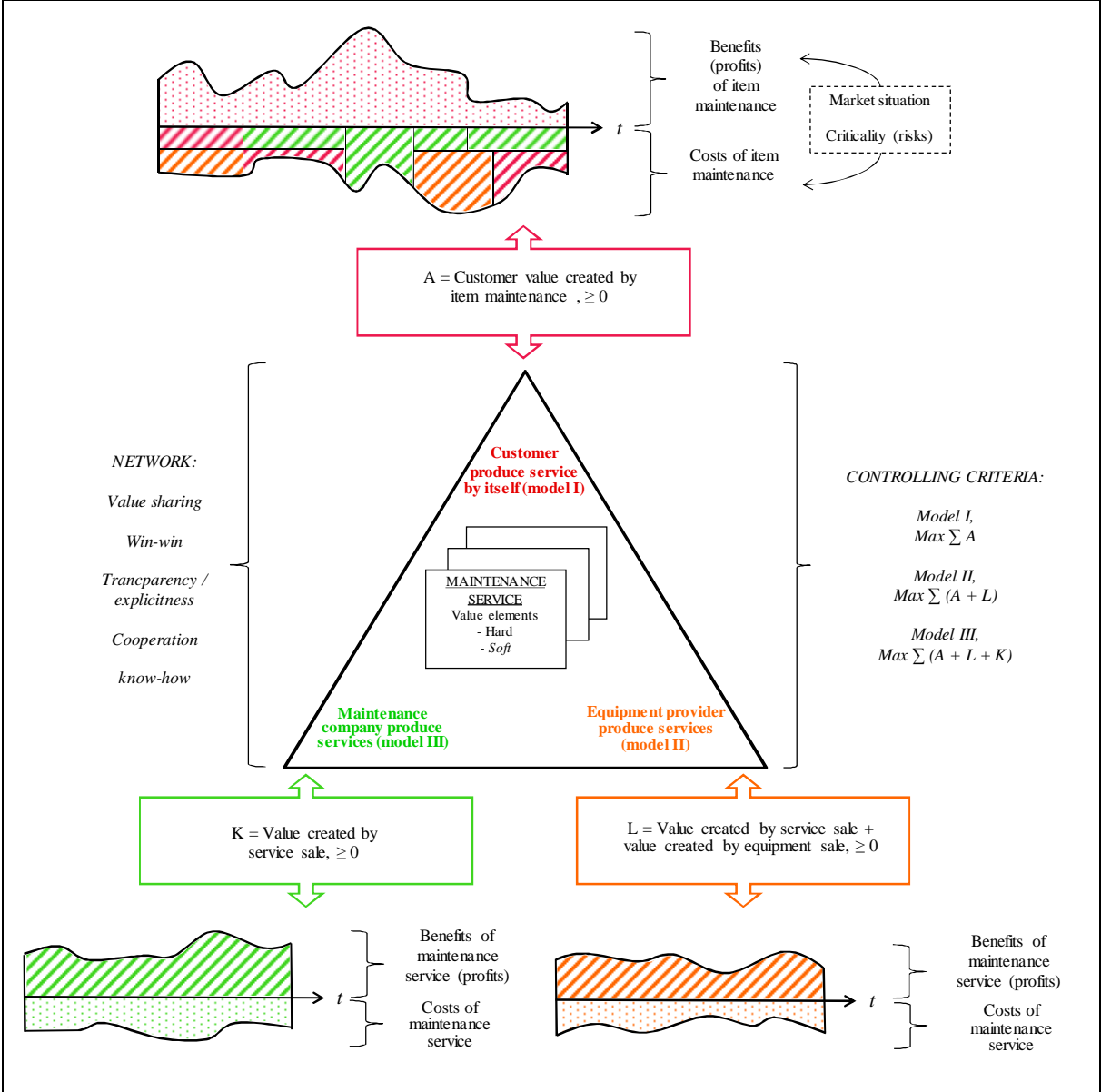

Figure 1. Value-based LCM of maintenance services

Nowadays, the interest of equipment providers is directed not only to comprehensive maintenance services, but also to providing more and more operating services. Thus from the perspective of an equipment provider, the total present value of equipment and service sales should be positive. The independent maintenance company can be responsible for producing services on either the item level or on the level of the whole factory. The role of the maintenance company in the network is justified if the company, as an integrator, is able to create additional value for the maintenance service packages. The created value should be higher than what the customer and the equipment provider can create either alone or in cooperation.

From the perspective of managing the whole network, it is a question of using life-cycle thinking to gain a better overall view of the creation of value and the distribution of the value between the various network members. Traditionally, each network member aspires to examine the created value only from their own point of view. If the customer works in close cooperation with the equipment provider, they can both create value through their own actions. However, the most interesting situation is the one in which all the network members try to create value collaboratively, using their potential know-how to improve the competitiveness of the whole network.

3 Research design

The group of researchers at Lappeenranta University of Technology started to develop their life-cycle model already in 2010 (Fig. 2), when they defined the cost structure of maintenance services together with a case network operating in the forest industry. The main goal of the research was to discover the most important cost categories of maintenance services from the perspective of either the service provider or the customer. This cost model was first presented in a conference paper for the MPMM 2011 conference (Sinkkonen et al., 2013B).

The next step was to get to know the definitions and structure of value and the value creation process in the field of maintenance. Value can be seen to comprise certain value elements, which are intended to be used as an input data for the LCM. Tynninen et al. (2012) found that a comprehensive list of the value elements of industrial maintenance was not available, and thus they constructed preliminary lists of value elements for maintenance customers and service providers on the basis of an extensive literature review. The preliminary list of value elements was tested and improved together with industrial maintenance professionals in a workshop. The theoretical lists were further tested through a survey among the representatives of customers and service providers working in the area of maintenance (Sinkkonen et al., 2013A). The results of this survey can be exploited in the next version of the LCM. However, the first version of the model, which is presented in this paper, was built by using the results of the workshop only.

The value-based LCM introduced in this paper was tested with real data in case studies with two companies (a customer and a service provider) operating in a mining network. Using this received feedback from testing the model, the researchers have already started to improve the model towards the second version. The future versions of the model will be further tested in an energy network, and internationally in Swedish companies.

This study is a part of a large ongoing project, and the case companies used in testing this model have been participating in the project closely. The companies have also their own interest in this kind of models because there is a clear need for long-term planning tools of maintenance services. Preventive maintenance has a very important role in the mining industry, and thus the failure of critical items may stop the whole process rapidly. The production equipment of the mining industry has a long life cycle, which makes it possible to get enough cost data and experiences of the maintenance services of the item to conduct research. In this case the customer and the service provider also have a long-term relationship in maintenance operations, which enables gathering experiences from both sides. In many occasions this kind of relationships do not exist, so our research environment was fruitful.

2010-2011	• Definition of the cost structure for maintenance services • Creation of the cost model
2012	• Definion of the value-elements for maintenance services • Creation of the value-element lists for the customer and the service provider

2013	• The first version of the value-based life-cycle model for maintenance services
	  • *Definition of the modelling object*
	  • *Definition of the parameters of the model and the relations between the parameters*
	  • *Construction of the model*
	• Testing the life-cycle model in a mining network

2013-2014	• Testing the life-cycle model in an energy network and in Sweden • Updating and redeveloping the model on the basis of feedback
2015	• Implementation of the value-based life-cycle model in the corporate sector

Figure 2. Development process of the value-based LCM. The current phase is highlighted in blue.

The maintenance processes in the case network were addressed through a case study, because it is a useful method for testing theoretical frameworks in real-life situations. This study contains two separate cases: a jaw crusher (Case 1) and a rod mill in the grinding and flotation phase of the process (Case 2). The relation of these two cases to the mining process can be seen in figure 3. These machines were selected in close collaboration with the network companies. The jaw crusher is a critical item in the mining process. The rod mill is not so critical, because there are in total three mills to do the grinding and flotation.

The two cases were studied through several personal interviews. After that the maintenance costs were collected using the same cost structure as in the cost model (Sinkkonen et al., 2013B). The received cost data covered from three to five years of preventive and corrective maintenance cost data. After testing the model with this data, the results were analyzed together with the companies.
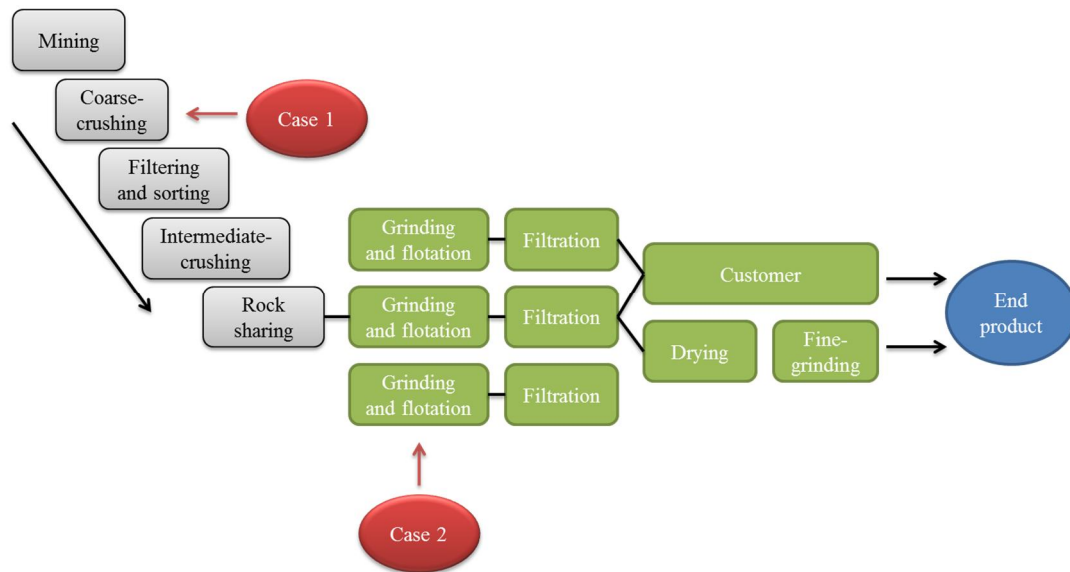
Figure 3. Case studies in relation to the mining process

4 Value-based LCM

4.1 Structure of the model

The developed model is suitable for item-level decision-making situations between companies buying and selling maintenance services. The model can be used as a mutual tool on the network level or separately in each company. Practitioners will be able to use the model in forecasting the future, but also in monitoring the realized costs and profits from the past. This way the model can be used as a tool for both forecasting and monitoring. The first version of the model has been developed by using Microsoft® Excel, and it consists of eight sheets. Depending on the user, these sheets include two or three input sheets and two result sheets.

The process of using the model is described in figure 4. The green boxes represent the sheets that are common for all users. On the front page and the instruction sheet the user can explore the content and structure of the model. In addition, the use of the model is described with elucidating figures on the front page and the instruction sheet. On the initial data –sheet the user can input the basic information of the item and the names of its maintenance operators. In this sheet, the user also has to decide on the length of the planning and inspection periods. In addition, the initial data –sheet allows the user to see what information is needed for the following calculation sheets and what the formal logic of the model is like. On this sheet, the user can also test the logic of the model and see how it works.

The LCC sheets are presented with red boxes in figure 4. The users (customers, service providers and equipment providers) input the maintenance costs and profits of the item on their own sheets. In addition, the customer must input all information related to the item and to the production process, as well as maintenance data, to the customer-sheet. All life-cycle calculations are carried out in customer, service provider and equipment provider -sheets. The user has to choose a discounting rate which is based on the company´s own targets. The discounting rate is used to calculate the net present value of past and future costs and profits. The cost categories used in the calculation sheets are based on a previous study where the cost categories of industrial maintenance services were developed and tested with three case

studies in the forest industry (Sinkkonen et al., 2013B). These cost categories and groups have been modified during the present research.
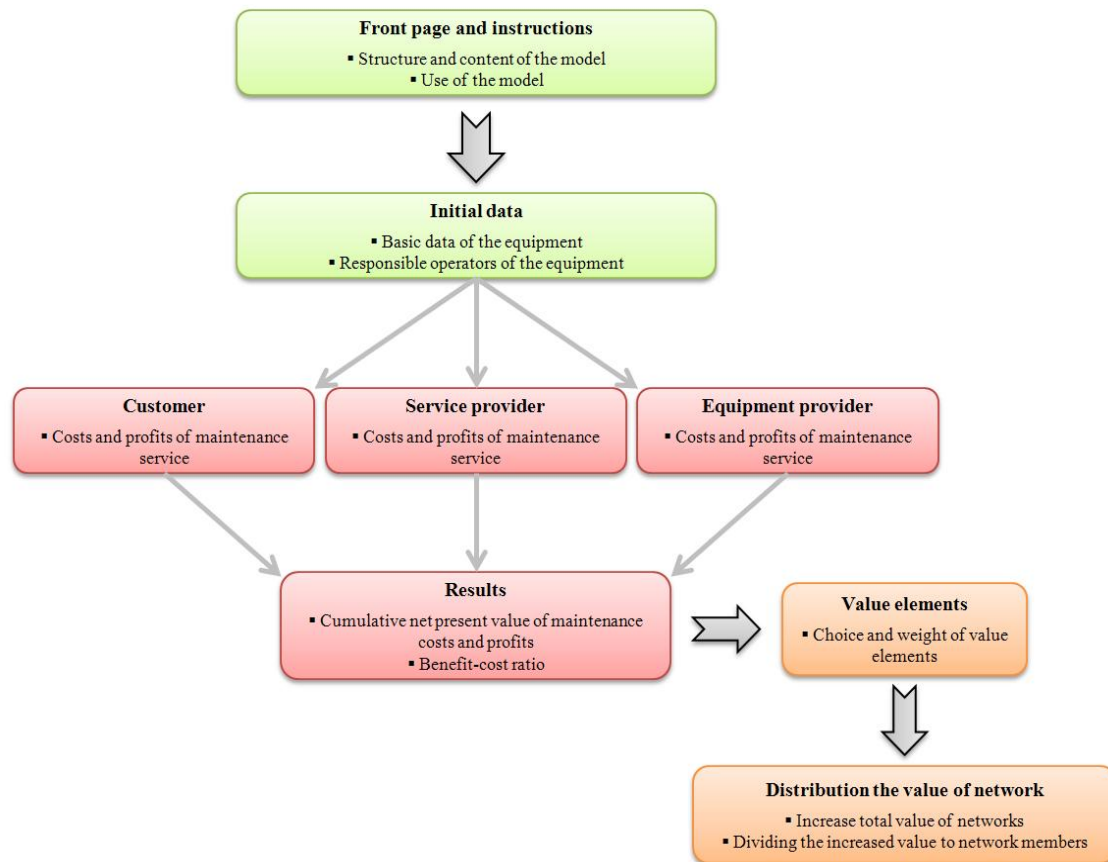
Figure 4. Structure and content of the value-based LCM

The results sheet includes the main results from the customer, service provider and equipment provider -sheets. Net present values of maintenance costs and profits are presented for all network members and for each year of the inspection period. In addition, cumulative net present values of the net profits are calculated and presented in this sheet. Benefit-cost ratios describe the relationship between cumulative profits and costs from each year. On the whole, the numerical value of the benefit-cost ratio should remain greater than one. This would mean that the profits are greater than the costs, and that the maintenance actions have been carried out profitably. The model also presents the main results through elucidating figures.

An important part of this model is connecting value thinking and LCC. The value thinking sheets of the model are highlighted with orange boxes in figure 4. In the value elements -sheet the user chooses one to five value elements. After that, the user weights the elements based on his perspectives and thoughts. On the basis of the chosen value elements, the model divides the cumulative net profits to the weighted elements. Therefore, the model gives a numerical value to all the chosen and weighted value elements. These numerical values and elements can be used as a basis for contracts and bonus systems. The increased value and sharing the value of the network can be analyzed in the distribution of the value of the network -sheet. The results of the distribution of the value of the network -sheet can be used to analyze how the gained profits and increased value can be distributed fairly to all network members.

To utilize the model for planning the future, all the results provided by the model should be considered. The benefit-cost ratio highlights the relationships between cumulative net profits and costs, while the net present values describe the cumulative profits and costs while taking the time value of money into account. In addition, the distribution the value of the network - sheet connects the value thinking and LCC. Utilizing all the above-mentioned results, the value-based LCM provides a useful tool for supporting contract negotiations and to analyze the distribution of the increased value of the network.

4.2 Testing and results of the value-based LCM

The value-based LCM has been mainly developed to support future planning. The model has been developed and tested with two independent cases. In this subsection we concentrate on the rod mill, which is a part of the grinding and flotation process (see figure 3). The model has also been tested with a coarse-crushing case, but this case is not presented in this paper. The reason for this choice is that the cost data of the rod mill case was more comprehensive and clearer. In addition, the maintenance processes of the rod mill consist of both preventive and corrective maintenance actions. Testing the model was carried out with real cost data and numbers, but as requested by the case companies, the numerical results are not presented here. That is why the following figures only present simplified results without specific numerical values. The input data included cost information (maintenance costs, material costs, subcontracting costs, and maintenance losses), equipment information (production, utilization rate, profit margins) and data of preventive and corrective maintenance actions from the past five years. The input data of the future includes the same information in the next five years. The information is based on estimates and views of the future.
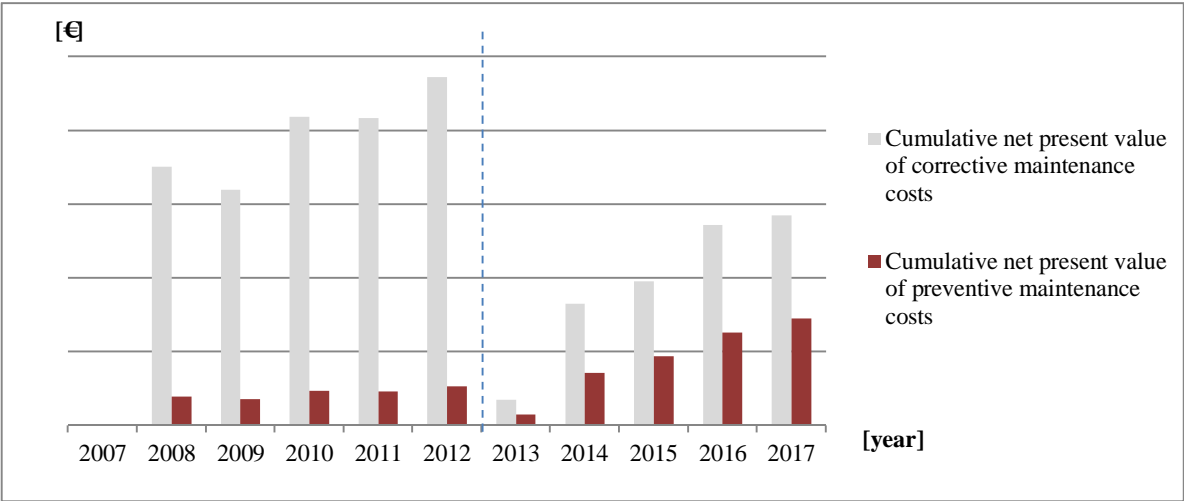
Figure 5. Cumulative net present values of customer maintenance costs

The cumulative net present values of customer maintenance costs can be seen in figure 5. During the last five years, the maintenance costs of the rod mill have mainly consisted of corrective maintenance actions. This may have had a raising effect on the total maintenance costs. That is why the company should concentrate more on preventive maintenance actions in the future. This way, the company will be able to improve the utilization of the device and to reach cost savings, because preventive maintenance is usually cheaper than corrective maintenance actions. Therefore, increasing preventive maintenance in relation to corrective maintenance, the customer company will be able to increase the total profits of equipment. However, the company will have this possibility to reach better profits only if they can utilize

all the stoppages and downtime to conduct preventive maintenance. All in all, this change can be seen as a raising trend of preventive maintenance in figure 5.

During the research it was discovered that profits can be reached by optimizing the maintenance actions and improving the utilization of the item. The cumulative net present values of maintenance net profits from both the customer's and service provider's point of view can be seen in figure 6. The past five years have been unprofitable because the operation of the item has not improved from the maintenance point of view. In addition, the share of maintenance of the maximal production time has been 10 percent each year. It is assumed that the investments in preventive maintenance seen in figure 5 will increase the effectiveness and utilization of the device. This enables the customer to reach better profits in the upcoming five years (see figure 6), even though there will be two big maintenance stoppages: in 2014 and 2016.

The better profits are possible not only for the customer but also for the service provider company. The service provider will benefit from the decreasing amount of corrective maintenance, because they will then be able to plan their maintenance actions better. This way the service provider will get the better margins from maintenance operations. In addition, the maintenance operations planned in advance allow the service provider to use their resources more efficiently. To reach more profits, the customer and the service provider must co-operate. The plans for item maintenance need to be done together, at least for two or three years forward. In long-range planning it is possible to define the needed maintenance actions for the upcoming years, and this way better reliability of the rod mill can be guaranteed.
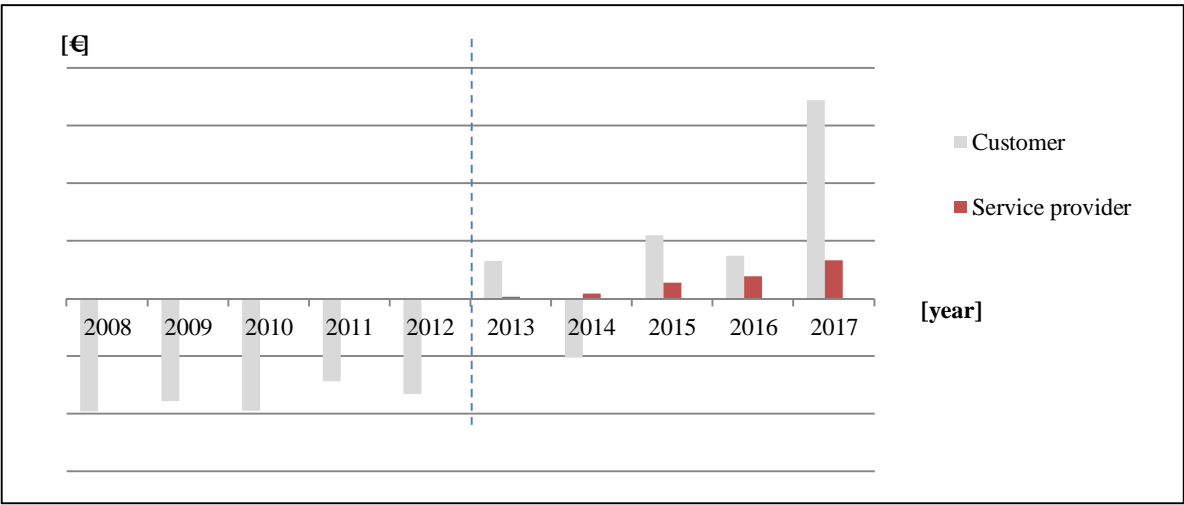
Figure 6. Cumulative net present values of maintenance from the customer's and service provider's point of view

In long-term planning, it is also important to find the optimal balance between maintenance costs and maintenance losses. Therefore, the benefit-cost ratio is a suitable indicator for analyzing the balance between costs and profits. Focusing too much on optimizing the maintenance actions may also increase the risks. This may lead to a situation where the costs of item maintenance are bigger than the received profits. That is why the benefit-cost ratio is a rational indicator for planning and controlling the total costs and profits of maintenance operations. In figure 7 it can be seen that the benefit-cost ratio values have been at a low level from both the customer's and service provider's point of view. It is assumed that the investments in preventive maintenance will increase the profits of equipment in the future.

Therefore, the costs of maintenance will decrease or at least stay at the current level. Based on this, the benefit-cost ratio will increase in years 2013-2017 (figure 7). In some years (like 2014 and 2016) the benefit-cost ratio may decrease considerably, because big maintenance actions will be carried out in these years. However, the long-term maintenance actions should result in increasing profits, and therefore improved benefit-cost ratio in the future.
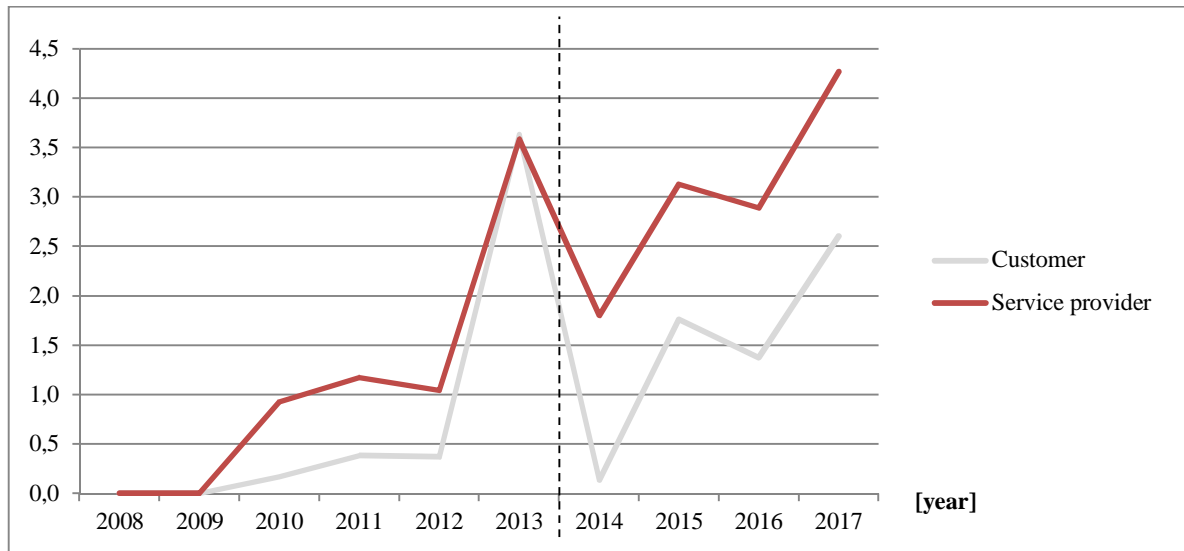
Figure 7. Benefit-cost ratio of maintenance from the customer's and service provider's point of view

Working in a network, it is usual that the achieved profits are divided in an unfair manner among the network members. In many situations, the customer company receives most of the increased value, whereas the service provider usually gets nothing. That is why it is important to think how the increased value can be distributed fairly among all network members. For example, the customer would be able to pay some kind of a bonus to the service provider when the availability of the item stays at the agreed level. In the rod mill case, let us assume that the customer pays a 10 percent bonus to the service provider each year during 2013-2017. After that, the service provider company would still receive only 15 percent of the total increased value of the network, whereas the customer would get almost 85 percent of the increased value of the inspection period. In the future, these kinds of models could be useful not only to support decision-making situations but also to analyze the distribution of increased value among the network members.

5 Conclusions

The purpose of this study was to create a general life-cycle model for maintenance decision making in different industries at the item level. Our first research question aimed at uncovering the structure for a model that takes the perspectives of different maintenance network members into account. Previous life-cycle models have mostly addressed the perspective of just one company, but our model connects these perspectives of different maintenance network members (customer, service provider and equipment provider) together in a new way. Each network member is able to input their own cost and profit data related to the maintenance services of one item. As a result, the model calculates the net present values of maintenance costs and profits and presents them from the points of view of all network members.

Our second research question aimed at uncovering the integration of value into the model. The user can choose one to five important value elements and weight the elements based on his perspective and thoughts in this particular maintenance service case. The model gives numerical values to the value elements, which can be then used as a basis for contracts and bonus systems between the network members.

The third research question aimed at uncovering the results generated by the model to be used in decision making. The model can be used either as a tool at the network level or separately in each company. The users can use the model for forecasting the future or analyzing the past. This model is also suitable for small companies for building active networks to offer outsourcing services for large companies. Traditionally, each network member has considered the created value only from their own point of view. The new approach in this study is examining the value from different maintenance network members and to connect these views to improve the benefits of the whole network. In this case study we have illustrated that by using the model for the better planning of preventive and corrective maintenance, both network members could increase their profits.

Working together with the case companies convinced us that there is a real need for a long-term planning tool of maintenance services. Maintenance costs are usually a notable part of the life-cycle costs of an item, and it is important to be able to plan the future maintenance operations for the strategic period of the company or for the whole life-cycle period of the item.

The presented life-cycle model has been developed in process industry and it does not yet take into account different manners of production, such as batch or serial production. The model must also be tested in other lines of business than mining, before it can be called a general model. The next step in further research is to improve the presented model by using the feedback received from the tests. This improved and expanded version of the model will be further tested in an energy network and also together with the authors' research partners in Sweden. It will be interesting to find out how the line of business, the size of the company or types of maintenance affects the value elements used in the model. It will also be interesting to find out the importance of the elements in different maintenance situations.

References

Barringer, H.P. (2003) ´A Life Cycle Cost Summary´, *International Conference of Maintenance Societies.* May, 20-23, 2012, Perth, Australia.

Blanchard, B.S. and Fabrycky, W.J. (1998) ´Systems engineering and analysis´ 3rd edition. Upper Saddle River, New Jersey. Prentice Hall. 738 s. ISBN 0-13-135047-1.

Dorf, R.C. 2004. The Engineering Handbook, Second Edition. [web document]. In the book Fabrycky, W.J. & Blanchard, B.S. 1991 (Eds.): *Life-Cycle Cost and Economic Analysis*. CRC Press. eBook ISBN 978-1-4200-3987-0. [referred 11.9.2012]. http://www.crcnetbase.com/doi/pdf/10.1201/9781420039870.ch209

Gokiene, R. (2010) ´Marginal Break Even Between Maintenance Strategies Alternatives´, *Engineering Economics*, Vol. 21, No. 2, pp. 136-141.

Gómez, J.F., Parra, C., González, V., Crespo, A. and De León, P.M. (2008) ´Outsourcing maintenance in service providers´, *Joint ESREL (European Safety and Reliability) and SRA-Europe (Society for Risk Analysis Europe) Conference*, September, 22-25, 2008, Valencia, Spain.

Hochschorner, E. and Noring, M. (2011) ´Practitioners´use of life cycle costing with environmental costs - a Swedish study´, *International Journal of Life Cycle Assessment*, Vol. 16, No. 8, pp. 897-902.

Idhammar, C. (2009) ´Cut costs or improve reliability?´ *Pulp & Paper International*, Vol. 51, No. 4, pp. 27-29.

Jun, H.K. and Kim, J.H. (2007) ´Life Cycle Cost Modeling for Railway Vehicle´, *International Conference on Electrical Machines and Systems,* October, 8-11, 2007, Seoul, Korea.

Kayrbekoya, D., Markeset, T. and Ghodrati, B. (2011) ´Activity-based life cycle cost analysis as an alternative to conventional LCC in engineering design´, *International Journal of Systems Assurance Engineering and Management*, Vol. 2, No. 3, pp. 218-225.

Knights, P.F., Louit, D. and Lay, A. (2004) ´Determining return on investment of maintenance projects using statistical cost modeling´, *Mining Engineering*, Vol. 56, No. 8, pp. 33-39.

Korpi, E. and Ala-Risku, T. (2008) ´Life cycle costing: a review of published case studies´, *Managerial Auditing Journal*, Vol. 23, No. 3, pp. 240-261.

Kumar, R. and Markeset, T. (2007) ´Development of performance-based service strategies for the oil and gas industry: A case study´, *Journal of Business and Industrial Marketing,* Vol. 22, No. 4, pp. 272-280.

Lad, B. K. and Kulkarni, M.S. (2012) ´Optimal maintenance schedule decisions for machine tools considering the user´s cost structure´, *International Journal of Production Research*, Vol. 50, No. 20, pp. 5859-5871.

Lindholm, A. and Suomala, P. (2007) ´Learning by costing – Sharpening cost image through life cycle costing?´, *International Journal of Productivity and Performance Management*, Vol. 56, No. 8, pp. 651-672.

Navarro-Galera, A. and Ortúzar Maturana, R.I. (2011) ´Innovating in defence policy through spending efficiency: The Life Cycle Costing Model´, *Journal of Policy Modeling*, Vol. 33, No. 3, pp. 407-425.

Sinkkonen, T., Kivimäki, H., Marttonen, S. and Kärri, T. (2013A) ´A value-based life-cycle framework for networks of industrial maintenance service´, *The 26th International Conference on Competitiveness Through Maintenance and Asset Management*, June, 11-13, 2013, Helsinki, Finland.

Sinkkonen, T., Marttonen, S., Tynninen, L. and Kärri, T. (2013B) ´Modelling costs in maintenance networks´, *Journal of Quality in Maintenance Engineering*, forthcoming, Vol. 19, No. 3

Tynninen, L., Sinkkonen, T., Marttonen, S. and Ojanen, V. (2012) ´Framework for the value elements of maintenance service´ *The 2nd International Conference on Maintenance Performance Measurement & Management*, September, 12-13, 2012, Sunderland, UK.

Waghmode, L.Y. and Sahasrabudhe, A.D. (2012) ´Modelling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems´, *International Journal of Computer Integrated Manufacturing*, Vol. 25, No. 4-5, pp. 353-367.

Wang, Z. and Xu, X. (2009) ´SVLC: Service value life cycle model´, *IEEE International Conference on Cloud Computing*, September, 21-25, 2009, Bangalore, India.

Corporate asset management – a semi-quantitative business-driven approach for evaluating improvement options

Helena Kortelainen*, Minna Räikkönen and Kari Komonen

VTT Technical Research Centre of Finland
P.O. Box 1300, FIN-33101 Tampere
Finland
*Corresponding author: Helena Kortelainen
e-mail: helena.kortelainen@vtt.fi
e-mail: minna.raikkonen@vtt.fi
e-mail: kari.komonen@saunalahti.fi

Abstract

The corporate asset strategy determines whether assets should be enhanced by capital investment, maintained to upkeep their position or disposed. Thus, the corporate asset strategy connects corporate objectives to the available production technology, and consequently, the production asset base has to be developed to support the company´s objectives. Even it is evident that physical assets are key elements in bringing the corporate strategy into action many asset owners still don't couple asset management with corporate strategy.

This paper examines the influence of the market demand and competitive situation to the asset management decisions, especially operative investment decisions in the capital intensive manufacturing industry. It proposes a practical semi-quantitative approach to support the business-driven asset strategy decisions. The empirical research was carried out in co-operation between researchers and companies. The results indicate that a systematic strategy oriented analysis can be successfully combined to the corporate asset management decisions.

Key words: Asset management, investment, strategy, market demand, competitive situation, risk, uncertainty

1   Introduction

Capital intensive companies are typically large and globally operating corporations that produce industrial intermediates in several locations and plants. The companies could be characterized as process- and product-driven, representing for example, pulp and paper, metal and process industry, and energy production. The branch is also characterized by the fact that sizeable investments are needed to maintain the production efficiency of the physical assets and to create competitive edge. Due to global restructuring of manufacturing industry and markets, the importance of strategy view on asset management has increased among companies operating in the capital intensive industry.

Corporate-level strategy relates to the product and market choices of a firm (Hatten et al., 1978) and describes the way it will pursue its goals given the threats and opportunities in the environment and its resources and capabilities (Rue and Holland, 1989). Komonen et al. (2012) define 'Corporate asset management' as the process from strategic planning through asset management activities to ensure business continuity at the corporate level. The corporate asset strategy is a driver for the operative investment portfolio and the strategy should help to decide which assets are enhanced by capital investment, maintained to upkeep their position or disposed. Thus the asset strategy connects corporate objectives to the available production technology (Komonen et al., 2010a). Even it is evident that physical assets are a key element that turns the corporate strategy into action many asset owners still do not couple the strategic asset decisions and evaluation of operative investments with the corporate strategy (Nource and Roulac, 1993; Tranfield et al., 2004). As a result very little attention has been paid to the research in this area and no comprehensive theory or practical solutions appear to exist.

In several industrial branches one of the key limitations to the strategy formulation and implementation is the difference between the ever shortening market life of products and relatively long life cycle of production systems. Some authors (e.g. Teece et al., 1990; Tranfield, 2004) describe this difference as ´stickiness´ of production assets: *"…resource endowments are "sticky": over any strategically relevant time frame, firms are stuck with what they have and must live with what they lack"* (Teece et al., 1990, p.7). The profits of an investment have to be earned during its economic life cycle (Suomala, 2004). Thus, understanding the constraints given by the production technology and the risks associated to the market life of products is crucial to the any effective strategy. We are convinced that market dynamics should be regarded as a key driver in the corporate asset management decisions and that the insight to the current and future market demand and situation as well as competition position of the company should be analyzed under the constraints given by the available production technology.

It is generally accepted that investment decisions are the most important decisions made by corporations (Harris and Raviv, 1996) As a consequence the revenue focus on planning often distracts attention from investments in productivity, replacement and maintenance, as well as from minor capacity expansions in existing business. We argue that in narrowly defining the view on which investments are worth optimising, companies may miss out huge opportunities to improve performance with moderate expenditure and risk.

In capital-intensive industries, the time horizon for the planning and evaluation of asset decisions is very long, even decades. Investment decisions are always made under uncertainty (Nowak, 2005; Piyatrapoomi et al., 2004) and there is significant uncertainty involved in all estimates of trends and major risks identified. The returns of an investment can be uncertain due to technical and production related factors, as well as to multiple market-related factors, such as the cost of raw materials, varying demand, or competing products. If uncertainties are not included in the evaluation process, a company is likely to fail to make the right strategic choice, which may result in loss of the market share and profits (Sihl and Allada, 2007). Even in uncertain business environment, total risk avoidance is a dangerous. Sadgrove (2005) illustrates the relation between risk taking and return with a citation: *"Our strategy is to accept more risk – calculated risk - in order to improve returns. This is being implemented by developing a portfolio of businesses, with a variety of risks and rewards, and continuing to exit from any high risk, low reward business."*

Risk analyses are clearly an underestimated part of strategic asset formation (Komonen et al., 2010a).

A considerable amount of research has been carried out in the area of investment appraisal (see e.g. Ahlmann, 2002; Dayananda et al., 2002; Götze et al., 2008; Harris and Raviv, 1996; Kettunen 2009; Nowak, 2005; Pike and Neale, 2003; Proctor and Canada, 1992; Shil and Allada, 2007). Furthermore, there have been many papers and published literature in relation to maintenance and manufacturing strategies and strategic processes, connections between manufacturing and maintenance strategies as well as linkage of these functional strategies to the corporate, business and marketing objectives (see e.g. Cooper et al., 2001; Hill, 1985; Jonsson, 1997; Kaplan and Norton, 1992; Pinjala et al., 2006; Porter, 1985; Robson et al, 2013; Skinner, 1969). However, research has tended to focus either on investment appraisal or linkage between strategies and to external environment rather than focusing on asset decisions and related investment decision-making e.g. how to link strategy, market and competitiveness considerations into decision-making and into evaluation of operative investments and improvement options. One reason is that analytical and normative models already developed to aid asset management related investment decisions are often too theoretic and complicated to be used in a practical context. In addition, methods do not typically link operative investment decisions to a strategic context which means that results of strategic analysis and financial analysis are examined and used separately. (see e.g. Hastings, 2009; Mather, 2005; Millet and Wedley, 2002; Tavana, 2002; Wilson, 2002; Yurdakul, 2004). As a result, companies in capital-intensive industry lack of adequate systematic approaches to combine market information to individual investment decisions and technological constraints, and methods and tools should be developed to facilitate defining and selection of strategic options in order to meet market requirements and to assess risks involved.

2   Research questions and methodology

The aim of this paper is to contribute to the understanding of the importance of combining strategy, market and competitiveness considerations into business-driven asset strategy decision-making and into evaluation of operative investments on production assets. The underlying research questions are:

- *how to combine strategy, market and competitiveness considerations into the corporate asset management decisions to estimate economic life cycle of an investment?*

- *how to elucidate business environment related uncertainty and risk in the context of investment decisions?*

In this paper we propose a practical semi-quantitative approach for covering the influence of various business environments, planning horizons and uncertainty aspects on corporate asset decisions. The focus is laid on market-related risks, which are characterized by the asset owner´s decision situation: *Which products could be profitable to us in the future? Are we competitive in the chosen market?*

This research paper is based on the research carried out in the time frame 2006–2008. During the research, the investment evaluation model and software application that support the evaluation of investment portfolios were developed, tested and validated. The work was carried out in co-operation between the researchers and four large companies from different sectors of capital-intensive industry (i.e. forest, chemical and oil refining industries) in Finland. (see e.g. Heikkilä et al., 2011; Komonen et al., 2010b, Komonen et al., 2012; Räikkönen et al., 2010).

Constructive research was chosen as the main research methodology, largely for practical reasons. According to Kasanen et al. (1991), finding a practically relevant research problem, obtaining a general and comprehensive understanding of the topic, and innovating and constructing a theoretically grounded solution are crucial steps in the constructive research approach. Although a relevant research problem can be discovered from a purely theoretical basis, it is more common to find actual research issues from premises of existing real-world business demands (Aaltonen et al., 2006; Labro and Tuomela, 2003).

Content analysis was used to examine and compare past and present methods of evaluation of operative investments and to discuss the different aspects of decision-making and uncertainty management in this context. In the final stages of the constructive research approach, the developed solution should be evaluated and tested through an examination of its applicability and though an illustration of its theoretical connections and research contribution (Aaltonen et al., 2006; Kasanen et al., 1991). During our research, thematic group discussions were arranged and facilitated by the researches in order to test and validate the developed approach as well as to gather ideas for further development. The participants were experts in their own competence area and the input data needed to test the method was mainly based on the subjective estimations of experts (expert judgement analysis). Lessons learned from the thematic group discussions were combined with findings from the literature to finalize and complete our method. The actual method development was based on problem solving and solution building.

3 Background for the method development

An essential part of asset management related decision-making process is the evaluation as it provides a link between the generation of decision proposals and the actual decision. Various aspects should be taken into account when combining strategy, market and competitiveness considerations into evaluation of operative asset management related investments. In other words the evaluation should include the assessment of uncertainties and cover both quantitative and qualitative factors.

Methods for evaluating investments can be classified into different categories like financial assessment, alignment with the business strategy, scoring models and checklists (see e.g. Cooper et al., 2001). It is worth noting that no method covers all aspects and a variety of approaches should be used. Figure 1 comprises all the aspects and analysis of our research within the asset management decision-making process. The practical semi-qualitative method suggested in this paper is integrating the strategic alignment and financial evaluation aspects, but is not covering the whole decision-making process. The positioning of this paper is presented in the following figure.
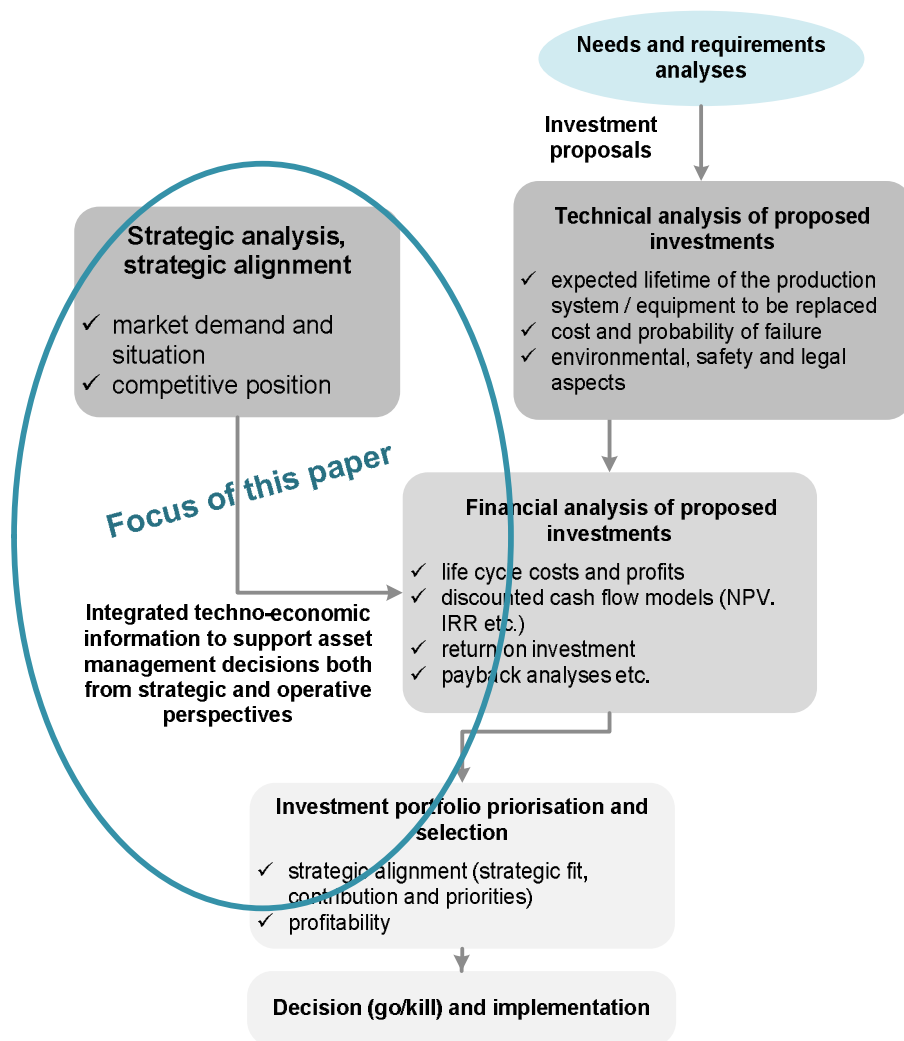
Figure 1. Integrated business-driven approach - linkage of strategic analysis into financial and economic evaluation of investments and investment portfolios

In practice, results generated by different evaluation methods should be used as a guide rather than as the sole basis for the approval or rejection of specific investment alternatives. Decision makers should also understand the key assumptions behind the evaluation. A major challenge in the early phases of the decision-making process is the vast amount of inadequate data. It is essential that the evaluation methods applied are in line with the quality and amount of data available. Used wisely, however, evaluation methods and tools are of help to companies making asset management related decisions. Next, we present briefly the methods and theories which inspired and supported our method development.

In our business-driven approach, *market and competitor related analyses* (see e.g. Bradley, 2007; Cooper et al., 2001; Emblemsvåg and Kjølstad, 2002; Godet, 2000; Homburg et al., 1999; Huff and Jenkins, 2002; Kaplan and Norton, 1992; Kotler, 1997; Porter, 1985) comprise the basis for internal company analyses and positioning of a company and its products and for assessing risk and uncertainty related to market and competitive environment. These analyses address also

corporate asset management issues like trends in product demand/future capacity needs, competitive environment of products, asset related barriers to new entrant, uncertainty and volatility of demand, and regulatory acts. Consequently, our method follows mainly *the Analytical Hierarchy Process (AHP)* (Saaty, 1980). Another possible and widely used method for this kind of problems could have been multi-attribute utility theory (Keeney and Raiffa, 1996). However, we chose the AHP (see Saaty, 1980) since it provides a flexible and easily understood way of analysing complicated problems. AHP allows subjective as well as objective factors to be considered in the decision making process and it can handle factors that may be conflicting. Additionally, AHP forms a systematic framework for group interaction and group decision making.

The concept of Stacey (1990) was utilized during our method development to demonstrate uncertainty of the future business environment. The scenarios are referred to as stable (closed future), predictable (contained future) and turbulent (open-ended) (see Figure 2). This division gives the executives a better understanding of the uncertainty involved in different asset management options.
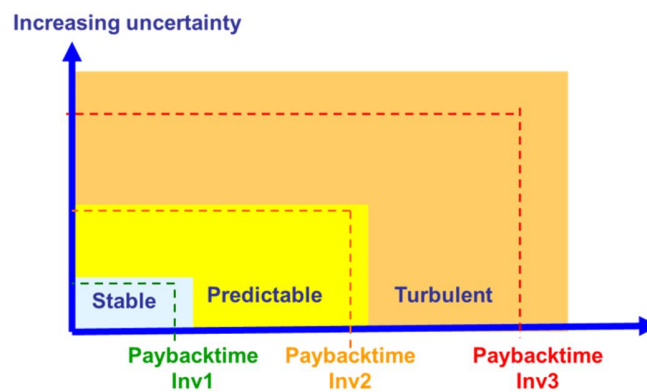
Figure 2. The time horizon and uncertainty according to the concepts of Stacey (1990)

When making analyses addressing product demand/future capacity needs, competitive environment and uncertainty, it also necessitate input data. *Brainstorming and expert workshops* are widely used to overcome the lack of information by exploiting and combining the different types of expertise and knowledge of the participants. The participants must be carefully selected to cover all relevant views and fields of expertise in the examined system or issue, and there are a number of formal methods for eliciting expert judgment, which provide an aid to the formulation of appropriate questions (e.g. IEC/ISO Risk management – Risk assessment techniques 31010:2009).

The next chapter describes in detail the suggested approach for covering the influence of various business environments, planning horizons and uncertainty aspects on corporate asset decisions.

4   Key findings – a business-driven approach for evaluating improvement options

Our approach of business-driven evaluation of improvement options is a decision-supporting method for use in groups, primarily during the early phases of the investment decision-making process. In order to meet the expert competence requirements, the analysis should be carried out in an expert session as a common exercise of the production and marketing departments (Komonen et al., 2012).

The approach consists of strategic market and competitive analyses which summarize the evaluation of the market demand trend and the competition position of the company, as well as specifying the additional capacity that can possibly be sold on the market. Both market and competitive analyses are semi-quantitative by nature. The analysing tool was realized using Microsoft Excel 2010 (Figure 3). In both analyses, the steps are as it follows:
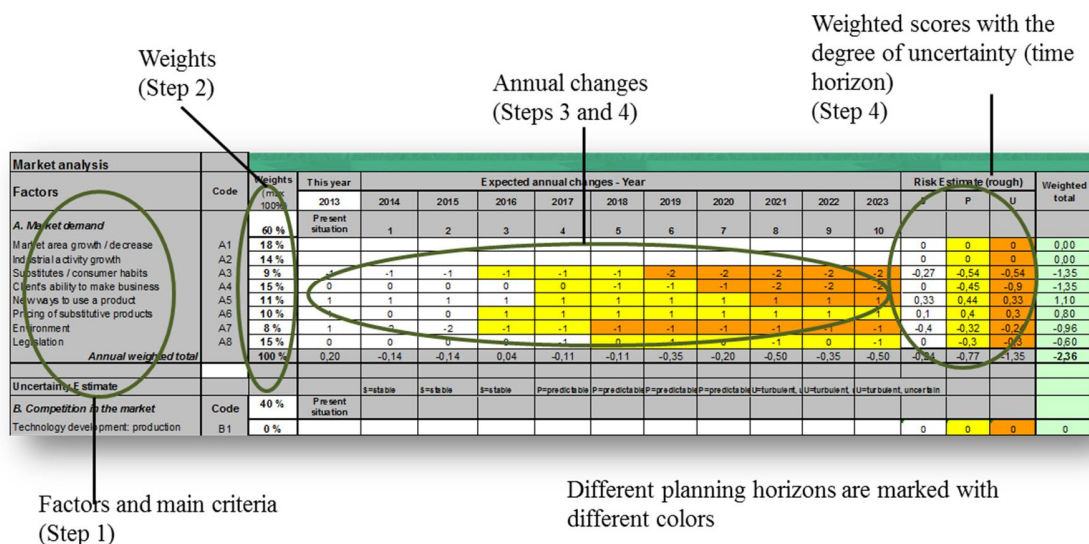
Figure 3. Extract from an MSExcel-analyzing tool

Step 1. Identifying and selecting the factors that are relevant for the company and/or for the product line in question

The initial factors for assessing market and competitive situation in the capital-intensive industries represent a combination of the insights dealing with the future prospects and knowledge of the persons who participated in the project, the results of the literature review and the researchers' own knowledge and experience. The market analysis and the competitive analysis tools both comprise two main criteria. Each of these criteria includes several pre-defined factors that will be later weighted and evaluated during the process. These pre-defined factors are summarized in the following table.

Table 1. Pre-defined factors for the market and competitive analyses

Market analysis	Competitive analysis
A. Market demand (main criterion)	**A. Competitive position** (main criterion)
Factors: Market area growth / decrease Industrial activity growth Substitutes / consumer habits Client's ability to make business New ways to use a product Pricing of substitutive products Environment Legislation	*Factors:* Market share New market impact New features available New ways to use available Coverage of various market segments Product itself Scale economies, volume Flexibility Environment
B. Competition in the market (main criterion)	**B. Economic performance** (main criterion)
Factors: Technology development: production Economic barriers Technology barriers Purchasing behaviour Capacity decrease/growth in the market: total supply Market size, demand Sources of differentiation, product Sources of differentiation, operations Cost competition	*Factor:* Cost competitiveness

In addition to the factors presented in the table above, the expert panel is allowed to add new factors as well as modify and delete the pre-defined factors.

Step 2. Defining the main criteria and factor weights

Multi-criteria decision-making techniques require the determination of a set of weights that reflect the relative importance of various competing objectives. The AHP approach is used to determine the weights of the independent components of the decision hierarchies. The underlying objective is to establish relative weights for the main criteria and factors by means of pairwise comparison. The method used in our business-driven approach is derived from the work of Saaty (1980) who proposed the use of the verbal descriptions and the corresponding scores in making the comparisons (see Table 2). Generally, the more critical a factor is in relation to any other, the more weight it should be given.

Table 2. Saaty's scale for pairwise comparison

Scale	Description	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very Strong importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Extreme importance	The importance of one over another affirmed on the highest possible order
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

We utilise expert judgements to assist in the weighting of the main criteria and factors of the market and competitive analyses. The group started the evaluation process by comparing pairwise the mutual importance of the criteria and factors. Weighting means on the other hand, in both analyses, the importance of two main criteria in relation to each other and on the other hand, the importance of each factor in relation to the other factors within the same criterion. The relative weight over all main criteria has to add up to 1. In the same way, the relative weight over all factors within one main criterion has to add up to 1. The priorities are compared pairwise in line with Saaty's scale, and compiled in a pairwise comparison matrix (see example Market demand Table 6).

Table 3. An example of the pairwise comparison of the pre-defined factors under main criteria market demand

Main Criterion: Market Demand	Market area growth / decrease	Industrial activity growth	Substitutes / consumer habits	Client's ability to make business	New ways to use a product	Pricing of substitutive products	Environment	Legislation	Weight	Relative Weight	
Market area growth / decrease	1	2	8	1/9	4	5	7	1/4	1,42	0,18	18 %
Industrial activity growth	1/2	1	1/3	4	6	1/3	2	5	1,15	0,14	14 %
Substitutes / consumer habits	1/8	3	1	1/3	1/4	7	1/3	1/2	0,71	0,09	9 %
Client's ability to make business	9	1/4	3	1	1/7	9	1/4	1/5	1,19	0,15	15 %
New ways to use a product	1/4	1/6	4	7	1	1/3	5	1/8	0,89	0,11	11 %
Pricing of substitutive products	1/5	3	1/7	1/9	3	1	1/3	4	0,86	0,10	10 %
Environment	1/7	1/2	3	4	1/5	3	1	1/2	0,61	0,08	8 %
Legislation	4	1/5	2	5	8	1/4	2	1	1,17	0,15	15 %
Sum	15,2	10,1	21,5	21,6	22,6	26,0	18,0	11,6	sum=8	sum=1	100 %

Step 3. Determining expected annual changes (scores) to each pre-defined factor

The next step is to evaluate the factors in accordance with expert judgment. In order to increase the objectivity of the evaluation, the factor scoring is based on a fixed system. The scores are connected to the expected annual changes of each defined and selected factor. These annual values describe the magnitude of changes. The scale for values is integers between -3 and 3 and the examples of the levels for integers are presented in the table below.

Table 4. An example of an annual change scale

Market analysis	Competitive analysis
Example of a scale	Example of a scale
+3 = 6 % annual growth	+3 = 3 % annual growth
+2 = 4 % annual growth	+2 = 2 % annual growth
+1 = 2 % annual growth	+1 = 1 % annual growth
0 = -1% - + 1% annual growth	0 = no annual growth/ decline
-1 = 2 % annual decline	-1 = 1 % annual decline
-2 = 4 % annual decline	-2 = 2 % annual decline
-3 = 6 % annual decline	-3 = 3 % annual decline

For example, change in market demand and/or competitive position gives some indication of viable strategies and decisions. If demand is growing (fast) and the competitive position of the company is strong, the company is able to stay in the market longer than its competitors and perhaps even when the market is decline. In this position, well-implemented investments are profitable and the payback time is shorter than the life cycle (Komonen et al., 2012).

Step 4. Evaluating the uncertainty (time horizon) with the help of the given annual values (scores)

The developed approach for market demand and situation as well as for competitive position estimation takes into account uncertainty horizons denoted as stable, predictable and turbulent according to Stacey (1990). The expert panel evaluates the degree of uncertainty (time horizon) with the help of the given scores (e.g. see Figure 3: white colour denotes a stable planning horizon, yellow a predictable horizon and orange a turbulent horizon). Multiplying the weights and the scores of different time horizons gives the profile for each factor (i.e. weighted scores). The results can be presented in the forms of tables and graphs, for example (Figure 4).
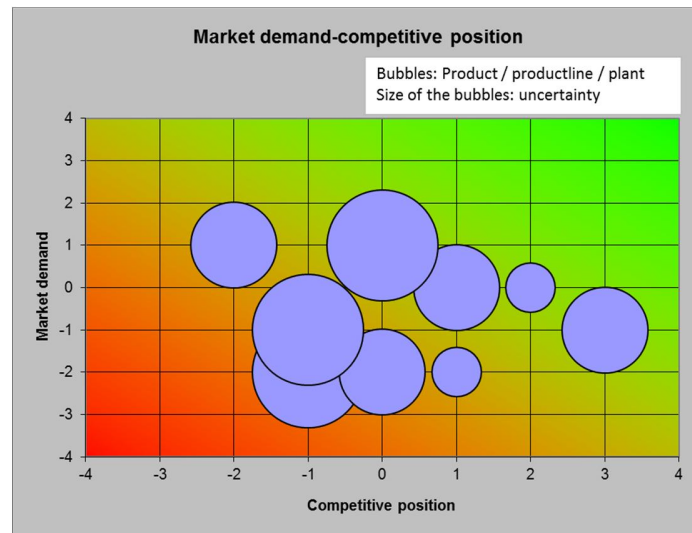
Figure 4. An example of the graphical results generated by the developed method and tool - market demand-competitive position matrix

The result of the market and competitive analyses summarize the evaluation of the market demand trend and competitive position of the company. Figure 5 shows a simple example of how to integrate the evaluation results with the length of a lifetime of an investment. For example, if both the trend of market demand and the competitive position of the company are strong, the lifetime which is suggested by the method to be used in the investment evaluation is 10 years. Thus, the life cycles of the different business and geographical areas are taken into consideration in investment calculations. The semi-quantitative evaluation of the market and competitive environment integrates the corporation's strategic objectives into the investment appraisal method.

**Economic lifetime to be used
in financial investment
evaluation (years)**

Strong	6	6	10	10	10	10	10
	6	6	6	10	10	10	10
	3	6	6	6	10	10	10
Market Demand	3	3	6	6	6	10	10
	3	3	3	6	6	6	10
	3	3	3	3	6	6	6
Weak	3	3	3	3	3	6	6

Weak   Strong

**Competitive position
of the company**

Figure 5. Impacts of market demand and competitive position to the economic lifetime to be applied in the economic evaluation of investments (adapted from Heikkilä et al. and Räikkönen et al., 2010)

To summarize, by using the result of the developed analysis method and the tool, the length of an economic life cycle to be used in the investment evaluation can be defined. Typically companies are using almost as a default "lifetime of 10 years" for production system and equipment in investment calculations. However, it can sometimes be misleading and even give unreliable results as the lifetime applied in investment calculations can have a significant impact on the profitability of the investment and investment portfolio. This is also why it is important to pay a special attention to the determination of length of a life cycle used in calculations and more co-operation is needed in companies between technical and financial experts than at present.

Limitations of the research and areas for further investigation

In this paper the focus is laid on market-related risks, which are characterized by the asset owner´s decision situation. However, the work carried out in the research project covered also the technical and financial analyses of the investment proposals like evaluation of replacement investments and development investment, and investment portfolio selection, as sketched in the Figure 1. The methodological framework and tools for evaluation of investment options will be presented in a forthcoming paper.

5   Conclusions

Asset management has often been considered to be business-driven maintenance. In our work we have adopted a wider scope of corporate asset management that is a process from strategic planning through asset management activities to ensure business continuity. In capital intensive industries, the constraints and limitations due to the production technology and existing production assets have to be taken into consideration when making decisions on business goals. However, in order to ensure business continuity in the long run, market dynamics should be a key driver in the corporate asset management decisions.

In this paper, we describe a practical semi-quantitative approach for covering the influence of various business environments, planning horizons and uncertainty aspects on corporate asset decisions, and present tools to support company decision-making. The method was developed in close co-operation between researchers who were responsible for the sound theoretical background and experts in industry who brought their domain competence to the development work. Methods and theories which inspired and supported our method development were, for example, strategic alignment methods, AHP, expert judgment and the concept of Stacey related to the time horizon and uncertainty. The interactive collaboration model proved to be fruitful and the direct feedback from thematic group discussions were immediately utilised in the method development.

The developed business-driven approach offers the asset managers in capital intensive industries a tool to evaluate market demand and competitive environment. The analysis of the market demand and competitive position of a product, product group or a plant and the corresponding growth/decline rates guides the decision maker in asset related decisions. Consequently, the result of the market and competitive analysis aids the decision-maker in defining the length of an economic lifetime to be used in the investment evaluation. The lifetime applied in investment calculations can have a significant impact on the profitability of the investment and investment portfolio. Thus, the detailed information on lifetime to be used as an input in investment calculations may be crucial, for example, in case the market life of a product differs significantly from the technical lifetime of the production assets. This is also where more co-operation between technical and financial experts in companies is needed than at present.

The proposed approach attempts to help the decision maker also to evaluate the uncertainty and risk related to asset decisions. The risk assessment is carried out by an expert panel that evaluates each market and competitiveness related factor with the different planning horizons: stable, predictable and turbulent. The experts are given the values for annual changes, i.e. integers between -3 and 3, for different planning horizons. Based on annual values, different time horizons and factor weights, the weighted scores are calculated by the tool. The weighted scores also indicate the uncertainty involved. The results are shown both numerical and graphical form. From the decision maker´s point of view the derived information is valuable contribution as it improves the transparency of the investment decisions and improves risk-awareness of decisions.

However, some challenges are inherent to the methods applied. Special considerations must be made regarding the expert judgement and expert panels. There are some generally recognised problems in expert judgment, for example, subjectivity and overconfidence of the experts. Consequently, there is a danger that someone is dominating the panel and that all the important aspects and factors to need be evaluated by the panel are not taken into account at all. Thus, the coverage of the expert group and competence of the experts is of prime importance. When applying the business-driven approach, insights from the product marketing and sales and knowledge of the relevant production technologies should be made available and expertise of production and marketing/sales departments are needed.

As with any empirical research, our model cannot be interpreted without taking into account its limitations. The research already made brought a good insight to the subject of the paper but the depth of the research was quite limited and the developed method is so far tested in one industrial

setting. Accordingly, all important viewpoints might not have come up in the research, and our method may therefore not cover all the important aspects of linking strategy, market and competitiveness considerations into the corporate asset management decisions and evaluation of operative investments. However, we believe that the method developed fulfils its intended purpose as a strategic analysis method in the context of strategic asset management and related decision-making.

Finally, it is important to notice that investment decisions are significant decisions to all firms and available investment options should be evaluated carefully from several points of view and with a variety of methods. The elements of the business-driven approach presented in this paper contribute to practical decision making by demonstrating the evaluation of market-related factors and by offering a method to evaluate economic life a product or a product line. Structured process and systematic corporate level tools enhance the transparency of company decision-making, support working group processes and are able to handle multi-faceted situations with uncertainties.

References

Aaltonen J., Rinne J., Tuikkala I. A. (2006) Multidisciplinary Framework for Concept Evolution: A Research Tool for Developing Business Models. *Global Conference on Emergent Business Phenomena in the Digital Economy*. Tampere, Finland, 28 November – 2 December 2006.

Ahlmann, H. R.(2002) From Traditional Practice to the New Understanding: The Significance of Life Cycle Profit Concept in the Management of Industrial Enterprises. *IFRIM Conference,* Sweden, 1–16.

Bradley, N. (2007) *Marketing Research: Tools and Techniques,* Oxford: Oxford University Press.

Cooper, R., Edgett, S. J. and Kleinschmidt, E. J. (2001) *Portfolio Management for New Products.* Perseus Books Group; Basic Books, New York.

Dayananda D., Irons R., Harrison S., Herbohn J. and Rowland P. (2002) Capital Budgeting: Financial Appraisal of Investment. Cambridge University Press.

Emblemsvåg, J. and L. E. Kjølstad (2002) Strategic Risk Analysis - a Field Version. *Management Decision*. Vol. 40, No. 9, pp. 842-852.

Godet, M.(2000) The Art of Scenarios and Strategic Planning: Tools and Pitfalls. *Technological Forecasting and Social Change* 65, 3–22.

Götze U., Northcott D. and Schuster P. (2008) Investment Appraisal: Methods and Models. Springer-Verlag: Berlin–Heidelberg.

Harris, M and Raviv, A. (1996) The Capital Budgeting Process: Incentives and Information. *The Journal of Finance*, Vol. 51, No. 4., 1139–1174

Hastings, N.A.J.(2009) *Physical Asset Management.* Springer Verlag London.

Hatten, K.J., Schendel, D. and Cooper A. (1978) A Strategic model of the US brewing industry: 1952-1971. *Academy of Management Journal*, Vol. 21, No. 4, pp. 592-610.

Heikkilä, A.,Komonen, K., Räikkönen, M. and Kunttu, S. (2012) Empirical experiences of investment portfolio management in a capital-intensive business environment : a dimension of strategic asset management. *International Journal of Strategic Engineering Asset Management (IJSEAM),* vol. 1, 2, ss. 117 – 134.

Hill, T. (1985) *Manufacturing strategy - The strategic manufacturing choice*, The Macmillan Press.

Homburg, C., Krohmer, H., Workmann, J.P.Jr. (1999) Strategic consensus and performance: the role of strategy type and market related dynamism. *Strategic Management Journal*, Vol 20, No. 4, pp. 339-57.

Huff, A.S, Jenkins, M. (2002) *Mapping strategic knowledge*. SAGE Publications Ltd.

IEC/ISO (2009) Risk management – *Risk assessment techniques* 31010:2009

Jonsson P. (1997) The status of maintenance management in Swedish manufacturing firms. *Journal of Quality in Maintenance Engineering*, 3, 233-258.

Kaplan, R. S., Norton, D. P. (1992) The balanced scorecard: measures that drive performance, *Harvard Business Review* Jan – Feb pp. 71–80.

Kasanen E., Lukka K. and Siitonen A. (1991) Constructive Approach in Business Studies. *Finnish Journal of Business Economics* XL.

Keeney L., Raiffa H. (1993) *Decisions with Multiple Objectives: Preferences and Value Trade-offs.* Cambridge University Press.

Kettunen, J. (2009) Applications of Stochastic Modeling for Investment Decision-Making under Market Uncertainties. Dissertation. Helsinki University of Technology.

Komonen, K., Kortelainen, H. and Räikkönen, M. (2010b) Corporate Asset Management for Industrial Companies: An Integrated Business Driven Approach. The 5th World Congress on Engineering Asset Management - WCEAM. Brisbane, AU, 25 - 27Oct. 2010, WCEAM - AGIC 2010

Komonen, K., Kortelainen, H. and Räikkönen, M. (2012) Corporate Asset Management for Industrial Companies: An Integrated Business-Driven Approach. p. 47 – 63. In: *Asset Management. The State of the Art in Europe from a Life Cycle Perspective*. Vander Lei, Telli; Herder Paulien & Ype Wijnia (Eds.). Springer Science; Business Media B.V. doi:10.1007/978-94-007-2724-3

Komonen, K., Räikkönen, M., Kunttu, S., Heikkilä, A. and Ahonen, T. (2010a) Investments, capacity and maintenance: ways to safely increase capital turnover. *Euromaintenance 2010. Conference Proceedings.* Verona, Italy

Kotler, P. (1997*) Marketing Management*, 9th Edition, Prentice Hall.

Labro E. and Tuomela T.-S. (2003) On Bringing More Action into Management Accounting Research: Process Considerations Based on Two Constructive Case Studies. *European Accounting Review*, 2003, 409–442.

Mather, D. (2005) *The maintenance scorecard: Creating Strategic Advantage*. Industrial Press Inc.

Millet, I. and Wedley, W.C. (2002) Modelling risk and uncertainty with the analytic hierarchy process. *Journal of Multicriteria Decision Analysis*; Mar/Apr 2002; 11; 2. pp.97-107.

Nourse, H.O. and Roulac S. E. (1993) Linking real estate decisions to corporate strategy. *Journal of Real Estate Research,* Vol.8, No 4.

Nowak, M. 2005. Investment projects evaluation by simulation and multiple criteria decision aiding procedure. *Journal of Civil Engineering and Management*, Vol. XI. No. 3, 193–202.

Pike, R. and Neale, B. (2003) *Corporate Finance and Investment: Decisions and Strategies*. 4. ed. Harlow, Prentice Hall.

Pinjala S. K., Pintelon, L. and Vereecke, A. (2006) An empirical investigation on the relationship between business and maintenance strategies. *International Journal of Production Economics*. Volume 104, Issue 1, pp. 214 - 229

Piyatrapoomi, N., Kumar, A. and Setunge, S. (2004) Framework for investment decision-making under risk and uncertainty for infrastructure asset management. *Economic Impacts of Intelligent Transportation Systems: Innovations and Case Studies Research in Transportation Economics*, Volume 8, 199–214

Porter, M. (1985) Competitive Advantage. Free Press.

Proctor, M. D. and Canada, J. R. (1992) Past and Present Methods of manufacturing Investment Evaluation. A Review of the Empirical and Theoretical Literature. The Engineering Economist, Vol. 38. No. 1., 45–58.

Räikkönen, M., Komonen, K., Heikkilä, A. and Kunttu, S. (2010) Life-Cycle Oriented Investment Portfolio Evaluation - Introducing a Multiphase Evaluation Method for Capital Intensive Industries. Pre-Prints. Volume 2. Linköping Institute of Technology & Universität Innsbruck, ss. 451 - 465. *Sixteenth International Working Seminar on Production Economics*. Innsbruck, AT, 1 -5 March 2010

Robson, K., MacIntyre, J. and Trimble, R. (2013) Measuring the alignment of Maintenance and Manufacturing Strategies – The development of a new model and diagnostic tool. *Journal of Quality in Maintenance Engineering*. ISSN 1355-2511 (In Press)

Rue, L-W. and Holland, P.G. (1989) *Strategic Management: Concepts and Experiences*. McGraw-Hill, New York. NY.

Saaty, T.L. (1980) The Analytic Hierarchy process. McGraw-Hill. New York,

Sadgrove K. (2005) Complete Guide to Business Risk Management. Second Edition. Gower Publishing Limited. England.

Shil, P. and Allada, V. (2007) Evaluating product plans using real options. *The Engineering Economist*, Vol. 52. No. 3., 215–253.

Skinner, W. (1969) Manufacturing - missing link in corporate strategy. *Harvard Business Review*, 1-10.

Stacey, R.D. (1990) *Dynamic Strategic Management for the 1990s – balancing opportunism and business planning*. Kogan Page Ltd, London 1990.

Suomala, P. (2004) *Measurement of New Product Development Performance - Life Cycle Perspective.* Dissertation. Tampere University of Technology.

Tavana M. (2002) Euclid: Strategic Alternative Assessment Matrix. *Journal of Multicriteria Decision Analysis*. Mar/Apr 2002; 11; 2. pp. 75-96.

Teece D.J., Pisano G. and Shuen A. (1997) Dynamic Capabilities and Strategic Management. *Strategic Management Journal*, Vol. 18, No. 7. (Aug., 1997), pp. 509-533.

Tranfield, D., Denyer, D. and Burr, M. (2004) A Framework for the strategic management of long term assets (SMoLTA). *Management Decision*. Vol. 42 No. 2, pp. 277-291.

Wilson, A. (2002) *Asset maintenance management: a guide to developing strategy & improving performance*. Industrial Press.

Yurdakul M. (2004) AHP as a strategic decision-making tool to justify machine tool selection. *Journal of Materials processing Technology* 146. pp.365-376.

Condition based monitoring for underground mobile machines

Arto Laukka[1], Juhamatti Saari[2], Jari Ruuska[1], Esko Juuso[1*] and Sulo Lahdelma[2]

[1]*Department of Process and Environmental Engineering*
Control Engineering Laboratory
P.O.Box 4300
[2]*Department of Mechanical Engineering*
Mechatronics and Machine Diagnostics Laboratory
P.O.Box 4200
FIN-90014 University of Oulu
Finland
*Corresponding author: Esko Juuso
E-mail: forename.surname@oulu.fi

Abstract

Maintenance operations have significant influence on the economy and performance of mining companies. Unpredicted repairs cause interruptions and breakdowns in production. This means economic losses but, in some cases, also increasing environmental emissions in off-gases and wastewater. Condition based maintenance (CBM) can significantly reduce maintenance costs. Sensors and measurement devices offer a lot of data and assist workers to identify upcoming maintenance needs in advance. Typical measurement variables are for example vibration, temperature, different speeds and pressures. DEVICO project aims to develop a framework for solutions and combine condition monitoring and process data to integrate CBM to control and timing of the maintenance actions. On-line and periodic CM measurements can be combined with process measurements by using signal processing and feature extraction. Case study is conducted in Pyhäsalmi mine with Sandvik load haul dump (LHD) machinery. The condition monitoring system is installed on LHD front axle. The choice for the installation position was made based on the feedback and maintenance data gathered from mining companies. This information indicates that the axles are among the most critical parts in LHD machines.

Key words: Data analysis, condition based monitoring, load haul dump, vibration

1 Introduction

1.1 Development needs in the maintenance of mining industry

Maintenance is a critical factor in the economic performance of mining companies, especially in the case of smaller mines. Maintenance costs can be 30-60 % of total operation costs in the mining industry. Currently the focus in maintenance operations is commonly in corrective maintenance. Common reason for this is the lack of knowledge and resources to invest in predictive maintenance and condition monitoring. For example, in paper industry condition monitoring and long-term maintenance schedules are used more widely. Condition-based

maintenance (CBM) program that is designed for the needs of mining industry could reduce the maintenance costs of mines. This program should also be easy to deploy even with a lightweight maintenance organization. One target for development in the DEVICO project is condition-based monitoring in mining industry. The purpose of condition monitoring is to reduce unnecessary breakdowns. In the mining industry, these breakdowns may also cause environmental emissions.

Mobile machines are widely used in the mining industry. Common mobile machines working in the mines are drill rigs and jumbos, excavators, wheel loaders, rigid trucks, concrete sprayers, charging vehicles and bolting machines. Maintenance of mobile machines causes a significant part of total maintenance costs in the mining industry. Load haul dumps (LHDs) are large loading machines that are used in the underground mining to load and they move ore from the drift. These machines can be operated remotely. Maintenance can cause up to 70% of total operation costs of LHD machines (Figure 1). Despite high maintenance costs, condition monitoring of mobile machines isn't widely used. A lot of different kind of data is available from the operation of mobile machines, for example maintenance, operation and production data. Fusion of these different data types is also still clearly under development. (Gustafson & Galar 2012)
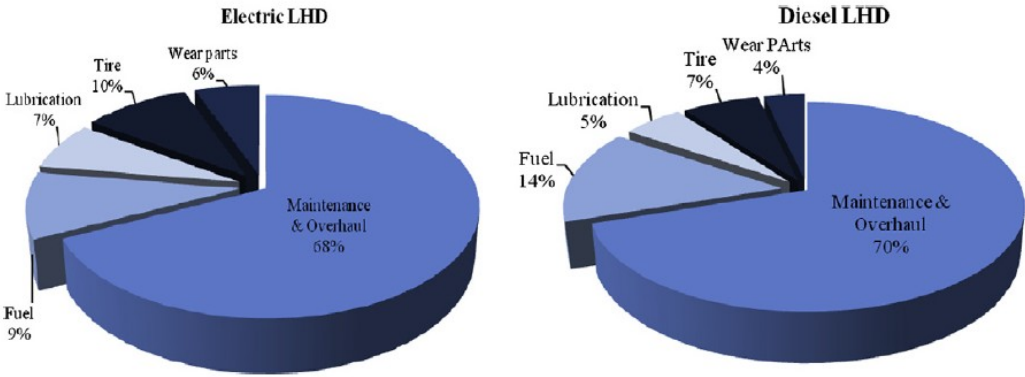
Figure 1. Share of operation costs of LHD machines (Sayadi *et al.* 2012)

1.2 Condition-based monitoring research

The objective of the DEVICO project in the University of Oulu is to provide certain means for integrating condition monitoring of mobile equipment to the maintenance strategies of a mining company. This can be achieved via development of condition and stress indices which are easily available for the use of maintenance personnel (Figure 2).

Case study is conducted in Pyhäsalmi underground mine with Sandvik LHD machinery. The condition monitoring system is installed on the front axle of LHD machine.
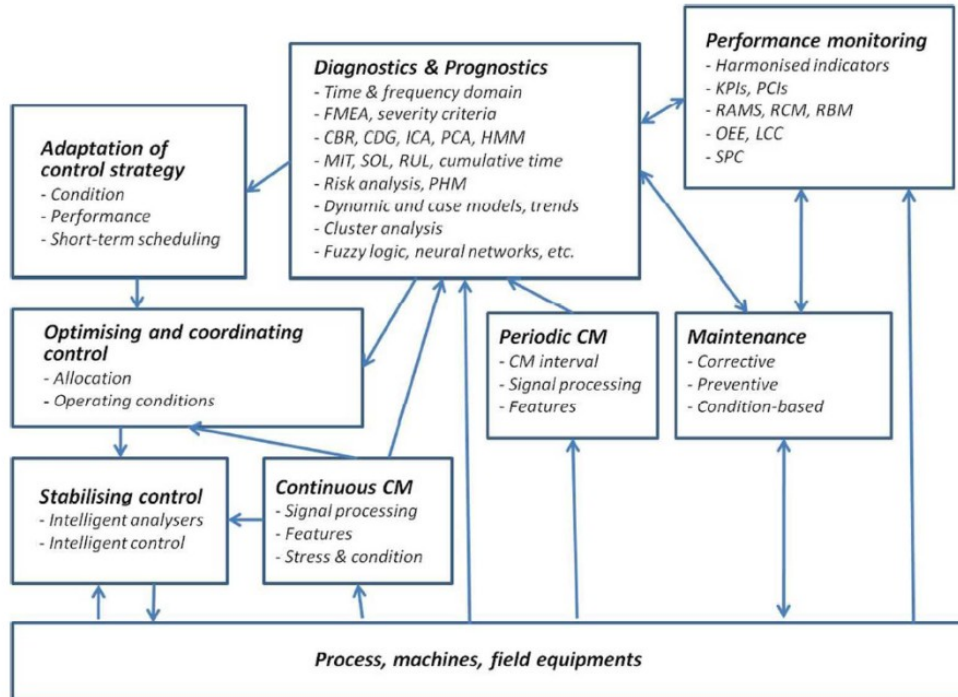
Figure 2. Development of condition-based monitoring. (Juuso & Lahdelma 2013)

2 Background

2.1 Vibration analysis and signal processing

Reliable condition monitoring can be achieved when advanced signal processing and automatic fault detection are combined (Lahdelma & Juuso 2007). Intelligent stress and condition indices can be developed by using nonlinear scaling. Features are extracted from derivatives of the vibration measurement signals to define normal operation conditions. When this definition is done, the changes in signals and their differences from normal values can be monitored. The condition indices are calculated by comparing the feature values with the values in normal operation. These indices can detect differences between normal and faulty conditions and indicate the severity of these faults. (Juuso & Lahdelma 2010)

Control Engineering Laboratory and Machine Diagnostics Laboratory in University of Oulu have previously developed applications of vibration analysis, e.g. the scraper of a continuous digester, a gearbox of a sea water pump and a turbo compressor system. (Lahdelma & Juuso 2011)

2.2 Fusion of maintenance, process and production data

Generally speaking, data fusion from different functional areas may offer advantages in maintenance operations. If the optimization of functional areas is independently done by different departments, problems may arise. As said in Galar *et al.* (2012), "low priority equipment problem may have been causing a large problem in achieving a desired or critical process control performance, but was not being corrected because it was not considered very

important in the context of equipment maintenance". A centralized solution to gather and distribute data to different departments could reduce these problems. (Galar *et al.* 2012)

Different data from various sources are available from the operation of mobile machines. In this case, the examples of available data are maintenance data (work orders, time used for maintenance), process data (temperatures, pressures) and production data (bucket weights, drive speed). Problematic part of maintenance data is that e.g. estimation of working hours is commonly entered manually. If this is done carelessly, a reliable analysis of data is difficult. An example of combination of production and maintenance data is shown in Figure 3, where the gap in production (left) is explained by maintenance operations (right). (Gustafson & Galar 2012) Also some incompatible technical solutions can cause problems: it can be very difficult to combine together e.g. timestamps and various data formats from multiple sources.

MAINTENANCE DATA

DATE	TIME
20XX-03-14	12:50
20XX-03-14	12:52
20XX-03-14	12:54
20XX-03-14	12:56
20XX-03-14	12:58

Date	Failure report	Measures taken	Entering workshop	Leaving workshop	Idle time
20XX-03-14	Fan belt broken	Changing all belts and generator	6:00 PM		
20XX-03-15				10:00 AM	16.00

DATE	TIME
20XX-03-15	12:27
20XX-03-15	12:29
20XX-03-15	12:31
20XX-03-15	12:33
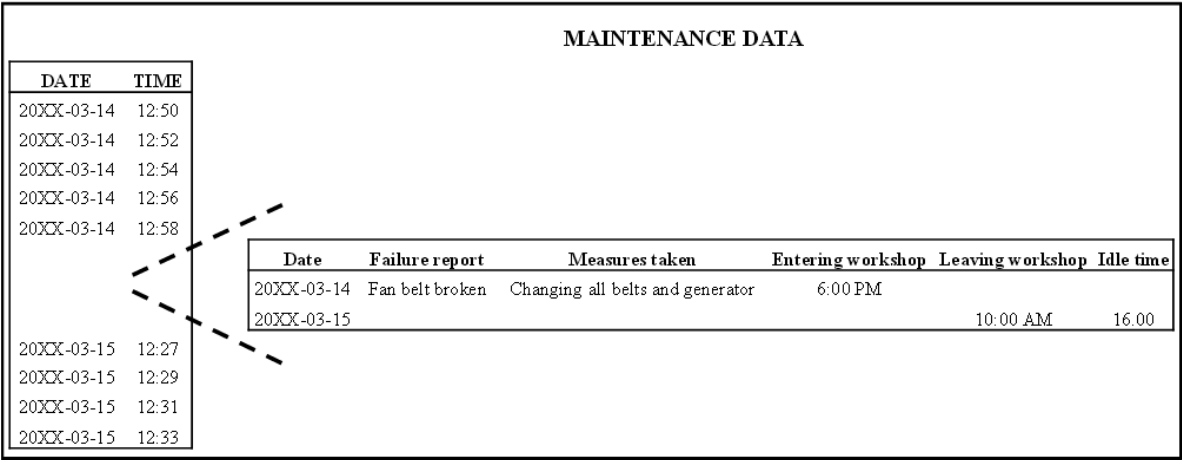
Figure 3. Combination of production and maintenance data. (Gustafson & Galar 2012)

A need for smooth co-operation between different departments of mine, especially in case when the ore production rate is increasing rapidly, was also identified by Sillanpää (2012). This co-operation also includes the utilization of production and maintenance data.

2.3 Condition monitoring of load haul dump machines

Although there is a lot of process data which is available for different purposes, condition monitoring usually requires additional measurements. Keski-Säntti (2006) conducted study about LHD condition prognostics. Typical measurements from LHD machines include e.g. hydraulic and air pressure sensors. However, these measurements don't give sufficient information for reliable condition monitoring, as Keski-Säntti (2006) states: "present measurements are not able to produce that kind of data which can be utilized in making reliable prognostics". A need for vibration measurements for the basis of condition monitoring was identified in the study. Preliminary vibration measurements indicated that different stages of LHD operation can be identified from the vibration signals, e.g. a movement from the service platform to the production area, the loading stage and the transport of ore to the ore pass. One conclusion was that with the synthesis of vibration measurements with other data, the maintenance operations can be prognosticated more reliably. (Keski-Säntti 2006)

If the remote-controlled LHD machines are used, an operator doesn't have direct feeling of machine vibrations. This kind of experience-based condition monitoring is still common. When this kind of direct feeling is lost, a need for the condition monitoring system is even more evident. (Keski-Säntti 2006)

2.4 Wireless data transfer

One future challenge in condition-based monitoring of underground mobile equipment is wireless communication. Underground mines are challenging environments for wireless communication. Wireless networks are used with load haul dumps to transfer production monitoring data, but condition monitoring via wireless data transfer hasn't been used widely. The data bandwidth of wireless networks isn't sufficient for transferring vibration data continuously (Timusk 2008). Development of event triggers for vibration measurements could reduce the bandwidth need significantly. A determination of events when faults can be identified well, e.g. moment when LHD is driving consistent speed, is a challenging task.

One practical possibility could be a system which transfers vibration data from a data logger to the servers when LHD arrives at a service platform, e.g. after the evening shift. In this option, the transfer of production monitoring data doesn't take up any bandwidth from vibration data. The best solution would be a data logger which calculates condition indices internally and sends only information about these indices to servers, not whole vibration measurement data. As described in Paavola (2011), a bandwidth needed for communications could be reduced if only the descriptive indices are transferred instead of raw data. The adaptation of wireless data transfer is helpful especially when condition monitoring is applied to a moving target in harsh environments, as described in Keski-Säntti *et al.* (2006).

3 Experimental study

3.1 Project partners

The experimental part of the DEVICO project is done in co-operation with Pyhäsalmi Mine Oy, Sandvik Mining and Construction Oy and SKF. Pyhäsalmi Mine is an underground copper and zinc mine located in central Finland. Pyhäsalmi Mine uses sub-level and bench stoping as a mining method.

Sandvik Mining and Construction Oy is a leading global supplier of equipment, cemented-carbide tools, service and technical solutions for the excavation and sizing of rock and minerals in the mining and construction industries. Sandvik has provided technical support in the DEVICO project.

SKF is a technology provider that is specialized in bearings and units, seals, mechatronics, services and lubrication systems. SKF has provided the accelerometer sensors that are used in the condition monitoring.

3.2 Selection of condition monitoring target

First task in the development of condition-based monitoring for load haul dump was the selection of the target component for condition monitoring. Decision for the target component was made based on the following factors:

1. Faults in monitored component cause long repair times.

2. Repair of a component is done mostly during the corrective maintenance.

3. There is a reasonable way to use vibration measurements in condition monitoring of the component.

LHD-related maintenance data gathered from several mines was analysed for the selection of the target component. Also direct feedback from mining companies and previous studies (Figure 4) was taken into account when selection was made.
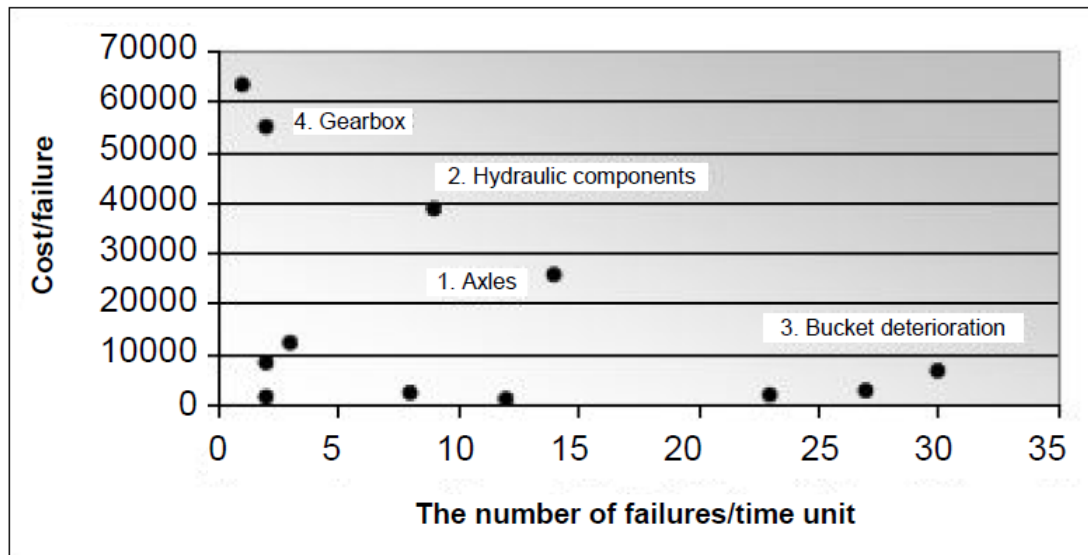
Figure 4. Criticality assessment of components and subsystems based on event data (Ahonen *et al.* 2006)

According to the maintenance data, most of the preventive maintenance works are related to simple tasks like oil changing and other little tasks that are not crucial to production. Because of this, preventive maintenance-related information from maintenance data was excluded. A focus was only in the faults that were labeled as a corrective maintenance work.

Maintenance data included information about the amount and repair times of specific faults. The amount of all work orders was counted and divided into the categories by components. This way the number of incidents in each part of the LHD was found out.

There are some components like hoses and connectors in which faults occur frequently, but an average working time caused by an individual fault is quite short. When all faults were summed together (Figure 5), it was clear that the hoses and connectors are reasons for most maintenance work orders and also result in the most working hours. However, the hose faults and other similar failures, which are easy to fix but difficult to measure and predict, aren't critical concerning condition-based research.

The faults in axles, cylinders and hydraulics result in a high percentage of maintenance working hours although the number of those faults is low (Figure 5). The faults in these components are more difficult to fix and could lead to more significant production stoppages due to long repair times. These components are good alternatives for condition monitoring targets. Based on these factors, the front axle was selected as the condition monitoring target.
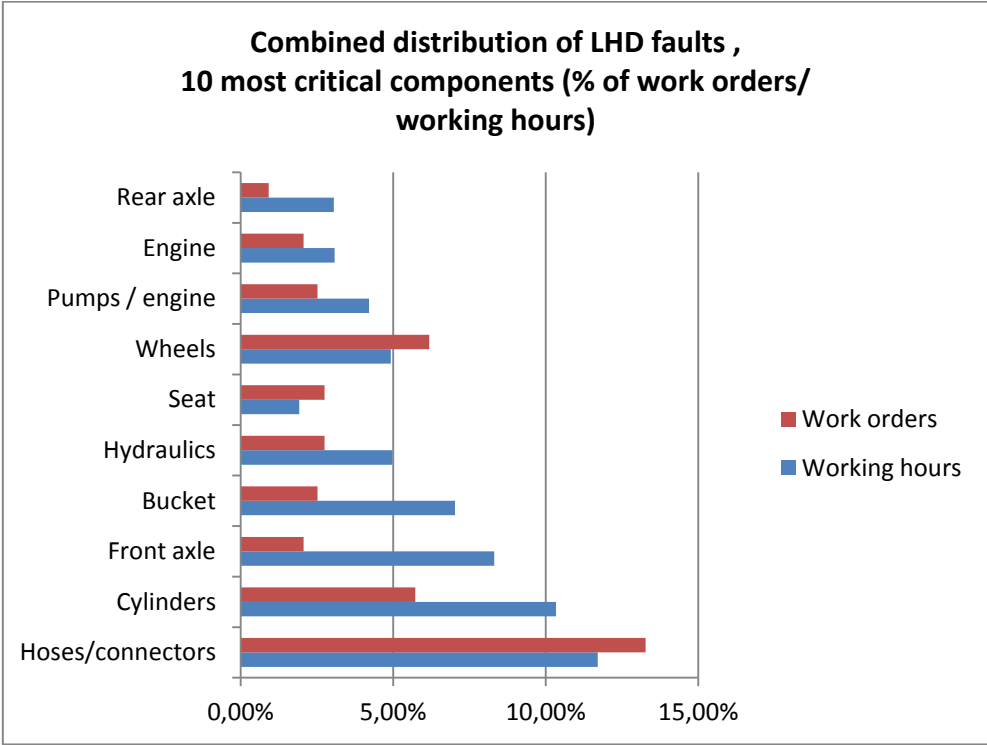
Figure 5. Critical components of LHD machine.

3.3 Condition monitoring system

The condition monitoring system was installed on a LHD machine working in underground mine environment. The LHD machine is Sandvik LH621 (Figure 6). Vibration measurements are done using National Instruments CompactRIO 9024 data logger and four SKF Copperhead CMPT 2310 accelerometer sensors. The accelerometer sensors have been installed on the front axle. Two accelerometers are installed on the left side of axle and two on the right side. On both sides, there are sensors for vertical and horizontal measurements. The vibration measurements are combined with the measurement of machine drive speed. The drive speed is measured from the drive shaft with a photoelectric sensor. The drive speed can be calculated from the tachometer pulse when a gear ratio is known. The measurement moments can be identified from the drive speed, e.g. when LHD is loading ore from the drift or dumps the ore to the ore pass. Measurement software was developed using LabVIEW development environment.

Figure 6. Sandvik LH621 load haul dump. (From Sandvik mediabase)

3.4 Preliminary vibration measurement data

First batch of vibration measurement data was recovered during April 2013. Signals can be examined by using analyzing software in LabVIEW environment. An example of collected data can be seen in Figures 7 and 8. In Figure 7 acceleration signals from two sensors (horizontal and vertical) are displayed with a measurement of drive shaft rotation speed. Figures 8 and Figure 9 display acceleration spectrums with two different drive shaft rotation speeds.

Preliminary analyses indicate that the working stages can be identified from signals. The biggest impacts on the front axle occur during the loading stage. This stage isn't suitable for condition monitoring, but it can be used to estimate the magnitude of impacts. The best stage for condition monitoring could be the transition to the loading position. In this stage drive speed is quite constant. Driving speed is an important factor when vibration levels are analyzed. As seen in Figures 8 and 9, certain frequency components are over ten times higher when drive shaft rotation speed increases from 9 to 22 Hz. (Saari 2013)
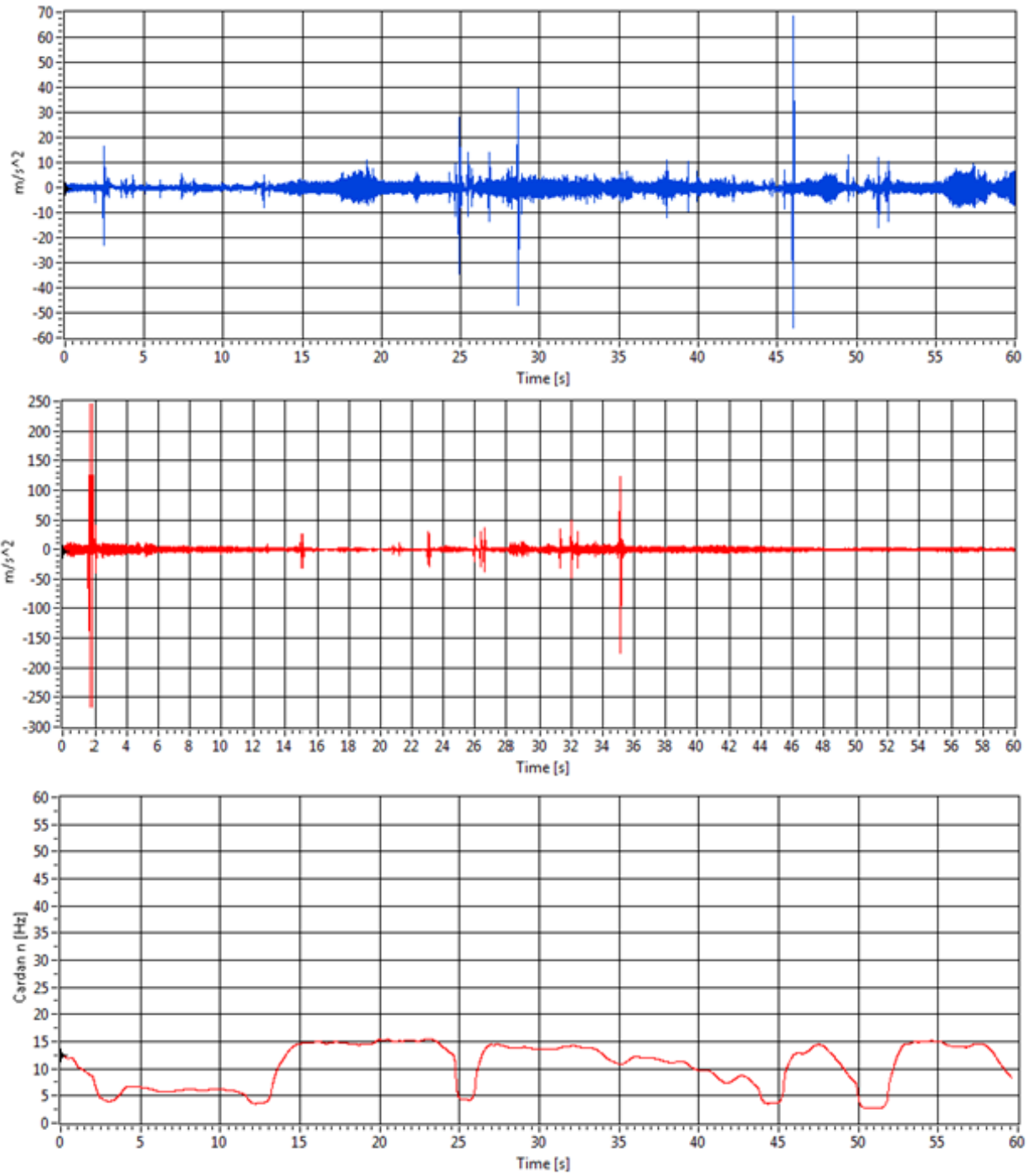
Figure 7. Example of acceleration signals from two accelerometer sensors with drive shaft rotation speed measurement.
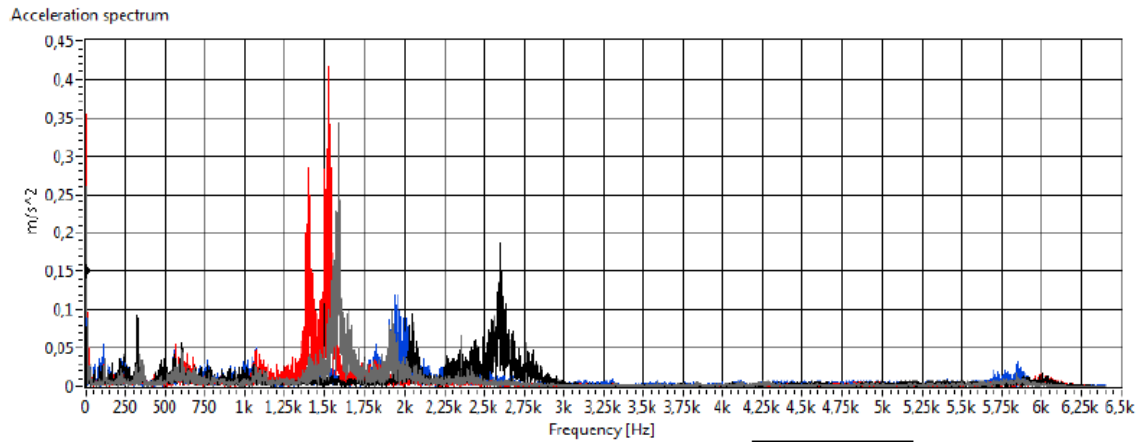
Figure 8. RMS spectrum of acceleration signal, drive shaft rotation speed of 9 Hz. (Saari 2013)
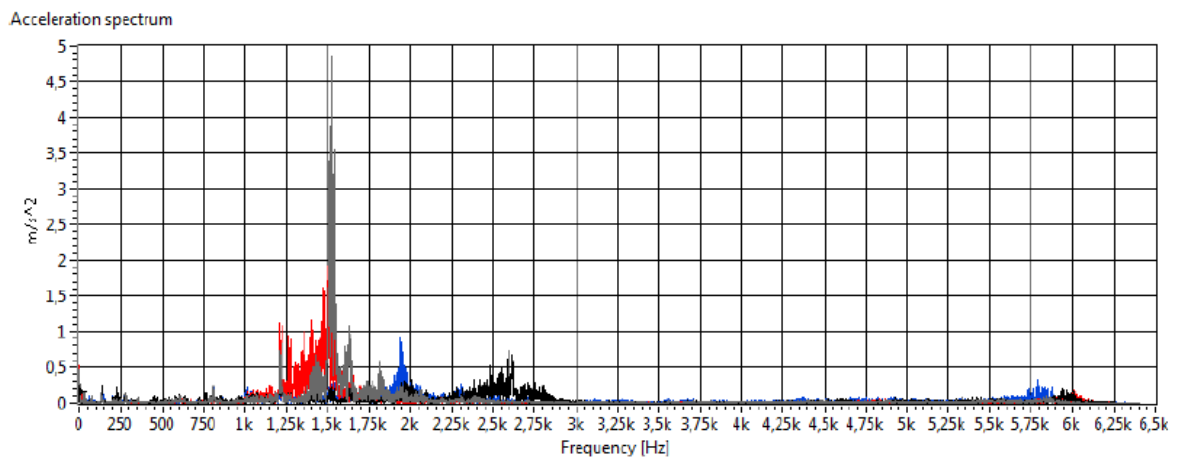
Figure 9. RMS spectrum of acceleration signal, drive shaft rotation speed of 22 Hz. (Saari 2013)

4 Conclusions and future work

Preliminary data analysis indicates that vibration measurements offer a good basis for condition monitoring development. Data collection is in its early stages so more precise analysis is done when more measurement data is available. As discussed in Section 2.1, the identification of the "normal" level of vibrations is needed for the development of stress and condition indices. Because in the case of LHD machines the "normal" operation is dependent on the working stage, there isn't only one vibration level which can be used as a base level. The best solution could be to identify a certain stable driving stage of the LHD where vibrations are always on the same level. A notable increase in the vibration levels could be an indication of a developing fault. Preliminary analysis indicates that the transition to the loading position could be the best stage for fault identification. Wireless data transfer of condition indices from a data logger to servers could offer maintenance personnel an easy solution to access data.

The load haul dump operators have different ways to operate the machine. Some operators accelerate, brake and load ore more carefully than others. Also the road conditions may change during time. These variables can cause variation in the vibration levels. This needs to be taken into account when the generation of features and indices is done. If there is a driving style which clearly reduces time used for the maintenance, the operators can be encouraged to use such style. The most important information that must be combined to the vibration measurements in future consists of the bucket weights and timestamps for the loaded buckets.

References

Ahonen T., Reunanen M., Heikkilä J. and Kunttu S. (2006) 'Updating maintenance programme based on various information sources', *The 4ᵗʰ International Conference on Safety and Reliability*, May-June, 30-2, 2006, Krakow, Poland.

Galar D., Kumar U., Juuso E. and Lahdelma S. (2012) 'Fusion of maintenance and control data: A need for the process', *18ᵗʰ World Conference on Non Destructive Testing,* April, 16-20, 2012, Durban, South Africa.

Gustafson A. and Galar D. (2012) 'Fusion of production, operation and maintenance data for underground mobile equipment', *9ᵗʰ International Conference on Condition Monitoring and Machinery Failure Prevention Technologies*, 12-14 June 2012, London, UK, BINDT, pp. 783-791.

Juuso E. and Lahdelma S. (2010) 'Intelligent Scaling of Features in Fault Diagnosis', *7th International Conference on Condition Monitoring & Machinery Failure Prevention Technologies*, 22-24 June 2010, Stratford-upon-Avon, UK, BINDT, pp. 1358-1372.

Juuso E. and Lahdelma S. (2013) 'Intelligent Performance Measures for Condition-based Maintenance' *Journal of Quality in Maintenance Engineering, Special Issue: Advances in Maintenance Performance Measurement and Management – selected papers from the First International Conference on Maintenance Performance,* Vol. 19, No. 3.

Keski-Säntti, J. (2006) 'Operational reliability of remotely operated underground loaders – prognostic needs and possibilities, Prognostics for industrial machinery availability', *VTT Symposium 243*, 2006, pp. 27-37.

Keski-Säntti J., Parkkila T., Leinonen J., Leinonen P. (2006) 'Wireless communication and mems sensors for cheaper condition monitoring and prognostics of charging crane.' *19ᵗʰ International Congress COMADEM,* June, 12-15, 2006, Luleå, Sweden.

Lahdelma S. and Juuso E. (2007) 'Advanced signal processing and fault diagnosis in condition monitoring', *Insight*, Vol. 49, No. 12, pp. 719-725,
doi: 10.1784/insi.2007.49.12.719.

Lahdelma S. and Juuso E. (2011) 'Signal processing and feature extraction by using real order derivatives and generalized norms. Part 2: Applications', *The International Journal of Condition Monitoring*, Vol. 1, No. 2, pp. 54-66, doi: 10.1784/204764211798303814.

Paavola (2011) 'An Efficient Entropy Estimation Approach', *Doctoral thesis,* pp. 17. Available in: http://herkules.oulu.fi/isbn9789514295935/isbn9789514295935.pdf

Saari J. (2013) 'Developing a monitoring system for mining loaders' *Master's thesis, Mechatronics and Machine Diagnostics Laboratory, Department of Mechanical Engineering, University of Oulu.* pp. 95-97. Available only in Finnish language.

Sandvik mediabase (2013) Available in mediabase.sandvik.com.

Sayadi R.S., Lashgari A. and Paraszczak J. (2012) 'Hard-rock LHD cost estimation using single and multiple regressions based on principal component analysis', *Tunnelling and Underground Space Technology*, Vol. 27, No. 1, pp. 133-141.

Sillanpää E. (2012) 'Utilising the information from vehicle displays at Kemi Mine ', *Master's thesis, Control Engineering Laboratory, Department of Process and Environmental Engineering, University of Oulu.* pp. 55. Available only in Finnish language.

Timusk M. (2008) 'Condition monitoring adapted for mobile underground equipment', *Sudbury Mining Solutions Journal*, Vol. 5, No. 2, pp. 14. Available in: http://www.miningexcellence.ca/news/media/links/SMSJ_200806_Condition_Monitoring.pdf

Modeling of decision making process using scenario methods in maintenance management of selected technical systems

Andrzej Loska

Institute of Production Engineering
Faculty of Organisation and Management
Silesian University of Technology
Roosevelt Street 26
41-800 Zabrze
Poland
e-mail: Andrzej.Loska@polsl.pl

Abstract

The paper presents the results of research on possibility of use of the methods of future modelling, including scenario techniques, for the needs of decision-making process of the maintenance works in the selected network technical system. Previous studies have shown the organizational and technical specificity of network technical systems (territorial dispersion, specific location of system components, high structural complexity, high dynamics of the system, uninterrupted operations for most of the installations), which requires different approach to maintenance work than in typical industrial enterprises focused on the production line exploitation (effects of manufacturing process). Searching for effective solutions, the author attempts to use methods of future modeling - particularly scenario methods, as a way of maintenance management of network technical system – on the example of water supply system. The article ends with the concept of building set of future models for the maintenance decision-making process on the example of one of Polish water supply companies.

Key words: exploitation decision-making process, scenarios, maintenance management, exploitation policy, network technical system.

1 Introduction

Maintenance management decision-making process should be considered from many points of view (Loska 2012a). In this perspective, effective implementation of the activities of the technical services in an industrial enterprise not only refers to the technical aspects and the "computer-based-tools", but also covers organizational, technical and information-related issues of supervision of company's machinery park, as well as preparation and execution maintenance work.

In the aforementioned meaning, the main objective of maintenance management, and thus the subject of the decision-making process, can be defined as optimization of tasks, taking into account three main criteria:

- time, in the sense of extending the periods of use of technical objects with simultaneous shorter periods of breakdowns or stop-overs,
- economics, in the sense of reducing the exploitation costs of facilities (direct and indirect), while preserving the required values of key performance features,
- exploitation characteristics in the sense of performance, functionality and safety, which allows for continuous improvement of the operation of technical systems in relation to man and the environment.

The effectiveness of the proposed concept strives to achieve the extreme values of characteristics (maximum or minimum), depending on the existing organizational and technical conditions of exploitation of technical objects, forming the basis for optimal decision-making process.

In the next part, the article presents the results of a study involving the review and discussion of the possibility, desirability and meaningfulness of use of selected methods and tools (in particular scenario techniques) of future modeling, for the needs of exploitation decision-making process. In particular, there was developed key decision problem of maintenance organization based on the conclusions resulting from the exploitation specificity of selected network technical system, as the following question: What decisions need to be taken today in order to achieve the expected operational efficiency of the technical system in the long term (future)? Attempt to answer this question will be reflected in the summary of the article.

2 Some aspects of exploitation decision-making process

Exploitation decision-making process can be analyzed in two aspects:

- subject and scope of exploitation decisions,
- the time point of effects and consequences of exploitation decisions.

The first aspect is related to the subject (the technical object or maintenance organization). In this regard, one can distinguish between decisions in closer and further environment. The decisions in closer environment are focused on technical object and its main features and result from the aging and wear processes taking place during regular operations period. The methods supporting such decisions, one should include the modeling of events and processes (Konieczny, 1975; Żółtowski, 2010), assessment of the technical condition - diagnosis and forecasting (Cempel, 1989; Cholewa and Kaźmierczak, 1995), reliability analysis, including forecasting of reliability (Wang and Pham 2010). Decisions in the further environment are focused on the site of functioning of a technical object and result from principles of functioning of the maintenance organization in the enterprise. The methods and tools, which support decision-making process could include strategies and maintenance systems, such as TPM, BCM, RCM, WCM (Kelly, 2006; Suzuki 1994), methods of analysis and assessment of models for work organizing of maintenance staff in enterprises (Campbell, 1995) or computerized maintenance management systems (Loska, 2012a).

The second aspect is associated with the time horizon and the moment in time in the future, where the effects and/or the implications of presentexploitation decisions take place. In this regard we can distinguish:

- short-term horizon, which is characterized by the expectation of results in one or more service cycles, that is, within the time window around next major repairs or renovations,
- long-term horizon, which is characterized by the expectation of results throughout the lifecycle of the object, that is, within the time window starting with the first launch of an object and ending with the final withdrawal from use.

At present, short-term decision making process based on diagnostics and reliability models is well-recognized and rather effectively applied in the industrial practice (Kaźmierczak, 2000; Żółtowski, 2010). Significantly greater problem, in terms of both theory and practice, is the process of decision-making in the long-term horizon, which often extends beyond classical time framework of operation of given technical object. In particular, the expectations of decision-makers are not only limited to the life cycle of selected objects, but they assume the possibility and the need to influence the functioning of machinery park within several or even dozens of years.

It should be noted that each decision on the future behavior of technical objects is subject to some level of uncertainty. This uncertainty increases with the extension of the time horizon. In line with the ongoing multi-annual research, uncertainty is unavoidable, which is important to take it into account in decision-making process (Van der Heijden, 1996). Important in this context are the answers to such questions as:

1. How long will the technical object perform its tasks at a given/desired level of performance?
2. When will occur a need to replace the technical object, in order to make optimal use of the exploitation potential of object, assuming cost minimization?
3. What decisions must be taken today to ensure maximum exploitation potential of machine park in the future?

The answers to these questions are possible on the basis of constructed, in an accurate and quantitative way, models of exploitation processes, including variability of the analyzed technical object, as well as dynamic environmental conditions of its operations. Simultaneously, there must be a reliable assessment of the future effects of decisions taken today, in particular, quantitative analysis of possible problems and potential effects and impact of particular decisions.

In this respect, there may be useful concepts and methods related to modeling and analyzing future variants of exploitation, which could result in scenarios of future behavior of technical objects and guidelines for the maintenance staff. The methods of future modeling, although known and used in the macro area, i.e. global strategic planning, they have yet to gain greater appreciation in terms of micro area, i.e. functioning of the individual technical systems under certain conditions(organizational and technical).

3 Overview of the terms of future modelling

Results of multiannual experience in relation to exploiters of various technical systems, complemented by the study of futurists (Godet, 2006), allow to develop the following thesis:

Exploitation future is closely linked to the present, taking the shape of the complex interactions between current decisions and actions implemented with regard to the technical facilities including environmental conditions, and their effects or impacts occurring in the future.

In other words, an insight into exploitation future is possible by recognizing current events.

Modeling of the future is connected with the elaboration of objectives and images, for the needs of identification of development of events that may occur in the future. The aim is to optimally prepare and implementa the decision-making process by keeping track of their possible future effects and impacts. In this area, there are two opposing general concepts, according to which the future behavior of technical objects can be based on forecasting, which results is a forecast or prediction, which results is the vision (Lindgren and Bandhold, 2009).

The specificity of exploitation decision-making process making in an industrial environment, based on both quantitative characteristics and difficult to measure descriptive features, justifies the need to link the quantitative nature of the forecasts of qualitative and descriptive nature of the vision. A tool that corresponds to these requirements is the scenario, which, in this case, can fill the gap between the aforementioned concepts and should form between them a kind of common part.

At present, the methods of scenario modeling, are one of the key methods of the future description, which are successfully implemented in practice. In the area of research, as well as practical applications, the scenario is defined inconsistently, due to the objective and scope of the inclusion in the interpretation of certain aspects of the future modeling. Based on its literature analysis, scenario definitions can be summed up two categories:

- scenario in the methodological approach, as a way to cope with the uncertainty of decision making, based on an internally consistent picture of the future, represented by a set of descriptions of possible variants of the future events or situations (Kahn and Wiener, 1967; Godet, 2006),
- scenario in the utility approach, as a response to results of research and application, in the form of a set of methods and tools to optimize the decision-making process on issues of strategic management (Schwartz, 1991; Ringland, 2006; Van der Heijden, 1996).

The scenario is a tool that helps to present the future and can answer the questions (Lindgren and Bandhold, 2009): what could conceivably happen if ...? or what could happen when ...?

The scenario is neither forecast nor vision in the terms presented above. However, forecasts, visions and scenarios should coexist together in relation to exploitation decision-making process. Forecast is short-term and allows to determine potential change of technical condition of the object, which allows to determine the direction of the decisions and actions. With the increase of the distance of time in the future, tools are required to assess the opportunities and risks of potential decisions concerning exploited objects as well as its economic and organizational environment. This allows to prepare for not one, but for more future images.

However, the structure and effective use of scenarios requires reaching for both the concept of forecasts and vision. Forecast can be a part of the input to scenario planning. In particular, at the input to the scenario project, there should be a clear set of information describing the main objectives of the entire project. In addition, the conclusions made when building of specific

scenarios, as well as their practical verification, require reliable test data about possible behavior of given object or maintenance organization, and in this respect should be of quantitative nature. On the other hand, the vision can be a part of the output from the scenario project as a tool for presenting and visualizing scenarios in a simple and understandable for non-professionals.

Driving force of the methodology of scenario is the uncertainty and associated risks that are the basis to generate different variants of the future. The uncertainty is treated as something natural, it is assumed that uncertain factors must be distinguished from certain and possible ones.

4 Overview of future modelling techniques for the needs of exploitation scenario building

The practical result of the future modeling process, is, or should be a set of indications and recommendations for responding to potential situations that may occur in a given period in the future. This set is created in the scenario process carried out by agreed methodology. It should be noted, that at present there is a large variety of interpretive freedom of aspects of future modeling. This has led to the creation of many methods and techniques used in the scenario processes and, consequently, to develop models describing future events and forms of behavior of technical objects. It is reasonable to extract and organize the methods and techniques, which can play a significant part in the exploitation process modeling. In this regard, there are three key concepts of modeling, in particular:

1. Intuitive logic concept focuses on methods and procedures that allow for generating of future options based on the outcome of the creative thinking process, building on the experience and opinions of people who form the scenario team. The result of most of the modeling procedures is a set of equivalent future options, in the form of narrative descriptions of the development of the identified events in a strictly defined time in the future. The main varieties of this concept are: GBN model (Schwartz, 1991), TAIDA model (Lindgren and Bandhold, 2009) SRI model (Ralston and Wilson, 2006), PBSS model (Chermack, 2011).

2. The "La Prospective" concept is based on the methodological assumption, saying that the future is not predetermined part of time continuity, but it is a series of emerging events and situations, consciously modeled for the benefits to the human (Bradfield et al., 2005). In practice, the starting point of La Prospective concept is similar to the concept of intuitive logic, but in this case, each of the major steps is mathematical and tool-supported. The most important methods of supporting this concept include (Ringland, 2006): structural analysis, actors analysis and morphological analysis. Among the available supporting computer tools the most important are: (Godet, 2006): MICMAC, MACTOR, MORPHOL, SMIC-PROB-EXPERT or MULTIPOL.

3. Probabilistic concept is rooted in the statistical analysis of trends and extrapolations. The basis of the most quantitative approaches to future modeling is a combination of the two methods (Glenn and Gordon, 2009):

- Trend Impact Analysis (TIA), which is an extension of classical trend analysis and extrapolations about the systematic study of the effects of possible future events, which are taken as valid,
- Cross Impact Analysis, which is used in conjunction with TIA and complements the probabilistic model about the need to determine the value of the conditional and mutual probabilities of possible pairs of potential future events.

5 Research of conditions of maintenance decision-making process in technical network system - case study

The considerations of decision-making process in terms of potential future modeling methods have become a prerequisite for scientific research undertaken by the author. These studies were carried out in a specific exploitation environment, which is technical network system.

Technical network systems are included in the technical infrastructure, which are crucial for industrial and municipal engineering sector. Technical network systems include (Fig. 1): water supply system, sewers system, gas supply system, heat supply system and electric transmission system.
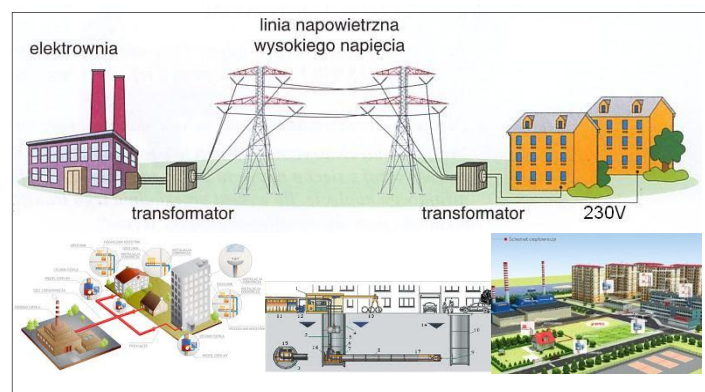
Figure 1. Examples of network technical systems

Through the technical network systems, various types of media complying with the required specifications are supplied to multiple groups of customers, belonging to different categories, such as households, industrial plants, utilities, service facilities and others.

Exploitation specificity of technical network system requires to ensure continuity and quality of supplies within an extensive technical infrastructure geographically dispersed over a large area. Therefore, such systems are characterized by a number of specific features, which include (Loska, 2012b):

- territorial dispersion of the system components,
- specific location of system components, often difficult to access - underground, at a height,
- high structural complexity, large number and variety of types of objects within the system, powerful links and relationships between system components,
- high dynamics of the system, which requires continuous control and monitoring of the processes performed,

- uninterrupted operation for most installations, equipment and buildings belonging to the system.

These features determine specific capabilities and limitations of maintenance tasks, that differ from the works in typical industrial enterprises focused on the production line exploitation.

A typical example of a technical network system is a water supply system which functions as a collective water supply which consists of the exploration, treatment and water supply to its customers. Water supply operating should meet the needs of the population in terms of organization and constance (continuity) , with the required level of pressure and of appropriate quality (i.e. smell, taste, chemical composition) (Kaźmierczak et al., 2012). Scheme of an exemplary water supply system is shown in Fig. 2.
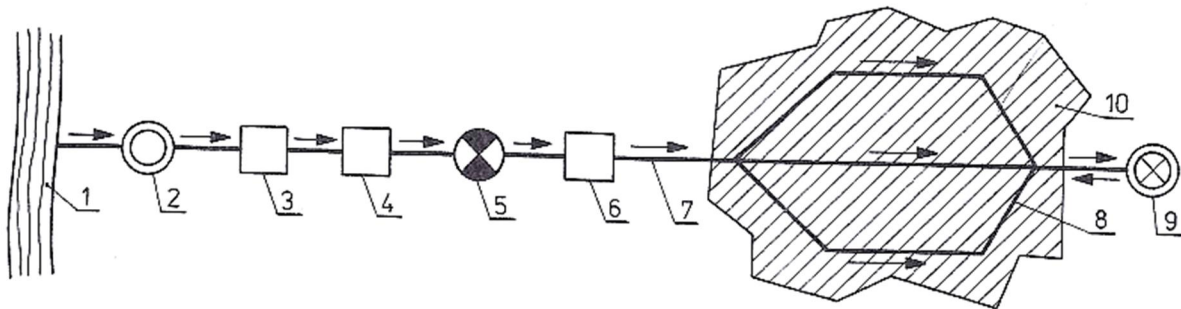
Figure 2. General scheme of the water supply system (Denczew and Królikowski, 2003)
1 - water intake, 2 - cumulative well, 3 - pump 1st degree, 4 - water treatment station, 5 - terrain lower reservoir, 6 - pumping station 2nd degree, 7 - main distribution pipe, 8 - distribution network, 9 - top marginal tank, 10 - the area of distribution

Research on the identification of key exploitation features of the water supply system, which can affect the decision-making process, included exploratory and analytical work in one of the water companies in Poland, in particular:

1. Identification and organization of information about on the functioning of the water supply network, collected in the documents of the maintenance department staff. The scope of the information collected and analyzed in this case, are shown in Tab. 1.

Table 1. Types of exploitation information resources collected (Loska, 2012a)

Permanent information resorces	Variable information resources
Information about exploitation processes and events	
• information about maintenance processes • procedural list of maintenance tasks • information about maintenance cycles and routes	• information about exploitation events
Information about the operating parameters of exploitation objects	
• information about permanent operating parameters	• information about variable operating parameters
Information about the possible causes of unintended events	**Information about exploitation history of technical objects** • information about history of exploitation events • information about exploitation object location • information about downtime history
Information about structures of technical objects	**Information about resources availability**

2. Analysis of information on the implementation of the maintenance works, collected in the ERP system - EGERIA
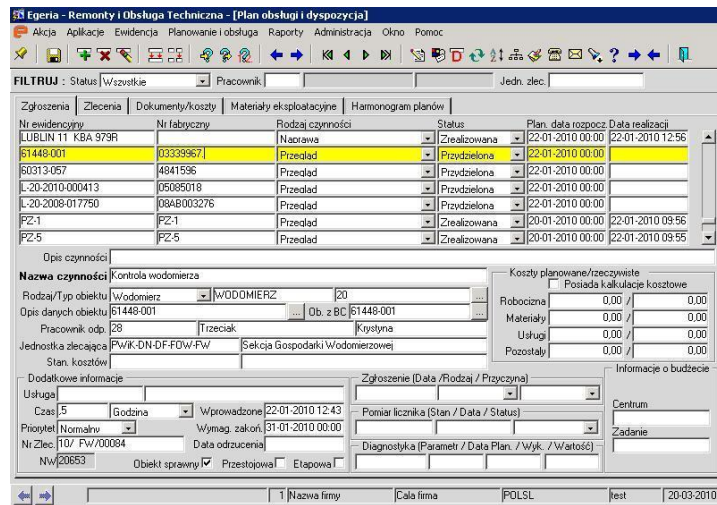
Figure 3. Sample screen of ERP Egeria system

3. Using the results of analytical tools ISSOE (Intelligent System for Supporting Operational Events), co-developed by the author of this article, the function of which is detailed assessment of maintenance activity within particular sections of the water supply system. Operations of ISSOE (Kaźmierczak et al., 2012) involve determination and interpretation of the ranking based on the prepared method for exploitation assessment (Loska, 2013). Set of exemplary screens of ISSOE system is shown in Fig. 4.
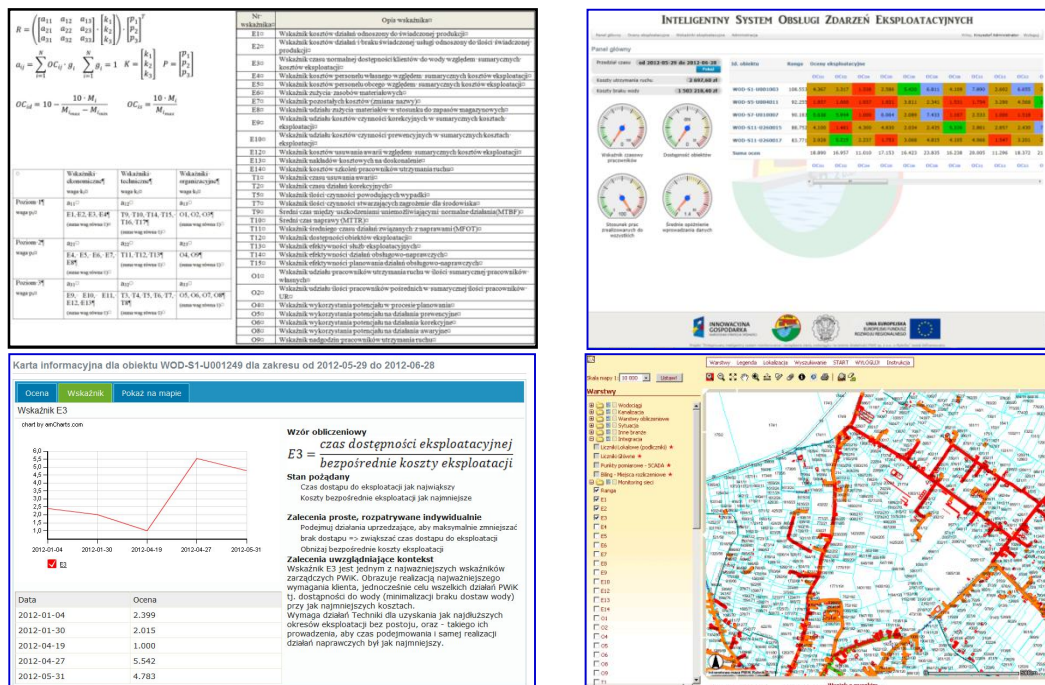
Figure 4. Selected screens of ISSOE system

Taking into account the results of studies performed, maintenance works characteristic for the water supply system are structured and ordered in the four groups:

A. Maintenance of water pipes, fittings and connected equipment capable of full technical efficiency, through systematic monitoring of network devices and objects, overview and control of technical infrastructure, maintaining the state of pipes and securing them against harsh weather conditions (eg. freeze).

B. Constant monitoring of water supply system operating parameters in terms of quantity and quality of water supplied. In this regard, continuous monitoring of pressure flow parameters in pipes and main distribution network is carried out. Moreover, regulatory actions are performed, which often rely on manipulation of bolts in order to compensate flow and pressure in the network.

C. Carrying out planned and corrective maintenance works, among which one can distinguish: water protection against infection/contamination, cleaning of sewage water pipes, scheduled inspections, repairs and possible replacement of individual elements of the water supply system.

D. Removal of damages and failures, which result mostly from the longitudinal and transversal cracks in pipes, damage to seals (eg. pushing the seal), pitting corrosion, damage to welds, inability of closing the ball valves in hydrants. For this type of works one should also include defrosting of ducts and their equipment, particularly those laid shallow subterrestrial. .

These groups of maintenance work, in the analyzed company, are placed in order according to the following typical classification:

- review - a collection of planned operations under appropriate schedules, which are intended to check the degree of wear or damage to the components of technical objects, to remove minor defects and to determine the approximate range of the nearest maintenance planned work (eg fire hydrants control, drainage control),

- preservation - a set of activities related to: cleaning, lubrication, checking the technical, exploitation security, maintenance of pressure reducing valves, flushing water mains terminals and other,

- repair - a task carried out as a result of failure to restore the performance of a technical object (eg. water supply pipe repair),

- overhaul - the corrective task, which is the result of the review conducted previously (pump repair PJM).

Analysis and assessment of share of different types of work in the total number of maintenance jobs is an indicator of the operational strategy of the company and manifests itself in the form of guidelines of the decision-making model. The analysis carried out in this area, including all processed maintenance work, in terms of quantity and cost, indicated preventive - quantitatively and intervention - cost character of exploitation decision-making process. Results of the analysis are shown in Tab. 1 and Fig. 5.

Table 2. Summary of quantities and costs of maintenance works in 2012

Data type	Reviews	Preservations	Repairs	Overhauls
Number of works	4124	815	395	400
Percentage of works	71,92%	14,21%	6,89%	6,98%
Costs of works	86 989,69 PLN	88 942,47 PLN	197 020,03 PLN	154 029,17 PLN
Percentage of work costs	36,36%	3,03%	9,09%	51,52%
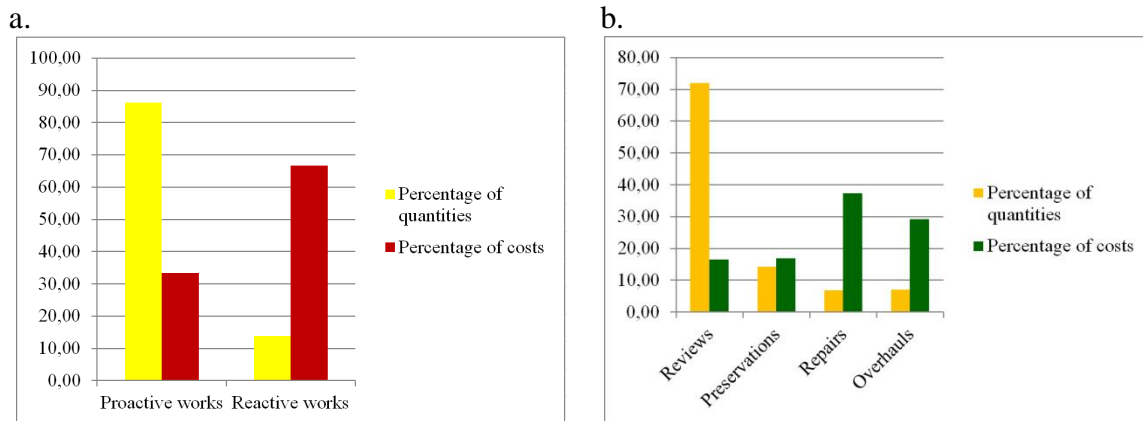
Figure 5. Chart of quantities and costs of maintenance works in 2012

Analysis results of quantity and cost of maintenance works, shown in Fig. 5, allow to make the identification and interpretation of the maintenance strategy of the water supply company. In particular, there should be paid attention to four aspects of:

- relatively large number of proactive works with simultaneously lower relative cost-share of these works (Fig. 5a),
- significant share of the costs of reactive works, with a significantly lower number of works of this type (Fig. 5a),
- significant share of the works of identifying the technical condition - overview, which are characterized by a relatively low cost in the analyzed network technical system (Fig. 5b),
- the largest in terms of costs, the share of repair works for the elimination of the consequences of failures, with the least amount of these works (Fig. 5.b).

The considerations given above and the results of the analysis, as well as highlighted earlier organizational and technical conditions of maintenance works in technical network systems, create the need for an individual approach to build maintenance strategy and exploitation policy model. In particular, the nature and location of individual network elements do not allow for a flexible approach to the types and quantity of work performed, and that limits the possibility of full optimization of costs of maintenance tasks.

For these reasons, it seems reasonable to identify possible future trends of selected features that may have influence on the maintenance strategy and exploitation policy of the analyzed company.

6 Construction of the future models for the needs of exploitation decision-making process - case study

In response to the conclusions drawn from the analysis of functioning of the maintenance staff of the water supply company, there was prepared a set of scenarios that demonstrated the potential and possible directions of development of the operational policies. These scenarios can also be the basis of current decision-making process in preparation of the company and itstechnical system to the possible effects and the results of changes in the future.

For this purpose, under the general steps layout of the scenario modeling (Schwartz, 1991), there was developed a procedure of future images construction of exploitation policy of analyzed water supply company. The procedure, consisting of four steps, is shown in Fig. 6.

| **1** Formulating the main scenario problem | → | **2** Identification of key forces and driving forces | → | **3** Developing a ranking of influence and relationships | → | **4** Developing the future scenarios |
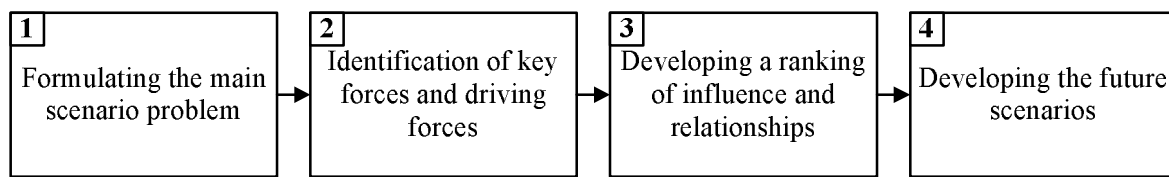
Figure 6. Procedure of constructing of future construction of exploitation policy in the water supply company

Stage 1 was part of the initialization of scenario process and it allowed identification the main scenario problem as a question:

Which aspects will have long-term impact on the development of exploitation policy?

Stage 2 focused on identification and select those factors, that influence the root problem or decision problem (decision). In this case, there were selected 25 factors in two areas (Fig. 7):

- closer environment (internal) of exploitation policy, as a so-called key forces, by the analysis of the method and conditions for the functioning of maintenance in the company,
- further environment (external) of exploitation policy, as a so-called driving forces, by implementing of the STEEPVL analysis (Nazarko, 2010), i.e. the identification of factors associated with the following categories: Social, Technological, Economic, Ecological, Political, Value, Legal.
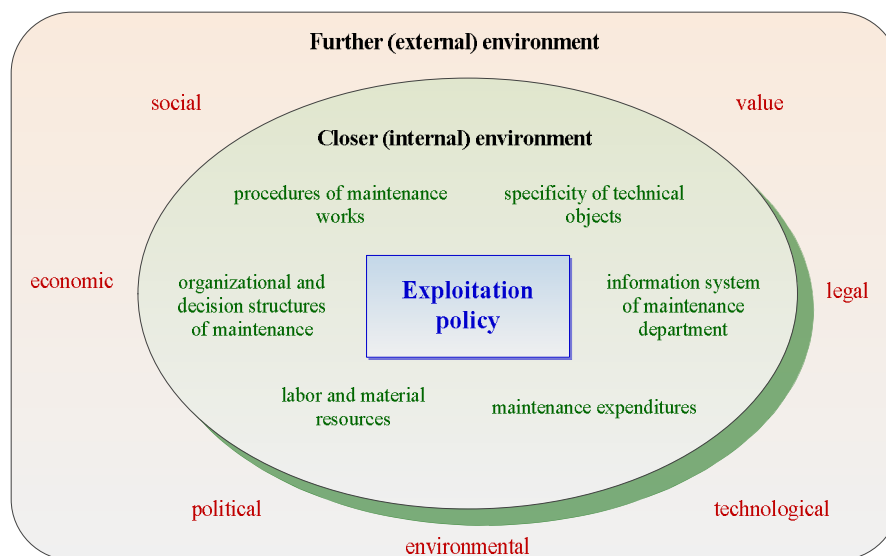
Figure 7. Factors categories of internal and external environment of maintenance department of the water supply company

Stage 3 involved extracting two key factors, which will be a kind of the scenario scheme for the needs of realization the next step. This stage was carried out on the basis of the following tasks (Fig. 8):

- identification of mutual influences and relationships between the factors, based on the assumptions of structural analysis using the MICMAC program,
- choosing two factors - the most important and the most uncertain, as the basis for building scenarios models, through analysis and discussion of the elaborated matrices and charts.
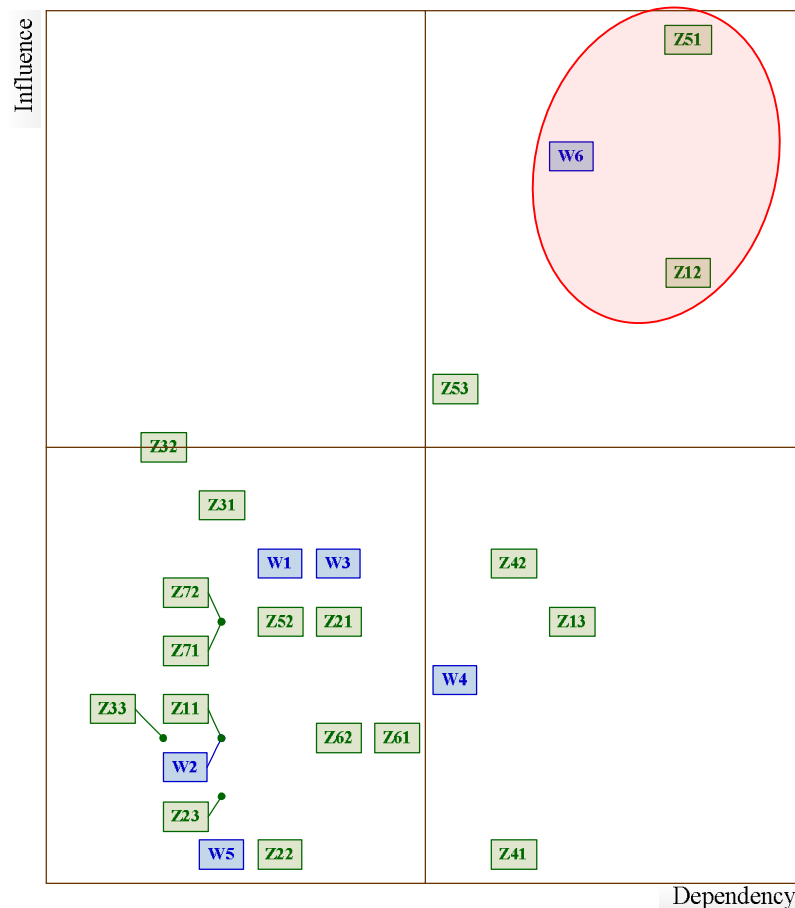
Figure 8. Graph of distribution of development factors of exploitation policy in the water supply company

As a result of stage 3, there have been extracted three factors (two primary and one supplementary) of exploitation policy development in the water supply company, in particular:

Z12   Dynamics of changes in water use
Z51   Knowledge and technical level of maintenance staff
W6   Expenditures invested to the development and implementation of modern maintenance methods and tools

Stage 4 was to study the structure and content of the scenarios. Scenario model was based on two axes of key factors, each of which allows you to assign two possible directions of development. It means the possibility prepare four separate future images, as a result of a combination of possible values of the anticipated results of the analyzed factors. Fig. 9 shows the result of the combining process of selected factors in the form of possible scenarios for the exploitation policy development.
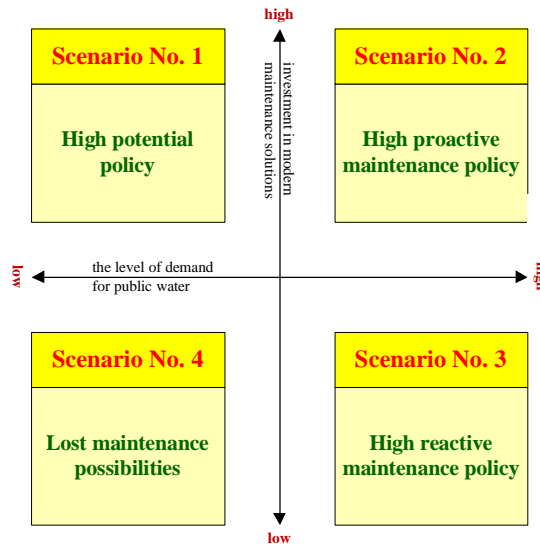
Figure 9. Layout of future scenarios of exploitation policy development in the water supply company

Presented collection of scenarios (Fig. 3) has been described in a table (Tab. 3), which was supplemented with the knowledge and technical level of maintenance staff.

Table 3. The collection of symbolic description of exploitation scenarios

Scenario 1: High potential policy	Scenario 2: High proactive maintenance policy
Long-term stabilization of water consumption at an average level. The high financial and human expenditures invested to the development and implementation of new methods and tools for maintenance work. A high level of knowledge and technical culture of maintenance staff.	Strong growth and continued high requirements of community for water. The high financial and human expenditures allocated to the development and implementation of innovation solutions of maintenance work. A high level of knowledge and technical culture of maintenance staff.
Scenario 4: Lost maintenance possibilities	**Scenario 3: High reactive maintenance policy**
Low requirements and water consumption. Low level of funding and a lack of willingness to use innovative maintenance solutions. Low motivation of maintenance employees to development activities.	Strong growth and continued high requirements of community for water. Low level of funding and low involvement of staff in sourcing innovative tools supporting maintenance activities. The low level of knowledge, but a high degree of technical culture of maintenance staff.

Symbolic (factorial) recording of possible directions of changes in the maintenance management of the water supply company, can be supplemented with a narrative description (mostly extensive) of additional facts and non-technical circumstances. However, descriptive form with a more explanatory character and introductory to the deeper discussion is of little value and effectiveness for the exploitation decision-making process.

7 Conclusions

A set of scenarios prepared by the author shows the possible directions of development of the maintenance policy of the exemplary company. However, to effectively use scenario models in exploitation decision-making process, it is necessary to develop detailed measures for the simulation of the effects and consequences of decisions made.

Therefore, presented in this article, methodological assumptions and example of construction of scenarios, are some of the aspects of the author's research (Loska, 2012c) on the use of future modeling techniques for the exploitation decision-making process. Ongoing work focuses on the quantitative interpretation of the factors of exploitation policies using a set of maintenance assessments (Loska, 2013), as well as on verifying the effectiveness of modeling the future in the areas of industrial technology, other than the networked technics.

5 Acknowledgements

References

Bradfield, R., Wright, G., Burt, G., Cairns, G., van der Heijden, K. (2005) 'The origins and evolutions of scenario techniques in long range business planning', *Futures 37*, pp. 795-812.

Campbell, J.D. (1995) 'Outsourcing in maintenance management. A valid alternative to self-provision', *Journal of Quality of Maintenance Engineering*, Vol. 1, No. 3, pp. 18-24.

Cempel C. (1989) 'Diagnostyka wibroakustyczna maszyn', *Państwowe Wydawnictwa Naukowe*, Warszawa, Poland.

Chermack, T.J. (2011) 'Scenario planning in organizations. How to create, use and assess scenarios, *Berret-Koehler Publishers, Inc.*, San Francisco, USA.

Cholewa, W., Kaźmierczak, J. (1995) 'Data processing and reasoning in technical diagnostics', *Wydawnictwa Naukowo-Techniczne*, Warszawa, Poland.

Denczew, S., Królikowski, A. (2003) 'Podstawy nowoczesnej eksploatacji układów wodociągowych i kanalizacyjnych', *Wydawnictwo Arkady*, Warszawa, Poland.

Glenn, J.C., Gordon, T.J. (2009) 'Future Research Methodology. Version 3.0', *The Millenium Project Publication*.

Godet, M. (2006) 'Creating Futures. Scenario Planning as a Strategic Management Tool - second edition', *Economica Ltd.*, Paris, France.

Kahn, H., Wiener, A.J. (1967) 'A Framework for Speculation on the Next Thirty-Three Years' *The Hudson Institute Inc.*, New York, USA.

Kaźmierczak, J. (2000) 'Eksploatacja systemów technicznych', *Wydawnictwo Politechniki Śląskiej*, Gliwice, Poland.

Kaźmierczak, J., Loska, A., Dąbrowski, M. (2012) '*Use of geospatial information for supporting maintenance management in a technical network system*', 21th European Congress on Maintenance and Asset Management Euromaintenance 2012, 14-16 May 2012, Belgrad (Serbia), pp. 287-297.

Kelly, A. (2006) 'Strategic Maintenance Planning', *Butterworth-Heinemann, Elsevier*, Oxford, UK.

Konieczny, J. (1975) 'Podstawy eksploatacji urządzeń', *Wydawnictwo Ministerstwa Obrony Narodowej*, Warszawa, Poland.

Lindgren, M., Bandhold, H. (2009) 'Scenario Planning. The Link Between Future and Strategy - second edition', *Palgrave Macmillan*, New York, USA.

Loska, A. (2012a) 'Wybrane aspekty komputerowego wspomagania zarządzania eksploatacją i utrzymaniem ruchu', *Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją*, Opole, Poland.

Loska, A.(2012b) 'The way of use scenario methods in maintenance management of selected network technical systems', *Proceedings of International Conference Narodne Forum Udržby (National Forum on Maintenance)*, 29-30 May, 2012, Vysoke Tatry, Slovakia, pp. 120-128.

Loska, A. (2012c) 'Remarks about modelling of maintenance processes with the use of scenario techniques', *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, 2012; 14 (2): 5–11.

Loska, A. (2013) 'Exploitation assessment of selected technical objects using taxonomic methods', *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, 2013; 15 (1): 1–8.

Nazarko, J., Kędzior, Z. (2010) 'Uwarunkowania rozwoju nanotechnologii w województwie podlaskim. Wyniki analiz STEEPVL i SWOT', *Oficyna Wydawnicza Politechniki Białostockiej*, Białystok, Poland.

Ralston, B, Wilson, I. (2006) 'The scenario planning handbook. Developing strategies in uncertain times', *South-Western Cengage Learning*, Mason, USA.

Ringland, G. (2006) 'Scenario planning. Managing for the future', *John Willey & Sons, Ltd.*, Chichester, GB.

Schwartz, P. (1991) 'The Art of the Long View. Planning fot the Future in an Uncertain World', *Currency Doubleday*, New York, USA.

Suzuki, T. (1994) 'TPM in Process Industries', *Productivity Press*, Portland, Oregon, USA.

Van der Heijden, K. (1996) 'Scenarios. The Art of Strategic Conversation', *John Wiley & Sons*, Chichester, UK.

Wang H., Pham H. (2010) 'Reliability and Optimal Maintenance', *Springer-Verlag*, London, GB.

Żółtowski B. (2010) 'Modelowanie procesów eksploatacji', *Wydawnictwo Naukowe Instytutu Technologii Eksploatacji - PIB*, Radom, Poland.

Economic and environmental impact analysis of maintenance policies for service planning through system dynamics

Marco Macchi[1], Klodian Farruku[1], Maria Holgado[1]*, Elisa Negri[1] and Daniele Panarese[2]

[1]*Department of Management, Economics and Industrial Engineering, Politecnico di Milano, 20133 Milano, Italy*
[2]*Fidia S.p.A.,Corso Lombardia 11, 10099 San Mauro Torinese, Italy*
*Corresponding author: Maria Holgado
e-mail: marco.macchi@polimi.it, klodian.farruku@polimi.it, elisa.negri@polimi.it, maria.holgado@polimi.it
e-mail: d.panarese@fidia.it

Abstract

Manufacturers of durable goods have experienced a growing interest towards the market of after-sales services as a mean of creating higher added value to their customers. This work focuses on maintenance services as the key to improve after-sales services, having a particular concern on the selection of policies. A trade-off analysis of economic and environmental impacts shows the contribution of maintenance services to the sustainable value creation in a service network. A particular attention is paid to the service delivery through technological platforms such as those due to the E-maintenance paradigm. In this regard, systems dynamics is used as a tool to assist the prediction of sustainable value creation of maintenance services through such platforms. Even if the focus is on each manufacturer – customer relationship, synergies at network level achievable when a market is expanding are envisioned as further gains to be investigated in future researches.

Key words: maintenance policies, service planning, system dynamics, eco-efficiency.

1 Introduction

Due to the high and fierce competitive pressure companies in the Business to Business (B2B) market are facing, it is more and more difficult to differentiate products on the basis of technological superiority only, margins associated to the product sale are decreasing and there is the need to exploit new growth potential in mature markets. In this context, services have become a possible source of competitive advantage (Cohen et al., 2006; Gebauer, 2008; Goffin, 1999; Wise and Baumgartner, 1999;) and an increasing number of traditionally product-oriented companies are investing on the extension of the service business linked to their products (Gebauer and Puetz 2009). This trend, commonly labeled as "servitization", refers to the process of creating value by adding services to products. The organizational shifts needed to undertake the servitization strategy lead to the development of new ways to process traditional services, whilst new services are also introduced.

Amongst the most traditional services, in the present paper attention is addressed towards technical assistance. Technical assistance has a key role in the industrial sector to ensure a relationship of loyalty and trust between manufacturer and customer: it consists in providing technical oriented services during operation and maintenance of an equipment, which may be relevant for the customer for a number of years, thus being an opportunity for important investments and for the creation of strategic partnerships. According to (Sheng et al., 2009) "the key to improve service for a manufacturer is to improve maintenance service". To achieve this objective, a number of technical and technological issues should be adequately developed. It is worth mentioning (Morel et al., 2009) in this regard: they suggest that the customer can effectively maintain remote (technical) service contracts with a number of Original Equipment Manufacturers (OEM) as suppliers (i.e., providers of the services) when a technological architecture is deployed to integrate different components such as the control, maintenance and technical management systems. This is well in phase with the actual trend of continuous development of Information and Communication Technologies (ICTs), which has in fact created new potentials for the manufacturer – customer integration. Indeed, thanks to technological advances in the fields of communications, electronics, information technology, an increasing part of ICT components can nowadays be distributed at the very heart of a product/equipment. The presence of such components (RFID, smart sensors, sensor networks, web services embedded in the product/equipment, etc.) plays a fundamental role in enhancing integration through product/equipment intelligence: the goal is the use of product/equipment intelligence to support an effective technical assistance (Lee et al., 2006) and to create more information and knowledge availability on services, thus adding value (Allee, 2000). The trend towards Intelligent Maintenance Systems (IMSs) is reinforcing such a concept, leading in the more recent years to visionary expectations on the transformation of Prognostics and Health Management to Engineering Immune Systems, which would end up with the availability of smarter machines operating based on autonomic and cloud computing (Lee et al., 2011).

In this scope, we are concerned with products in a B2B relationship (hence durable equipment like machine tools), and the ICT potentials in order to improve intelligence for Condition Based Maintenance (CBM) and, further on, Prognostics and Health Management (PHM). The integration between ICT and CBM techniques has been traditionally discussed under the E-maintenance paradigm. This is thought as an avant-garde strategy that can be followed to deploy CBM programs. (Muller et al., 2007) gave birth to an E-maintenance definition, keeping in mind also the European standard (EN 13306:2001): "*maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (ICT, web-based, tether-free, wireless, infotronics technologies) but, also, e-maintenance activities (operations or process)*" Through E-maintenance technologies and related activities, CBM programs can bring benefits both for the customer, as owner of the product/equipment, and for the OEM, as provider of the maintenance services. Benefits can be further enhanced considering the convergence of PHM in the scope of E-maintenance, as it is nowadays observed. All in all, E-maintenance technologies are becoming relevant enablers for many issues in maintenance management, e.g.: (i) to support accurate diagnosis of faults, thus speeding up the time needed for the on-call repair; (ii) to analyze the potential faults, in order to anticipate incoming failures, thus avoiding undesirable stoppages for the customer using the product; (iii) to better plan maintenance interventions and related requirements for spare parts and technical personnel thus optimizing the logistics support, which can be also closely linked to prognostics and health management especially for short term planning; (iv) to get important information about

the evolution of the state of the product during the time and its use, in order to finally customize the service provision based on customer requirements; (v) to further retrieve information for continuous improvement of the product-service performance.

All these potentials are widely discussed in literature, for example (Lee et al., 2006, Lee et al., 2011, Levrat et al., 2008, Muller et al., 2007). Nonetheless, they should be studied in more detail in order to properly quantify the values that can be achieved. It is indeed clear that the industrial application of E-maintenance technologies is a matter worth of discussion for an enhanced understanding of their values for business. To this concern, the typical questions that have to be answered can be e.g.: how much money would a company save, or gain, by adopting this kind of technologies? how much is the investment rewarding for the invested capital? Furthermore, since E-maintenance has been claimed as a lever for sustainable manufacturing, especially considering the eco-efficiency (Levrat et al., 2008; Garetti and Taisch, 2012), the relevant stimulus is today also to investigate environmental issues. Accordingly, the questions may be the following ones: which value can a company achieve from this kind of technologies in terms of resource and energy use, carbon emissions, waste management? Is there any relevant environmental impact from the Product-Service System resulting from E-maintenance service technologies deployed on a product/equipment? Such questions – leading to economic and environmental concerns – relate to the understanding of relevant levers enabling and/or boosting the competitiveness of OEMs implementing a servitization strategy with the final goal of increasing market share, financial health and profitability.

This paper should be considered as a further development of precedent researches, focused on cost-benefit analysis, e.g. (Fumagalli et al., 2010), and value assessment of E-maintenance platforms (Macchi et al. 2012): the paper aims at enlarging the discussion on economic and environmental impact analysis. Besides, system dynamics is used with the aim of unveiling the trade-offs of different impacts of interest: in this regard, the research can also be considered as an extension of a previous experience dealing with the support of an OEM – customer relationship, and using system dynamics to set-up CBM services in view of their technical and economic impacts for the customer (Ferri et al., 2012). Therefore, the paper extends the target impacts considering some environmental factors relevant for the machine tool sector; the focus is still on the OEM – customer relationship, even if a broad scope can be also taken into account, as synergies at the network level are promising for CBM/PHM delivery through E-maintenance platforms. The work is now on progress in the frame of an EU funded project on "Sustainable value creation in manufacturing networks", SustainValue: this paper is bounded to maintenance service, and on the project results currently achieved at demonstration phase in FIDIA, a machine tool builder whose strategy aims at offering competitive services for an economic and eco-efficient manufacturing.

The paper is organized in four other sections. Section 2 introduces a review of performance measures for economic and environmental assessment. Further on, the literature review is focusing on the assessment methodologies oriented to the life cycle: this aims at providing the background for impact analysis of maintenance services in the product/equipment use life. Section 3 presents system dynamics applied to analyze maintenance policies, in order to eventually support the maintenance service planning; life cycle costing and environmental assessment are then discussed, as they frame the adoption of system dynamics in order to predict the expected impacts of maintenance policies planned in a service contract. Section 4

focuses on the FIDIA case study, showing a trade-off analysis of economic and environmental impacts of maintenance policies, with a special concern on the customer as main stakeholder. Concluding remarks of section 5 shortly extend the discussion at the network level.

2 Literature analysis

2.1 Performance measures for economic and environmental assessment

Economic performances to evaluate alternatives have always been subject to a great interest both in literature and in practice, due to their fundamental importance for organizations. The traditional economic performance measures are the well known total costs and revenues estimations (an example of indicator is the Net Present Cost). Alongside to these are the project performance evaluation measures (an example is the Payback Period). Some authors maintain also that not only costs and revenues must be the focus of the economic evaluation, but also the revenue loss must be kept monitored (Chang and Lewins, 1996). This is also relevant for maintenance management: indeed, the theory of hidden costs considers costs resulting from performance losses, subsequent to downtimes/unavailability, non-quality/low product rate, etc… (Furlanetto et al., 2006, Crespo et al., 2009, Salonen and Deleryd, 2011). The theory recommends the calculation of indicators separating the hidden from the visible costs (these include the resources directly spent in the maintenance budget, such as for spare parts or services from third parties, or indirectly, e.g. for maintenance coordinators or other roles in the maintenance staff).

The environmental dimension has also received an extended exposition in literature: many authors have proposed formulas for the computation of many indicators. Energy consumption and global warming potentials are amongst the most relevant impact categories, because of the strict regulations from government and public awareness. Indicators for these impacts are, respectively, the needed kWh and the emitted kg of CO_2 equivalents. The meaning of the latter lies in the fact that the several greenhouse gases, which are main cause of the global warming, impact on the temperature raise potential to a different extent; a reference substance (carbon dioxide – CO_2) is defined, to which the other compounds are referred to through a multiplication factor which expresses the CO_2 equivalence for each of them (Narita et al., 2006). The total global warming potential of an industrial activity would, therefore, be the sum, for all harmful substances, of the emitted quantity due to the system in question multiplied by the CO_2 equivalence factor of each substance. Besides energy and global warming potentials, literature presents also other impact categories, such as total resource depletion, expressed in kg (Ritthoff et al., 2002). Moreover, emissions also lead to other impacts: articles suggest to consider many indicators, out of scope of this paper (Derwent et al., 1998; Pehnt, 2006; Seppälä et al., 2004; World Meteorological Organization, 2006).

Eventually, there are examples in literature of performance measures that could be considered both accounting for economic and environmental impacts at the same time. These are due to the techniques of Total Cost Accounting, consisting in the attempt to monetize environmental effects as additional costs and to enclose them into the economic assessment, by summing them to the other financial parameters (Norris, 2001). However, the difficulty in computing these costs has prevented the diffusion of these techniques.

2.2 Life cycle costing and life cycle environmental assessment

The most relevant performance measures can be assessed considering the total contribution, both for economic and environmental dimensions. The totality is intended with respect to the equipment life cycle time span.

Life Cycle Costing (LCC) is defined as "all costs associated with the system as applied to the defined life cycle" (Rebitzer et al., 2003). It is usually measured through the Net Present Cost indicator, which can be interpreted as Total Cost of Ownership (TCO) in case the focus is on the customer/user of the good in question (Rebitzer et al., 2003). On the other hand, Life Cycle Assessment (LCA) is the denomination that the environmental impacts assessment has received by the International Standard ISO (ISO 14040, 1997). This defines that all effects of a product on the ecosphere must be accounted for. For this reason, the complete life of the product, from cradle to grave, must be considered, including all the phases such as raw material extraction, materials processing, manufacture, assembly, distribution, use, repair and maintenance, and disposal or recycling. All in all, it may be considered that the natural economic counterpart of the environmental LCA is the LCC, even if, in the two domains, accounting for life cycle impacts reflects different meanings: if the environmental sphere wants to account for all of the consequences that can be connected to the system production, use and disposal, the economic sphere accounts for financial flows in the perspective of one single player (especially because inflows of a player are outflows for its customer and so on). These differences must be kept in mind when performing both assessments, economic and environmental, on a certain system. Moreover, the environmental assessment presents a degree of freedom, consisting in the fact that the performer of the LCA is required to choose the "types of impact and methodology of impact assessment" (ISO 14040:1997). This means that a discretional choice must be performed among the several possible environmental impacts that are suggested in literature, such as energy consumption, global warming, acidification, euthrophication, ozone depletion, resource consumption, waste generation ...

3 Models for impact analysis of maintenance policies

3.1 State based modelling

Maintenance policies are analyzed through modeling of the degradation and repair processes of the target equipment. The following assumptions stand:

i) the degradation process consists either of a progressive wearing out or of a sudden failure; the progressive wearing out is modeled by using a discrete and finite set of states, with the purpose to represent intermediate states for the degraded conditions in between the default states of ′working as good as new′ and ′fault′;
ii) the repair process consists of two types of activity, either a perfect or a minimal repair; the perfect repair results in the ′working as good as new′ state, after replacing the worn-out or broken parts; the minimal repair consists of a reconfiguration action – in the remainder mentioned to as conditioning intervention –, carried on in order to allow the equipment to continue its mission but at a ′reduced speed′;

iii) in case of a corrective maintenance policy, repair is activated when the customer detects more ′product quality defects′ than expected (e.g. by means of a control chart), or has to stop the equipment because some functional anomalies occur not allowing further working (which is the ′fault′ state); as an assumption, perfect repair is carried on whenever the ′fault′ state is reached, while in case of ′product quality defects′ it is decided whether making a minimal or a perfect repair, based on the equipment condition.

Next Figure 1, correspondingly, draws out the state space model of the equipment, classifying its finite set of states according to their functional and technical performance. In particular, technical performance relates to the Overall Equipment Efficiency (OEE) of the equipment: it is easy to deduce that performance in production speed (P), product quality rate (Q) and availability (A) are resulting factors of the state space model, hence OEE can be subsequently calculated (i.e. OEE = P x Q x A).
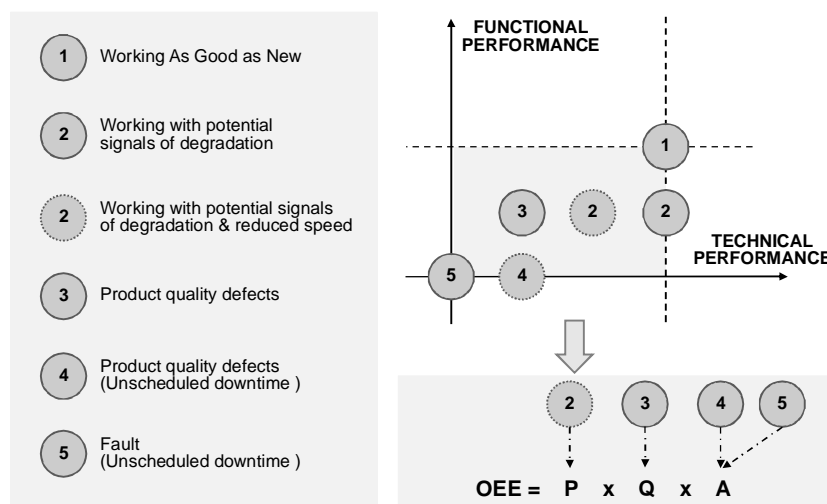
Figure 1. Model of functional - technical performance of the equipment as a finite state space

Further assumptions relate to the preventive maintenance policy:

iv) it is considered a periodic inspection aimed at assessing the equipment health state through its ′potential signals of degradation′ (at state 2); repair is then scheduled as a consequence of the inspection results; hence, two further states – additional to the state space model of Figure 1 – are the inspection (i.e. state 6) and the preventive repair (i.e. state 7);
v) preventive repair may lead either to state 1 in case of perfect repair, or back to state 2 after a minimal repair; this depends on the equipment condition, similarly to what happens in the case of a corrective maintenance subsequent to ′product quality defects′.

A state based modeling technique is now adopted with the purpose to represent the dynamical behaviour of the equipment through its discrete state changes. Several state based modeling formalisms are available, such as State Transition Diagrams (STDs), Markov Chains, Petri Nets and any of their extensions (Trivedi and Malohtra, 1993). This work adopts STD, exploiting its generic modeling features which allow to formalize transitions according to their triggering events, eventual actions carried on, and the guarded condition under which the transitions may happen (according to the formalism, a label along a transition is reported as

"event / action [condition]"). As a result, the following STDs (see in Figure 2) describe the dynamics of the degradation and repair processes considered for the analysis. According to the modeling assumptions kept for this work, a relevant condition occurs whenever it has to be decided whether carrying on a perfect or a minimal repair (i.e., both at state 4 and 7, respectively for the case of corrective and preventive maintenance policy).
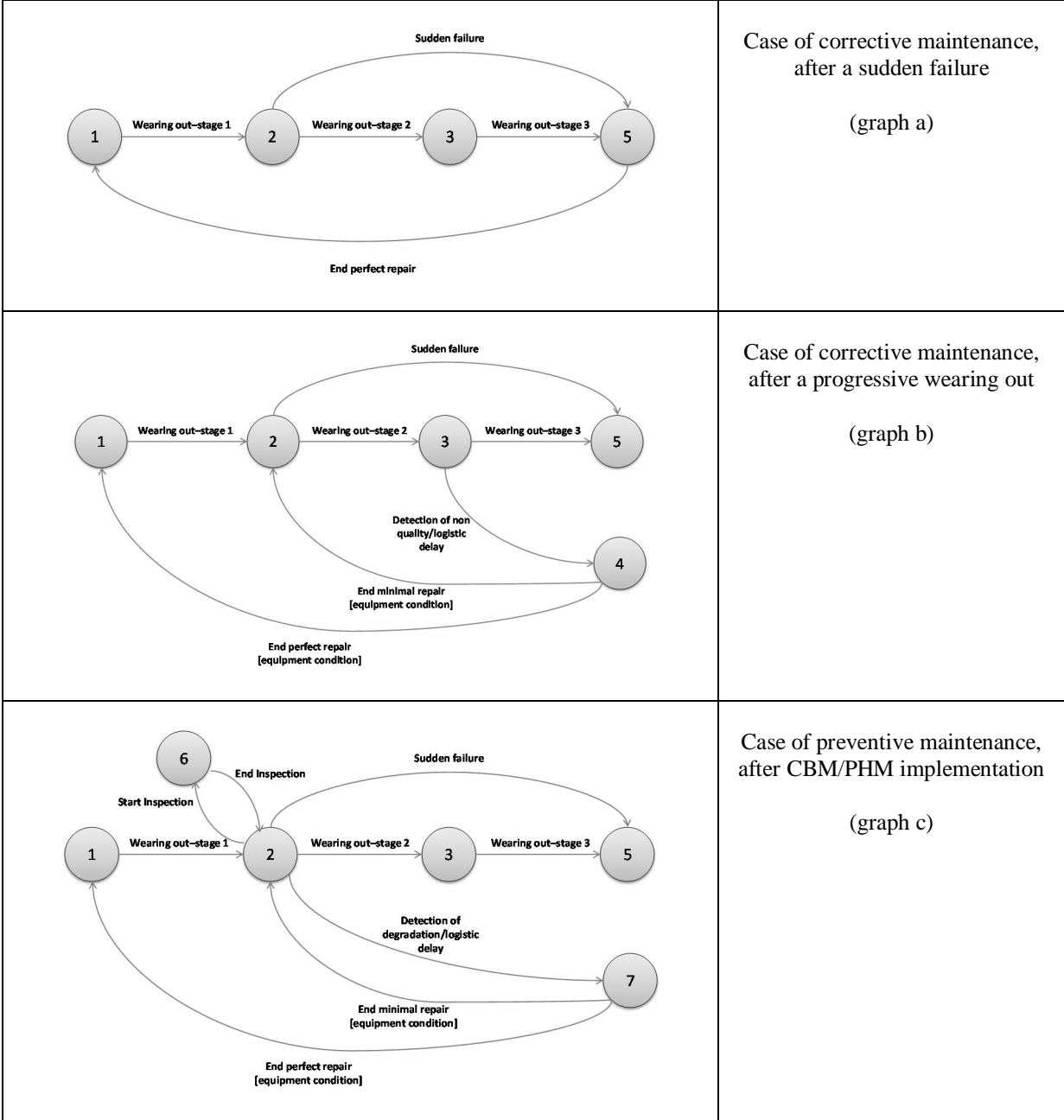

	Case of corrective maintenance, after a sudden failure (graph a)
	Case of corrective maintenance, after a progressive wearing out (graph b)
	Case of preventive maintenance, after CBM/PHM implementation (graph c)

Figure 2. State transition diagrams of degradation and repair processes under concern

3.2 System dynamics modeling

System Dynamics (SD) is the modeling technique used to simulate the equipment life cycle. SD is a well known methodology and mathematical modeling technique (Forrester, 1961; Sterman, 2003) and its simulation approach is based on discrete time advancement, in which the state of the system – measured by means of different types of variables – changes

periodically at discrete times. In particular, using SD, the dynamic evolution of complex systems with interlocked variables – linked through feedback loops and time delayed relationships (Forrester, 1961; Sterman, 2003) – can be generated also based on given stochastic laws (probability density functions) thanks to Monte Carlo method.

Vensim Ple is the SD software tool selected for the case study analysis. Accordingly with SD, a model in this tool is expressed by two main types of variables: i) flow variables, whose values are influenced by value(s) of other variable(s), and may change at some discrete instants in time; ii) stock variables, that assume values resulting from the accumulation of values of other variables during the simulated time. This simple mechanism – well known as "stock and flow" – is highly flexible and allows to express different events occurring within the system such as those required in the STDs previously formalized. Indeed, based on such a flexibility, STDs can now be broken down into four building blocks according to their logics: i) to simulate just a time based transition (e.g. from state 1 to state 2 in Figure 2); ii) to simulate a time based transition, with mutually exclusive branches (e.g. from state 2 to state 3 or, mutually exclusive, 5 in Figure 2, graph a-b); iii) to simulate a time based transition with mutually exclusive branches dependent on a condition (e.g. from state 7 to state 1 or back to 2 in Figure 2, graph b); iii) to simulate a time based transition with mutually exclusive branches, with complex behavioral rules to manage the branches (the only case is from state 2 to state 3, 5, 7 or 6 in Figure 2, graph c)). The composition of such building blocks – used as archetypes – allows building SD models with all the different dynamics expressed in the STDs. This is quite promising for a further extension to other more complex reliability and maintenance behaviors, expressed as different degradation and repair processes.

3.3 Models for life cycle costing and environmental assessment

SD models provide simulated data for enabling the economic and environmental assessment for the equipment life cycle. Each assessment is developed based on specific concepts.

The economic assessment follows the LCC concept illustrated previously, basing on the cost classification of visible, i.e. direct/indirect, and hidden costs. Besides the visible costs of the maintenance service contract (such as the contractual fees, spare part costs, etc…), the hidden costs consist in the monetization of lower performances, due to unavailability and low product quality rate. The focus of LCC is on the customer of the machine, hence it should be better referred to as TCO.

The environmental assessment focuses on the life cycle energy consumption. The total energy consumption is in fact computed by considering separately the needed power in each of the equipment states and the respective time spent during the equipment life. Three possible states of the equipment under concern are defined considering the typical dynamics of a machine tool (target of interest of this work) during its usage: the ′idle′ state (when the auxiliary components of the machine are running even if the machine is not processing any work-piece), the ′ready′ state (when some components of the machine are moving to prepare processing, but material is not yet removed) and the ′machining′ state (with material removal). This state-based model is complementary to those defined for the degradation and repair processes (as in section 3.2): it represents how the machine is consuming the installed power,

which can happen in the ′working as good as new′ state as well as in other degraded states featuring reduced technical performance such as the ′product quality defects′ and the ′reduced speed′ states (see back Figure 2). The environmental assessment eventually considers the global warming potential generated by the use of electric energy to run the equipment. The production of electric energy required to run the equipment in fact generates the emission of greenhouse gases, main cause of global warming. According to (Narita et al., 2006), the most impacting of these are carbon dioxide (CO_2), dinitrogen monoxide (N_2O) and methane (CH_4), whose CO_2-equivalence factors are respectively: 1, 310 and 21 (Narita et al., 2006). The total CO_2 equivalent emissions are computable as a sum of the contributions of the three most impacting substances, neglecting the impacts of less relevant chemicals. Each of these contributions can be obtained by multiplying the energy use times a factor that depends on the geographic area, on the mix of energy sources used to produce electricity and on the CO_2 unit emission for each type of energy source.

4 The case study

4.1 Introduction

FIDIA is a milling machines' manufacturer. Milling is the process of cutting away material from a work-piece by a rotating cutter. Cutting accuracy, quality of finished products, cutting speed are currently the most important features for competitiveness: FIDIA milling machines are in fact small-medium working range high-speed systems, offering substantial advantages compared to traditional machines; in particular, FIDIA's high-speed technology has significantly improved quality and reduced manufacturing times. FIDIA machines are used by customers in order to produce molds and dies needed for manufacturing parts especially in the automotive and aeronautic sector.

FIDIA's worldwide presence consists of four manufacturing facilities, eight subsidiaries and eleven service centers: the importance of maintenance service offered after sales is evident. Maintenance services of its milling machines are considered by FIDIA as a relevant lever for enhancing competitiveness in the next years. Another relevant driver is the support to eco-efficient manufacturing, with special concern to energy efficiency. The case study focuses on a subsystem of the machine, which is the multiple mechanical axes moved by electric drives used to translate and rotate the milling head in the workspace. Well in phase to E-maintenance trends, FIDIA is implementing a diagnostic tool directly running on the CNC of its milling machines: one of its functions is to allow diagnosis for the subsystem target of the case.

4.2 E-maintenance scenario

The scenario fostered for the FIDIA case is shown in Figure 3: the service department decides the configuration of a service contract by planning the resources' allocation – i.e. field service technicians, spare parts, a diagnostic tool on board the smart machine. The use of a diagnostic tool on board (on FIDIA CNC) leads to think of FIDIA case as an example of E-maintenance solution delivered on top of its products by an OEM to its customers; the diagnostic support is in fact a lever towards releasing CBM/PHM programs for the milling machines, leading to offer a preventive maintenance policy in the service contract to a customer.

The expected frequency of maintenance interventions, resulting from applying the corrective or a mix between corrective and preventive maintenance, is the planning driver. Furthermore, as main rationale of the scenario, the frequencies should be defined based on the customer as

the primary stakeholder of interest: a contract should be fitting to the customers segment, to improve the alignment, hence attractiveness, with respect to customer requirements therein. Hence, it is not a default that the preventive maintenance is always the best choice, sometimes still the corrective maintenance is enough: customer requirements should be the second driver of decision in order to select the best policy to be delivered in the contract.
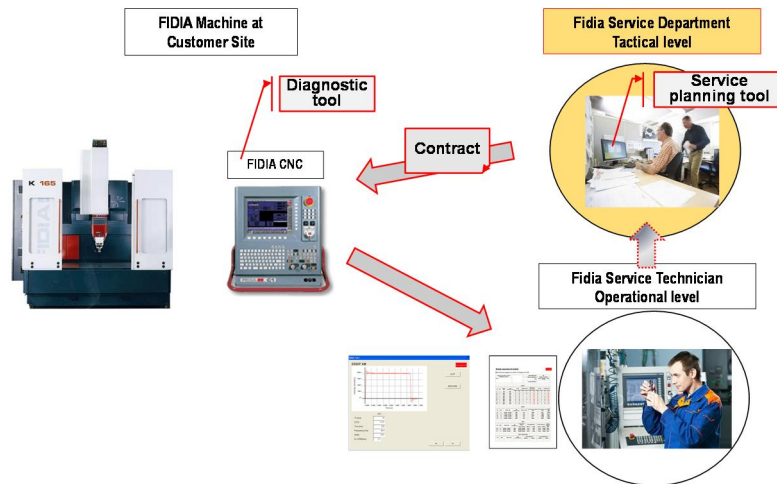

Figure 3: CBM/PHM service delivery in a smart machine

4.3 Economic and environmental impact analysis

This section provides an overview on the economic and environmental impact analysis carried on thanks to the model-based decision support of systems dynamics, life cycle costing and environmental assessment previoulsy presented. The models serve to analyze maintenance policies in order to finally support maintenance service planning for a contract offered to a target customer. Life cycle costing and environmental assessment – with respect to energy and CO_2 equivalent emissions – are needed to predict the expected impacts of maintenance policies planned in the contract. The overview aims at demonstrating some clues to the support to decision making: examples of analysis, supporting decisions of service planning, are then reported; they are focused on a FIDIA – customer relationship, hence considering a single maintenance service contract.

The results shown in the remainder come out from a number of simulation replicas of the SD models along the machine use life (i.e. 15 years). Furthermore, two assumptions stand for the simulation experiments: i) a customer type is considered, with given processing requirements; ii) CBM/PHM works with a perfect visibility on future events, knowing without uncertainty the Remaining Useful Life. The simulation results allow then to calculate the performances of interest for making the economic and environmental impact analysis, both as average and confidence interval, and other graphical tools showing variances such as box plots (the box plots shown in the remainder are built separating data in 25th – 75th percentiles).

Next Figure 4 shows a trade off of technical performances resulting from adopting different maintenance policies in the service contract. Even if box plots are partially overlapping, it is worth observing the best result obtained for availability (A) when using CBM/PHM program. Conversely, production speed (P) is not a good outcome for CBM/PHM program: this should be motivated by better understanding the dynamics of conditioning interventions.
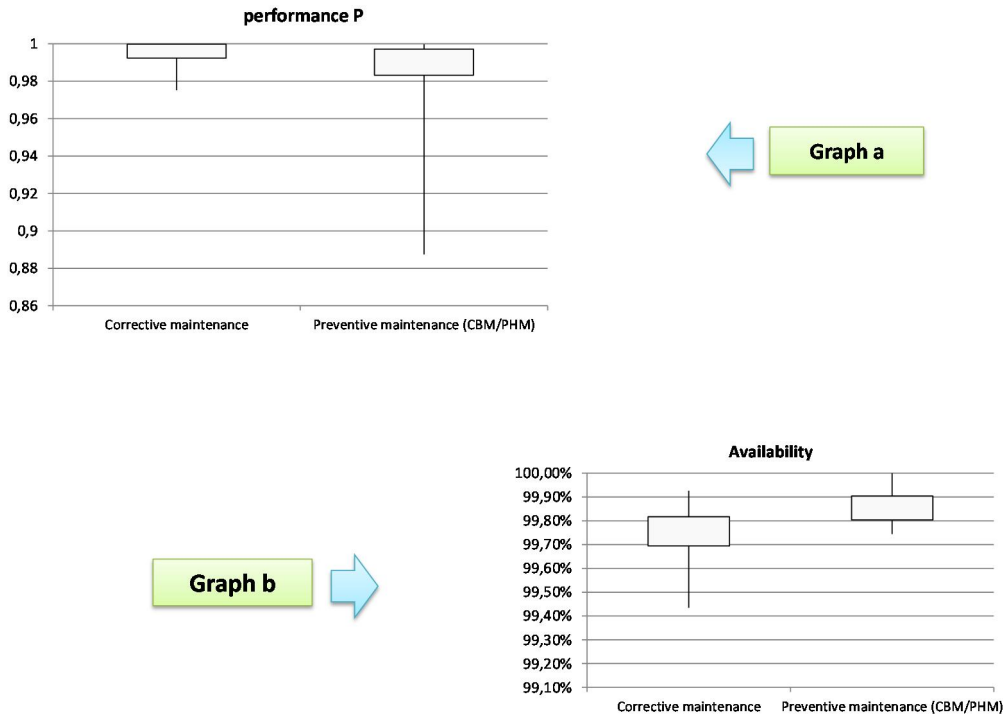
Figure 4. Availability and production speed achievable with different maintenance policies

Figure 5 focuses on how the number of conditioning interventions increases with longer ′time between inspections′ (see graph a), which results in a subsequent reduction of production speed (see graph b). In particular, graph a quantifies an intuitive expectation: a longer ′time between inspections′ leads the field technician anticipating a conditioning intervention, with the purpose to avoid the risk that ′product quality defects′ or ′fault′ would happen before next inspection is scheduled; this behaviour results in higher number of conditioning interventions, hence higher machine speed reduction as result of the preventive repair, which finally motivates the result shown for the production speed of graph b.
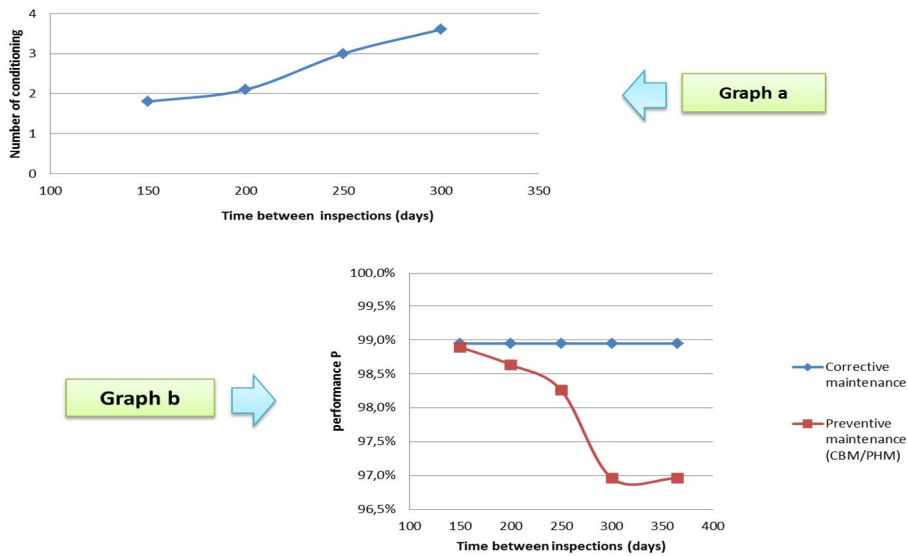
Figure 5. Effects of different time between inspections offered in the service contract

The low performance in production speed has an effect on the total energy consumption: even if it shows higher variance (hence overlaps still exist with preventive maintenance), the total

energy consumption is lower with corrective maintenance (Figure 6). This is instricically due to machine speed reduction (see back graph a of Figure 4): as a result of conditioning, in fact, the mechanical axes move slowly, even if it can be assumed that power consumption is almost the same; on the whole, the machine works less work-pieces per hour (i.e. less throughput), this is the main reason for growth of energy inefficiency / total energy consumption.
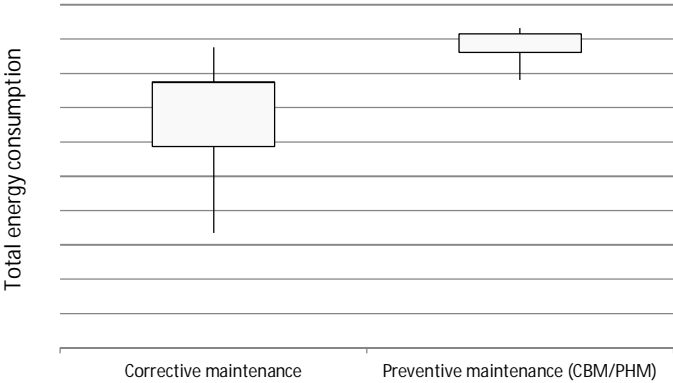
Figure 6. Effects of different maintenance policies on energy consumption

This is clearly affecting also CO_2 equivalent emissions, which seem a bad effect of applying the preventive maintenance policy. Nonetheless, deciding a continuous monitoring (or close to, hence applying a tight period between two inspections), the expectations are for a reduced number of conditioning interventions and a production speed P at its inherent technical level, approaching the results of corrective maintenance (see again graph a-b of Figure 5); the advantage of applying CBM/PHM could be then to reduce other undesired states, ′product quality defects′ or ′fault′ state, achieved for sure when applying corrective maintenance.

Economical concern is now needed in order to justify whether a CBM/PHM program with a given inspection period is convenient or not. A sensitivity analysis of the total maintenance service costs is shown in next Figure 7: assuming a variation of the cost of performance losses due to the machine unavailability (that is, a range of unitary hidden costs due to unscheduled machine downtimes), it is clear that an equilibrium point is reached; the higher the hidden cost of unavailability with respect to equilibrium point, the higher is the convenience running the CBM/PHM program.
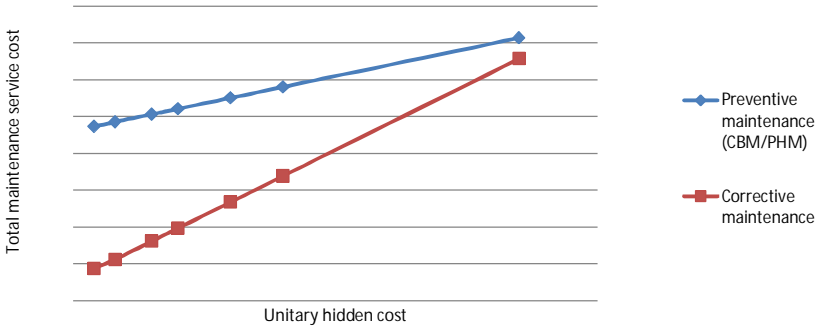
Figure 7. Sensitivity analysis of different maintenance policies provided in a service contract

If the hidden costs keep into account also ′product quality defects′ – accounted in OEE as a reduced product quality rate Q – besides the performance losses in the ′fault′ state – accounted as reduced availability A –, the economic convenience of CBM/PHM may be even higher. In particular, the unitary hidden cost for material wastes due to the non qualities is very often

relevant for the FIDIA's customers in some market segments (in automotive and aeronautic sector). This calls for more in-depth and a clear customer segmentation is needed to identify to whom offering contracts with preventive maintenance, based on customer requirements expressed also in terms of hidden costs, related to unavailability and/or product non qualities.

5 Conclusions

Next research steps will consider the extension of impact analysis at the network level, considering more OEM – customer relationships and the presence of the OEM's business partners. The main assumption will be that the network level should help achieving some organizational synergies for the implementation of a servitization strategy, in particular for releasing more effective CBM/PHM programs through the diagnostic tool run in the smart machine. To this concern, the main research interests are twofold: i) to verify if synergies are leading to service eco-efficiency on the whole network; ii) to envision the market expansion as a lever to achieve synergies for knowledge growth of field technicians as well as technical improvement of the diagnostic tool itself; in particular, it could be expected that the higher number of customers / installed base of smart machines would favour knowledge growth and technical improvement after operations in many operational conditions and under different customer requirements, with the final effect on a better service planning.

6 Acknowledgements

References

Allee, V. (2000) 'Reconfiguring the Value Network', Journal of Business Strategy, Vol. 21, No. 4, pp. 36-39.

Chang, M., Lewins, J.D. (1996) 'Using Life Cycle Revenue Loss And Monte Carlo Simulation as a Prior And Direct Assessment of Consequences of Un-wished Events', *Ann. Nucl. Energy*, Vol.25, No.1-3, pp.117.127.

Cohen, M.A., Agrawal, N., Agrawal, V. (2006) 'Winning in the Aftermarket, Harvard Business Review', May, 84 (5), 129-138.

Crespo, M.A., Moreu de Leon, P., Gòmez Fernàndez, J.F., Parra Màrquez, C., Lòpez Campos, M. (2009) 'The maintenance management framework: a practical view to maintenance management', *Journal of Quality in Maintenance Engineering*, Vol. 15, No. 2, pp. 167-178.

Derwent, R.G., Jenkin, M.E., Saunders, S.M., Pillings, M.J. (1998) 'Photochemical Ozone Creation Potentials for Organic Compound in Northwest Europe Calculated with a Master Chemical Mechanism', *Atmospheric Environment,* Vol 32, No. 14/15, pp. 2429-2441.

EN 13306 - European Committee for Standardization (2001), European Standard EN 13306: "Maintenance Terminology".

Ferri, G., Fumagalli, L., Jantunen, E., Salokangas, R., Macchi, M. (2012) 'Simulation Tool Development to Support Customer-Supplier Relationship for CBM Services' , in *Proceedings of PSAM 2011 & ESREL 2012*, 25 – 29 June 2012, 1-10, Helsinki, Finland.

Forrester, J.W. (1961) *Industrial dynamics. Pegasus Communications*, p.449.

Fumagalli, L., Di Leone, F., Jantunen, E., Macchi, M. (2010) 'Economic Value of Technologies in an e-Maintenance Platform', *in Preprints of 1st IFAC Workshop, A-MEST'10, Advanced Maintenance Engineering, Services and Technology*, 1-2 July 2010, 23-28, Lisboa, Portugal.

Furlanetto, L., Garetti, M., Macchi, M., (2006) 'Principi generali di gestione della manutenzione', Franco Angeli.

Garetti, M., Taisch, M. (2012) 'Sustainable manufacturing: trends and research challenges' *Production Planning and Control*, 23 (2-3) February-March, 83-104.

Gebauer, H. (2008) 'Identifying service strategies in product manufacturing companies by exploring environment – strategy configurations', *Industrial Marketing Management*, vol. 37, pp. 278-291.

Gebauer, H., Putz, F. (2009) 'Organisational structures for the service business in product-oriented companies', *International Journal of Service Technology and Management*, 11(1) 64-81.

Goffin, K. (1999) 'Customer support – A cross-industry study of distribution channels and strategies', *International Journal of Physical Distribution and Logistics Management*, 29(6), 374-397.

International Standard ISO 14040: 1997 (E) Environmental Management – Life Cycle Assessment – Principles and Framework

Lee, J., Ni, J., Djurdjanovic, D., Qiu, H., Liao, H. (2006), "Intelligent prognostics tools and e-maintenance". *Computers in Industry*, Vol. 57, pp. 476-489.

Lee, J., Ghaffari, M., Elmeligy, S. (2011) 'Self-maintenance and engineering immune systems: Towards smarter machines and manufacturing systems', *Annual Reviews in Control*, 35 111-122.

Levrat, E., Iung, B., Crespo, M.A. (2008) 'E-maintenance: review and conceptual framework', *Production Planning & Control*, 19:4, 408 — 429.

Macchi, M., Barberá, M.L., Crespo, M.A., Fumagalli, L., Holgado, G.M. (2012) 'Value assessment of an E-maintenance platform', *in Preprints of 2nd IFAC Workshop, A-MEST'12, Advanced Maintenance Engineering, Services and Technology*, 22-23 November 2012, Seville, Spain.

Morel, G., Pétin, J.F., Johnson, T.L. (2009) 'Reliability, Maintainability, and Safety', in *Handbook of Automation*, Nof Editor, 735-747.

Muller, A., Crespo, M.A., Iung, B. (2007) 'On the concept of e-maintenance: review and current research', *Reliability Engineering and System Safety*, 93, pp. 1165-1187.

Narita, K., Kawamura, H., Norihisa, T., Chen, L., Fujimoto, H., Hasebe, T. (2006) 'Development of prediction system for enviromental burden for machine tool operation' *JSME International Journal,* Series C, Vol. 49, No. 4.

Norris, G.A. (2001) 'Integrating Life Cycle Cost Analysis and LCA', Int J LCA 6 (2) 118-120.

Pehnt, M., (2006) 'Dynamic life cycle assessment (LCA) of renewable energy technologies', *Renewable Energy* 31 (1), pp. 55-71.

Rebitzer, G., Hunkeler, D., Jolliet, O. (2003) 'LCC – The Economic Pillar of Sustainability: Methodology and Application to Wastewater Treatment', *Environmental Progress* (Vol. 22, No. 4) December 2003.

Ritthoff, M., Rohn, H., Liedtke, C. (2002) 'Calculating MIPS – Resource Productivity of products and services', *Wuppertal Institute for Climate, Environment and Energy*.

Salonen, A., Deleryd, M. (2011) 'Cost of poor maintenance: a concept for maintenance performance improvement', *Journal of Quality in Maintenance Engineering*, Vol. 17, No. 1, pp. 63-73.

Seppälä, J., Knuutila, S., Kimmo, S. (2004) 'Eutrophication of Aquatic Ecosystems. A New Method for Calculating the Potential Contributions of Nitrogen and Phosphorus', Int J LCA 9 (2) 90-100.

Sheng, T., Chen, X., Yi, S., Gao, X., Ye, Q., Lee, J. (2009) 'Probe on network based collaborative maintenance mode for after-sales equipment', *Yugoslav Journal of Operations Research*, vol. 19, no. 2, pp. 299-313.

Sterman, J.D. (2003) 'Business dynamics, systems thinking and modeling for a complex world', Irwin Mc Graw-Hill.

Trivedi, K.S., Malhotra, M. (1993) 'Reliability and Performability techniques and tools: a survey', invited paper , *Proceedings 7th ITG/GI Conference on Measurement, Modelling and Evaluation of Computer and Communication Systems*, 27-49, Aachen University of Technology.

Wise, R., Baumgartner, P. (1999) 'Go downstream - the new profit imperative in manufacturing', *Harvard Business Review* ,77(5), 133-141.

World Meteorological Organization (WMO) (2006) 'Scientific Assessment of Ozone Depletion: 2006'. www.wmo.int.

Information gaps and lack of competence in maintenance

Lasse Metso*

Faculty of Industrial Engineering and Management
Lappeenranta University of Technology
P.O.Box 20
FIN-53851 Lappeenranta
Finland
*Corresponding author: Lasse Metso
e-mail: lasse.metso@lut.fi

Abstract

Information gaps or lack of competence can cause serious problems in maintenance.

This paper focuses on recognizing problems in knowledge management in maintenance, and also on learning about critical information breakdowns. The literature dealing with competence shortage in maintenance and missing data or information is discussed first. It was found that articles concerning maintenance and information gaps at the same time were few in number, meaning that more research is needed in this issue.

The method of data collection in the study is a questionnaire to maintenance professionals. According to the answers, there are several different methods to minimize the occurrence of missing information. It is more difficult to ensure that a lack of competence in maintenance will not appear, as for example a competent worker may be sick at a critical moment.

Key words: Lack of information, lack of competence, missing knowledge, missing data, maintenance

1 Introduction

Factors that influence product quality, production cost, machine condition and the length of its life are usually the quality of the input raw materials, production tools, methods and procedures, the competence of the operating and maintenance staff, and the operating conditions. The technical competence of the personnel influences the production and maintenance costs, as well as the efficiency of machine performance because this kind of competence affects the practice of operating and maintaining the machine. (Al-Najjar, 2007)

The South Indian Textile Association found that poor maintenance was one of the major causes of problems in production. Each machine needs different maintenance instructions and a trained person in maintenance work, because machine breakdown will affect the operation of the plant and increase the maintenance cost. (Shyjith et al., 2008)

The maintenance system plays an important role in reducing equipment downtime, improving quality and increasing productivity (Shyjith et al., 2008). Lack of equipment maintenance records is common in maintenance management organizations. Lack of knowledge in handling maintenance data is a common problem in identifying the causes of fault modes (Crespo Márques and Sánches Herguedas, 2004). On the other hand, lack of competence in maintenance can lead to an increase in the equipment downtime, and a decrease of quality and productivity. The same unwanted results can be caused by lack of data or information.

The main target of this paper is to find out if there are information gaps or missing knowledge in maintenance, and if this is the case, how the occurrence can be reduced. Section 2 of this paper discusses previous literature on the topic, while section 3 focuses on methodology. The results of the research are presented in section 4, and section 5 contains conclusions.

2 Literature survey

2.1 Outsourcing and information-sharing problems

The challenge in maintenance is changing a product-oriented business strategy to a service-oriented one. The product-oriented strategy is based on transaction and exchange marketing, while the service-oriented one highlights the relation between the provider and the customer. A service-oriented business strategy requires the harmonization of support processes, such as maintenance, to the core process of the business. (Candell et al., 2009)

Outsourcing is used in maintenance increasingly. The decision to outsource is a strategic decision inside the company. Gómes et al. (2009) present a framework about management in maintenance outsourcing in a service provider company. The advantages and disadvantages of outsourcing are presented in table 1.

Table 1. Advantages and disadvantages of outsourcing (Gómes et al., 2009; modified)

Advantages in outsourcing	Disadvantages and risks in outsourcing
Reduction costs, at same time quality to employ a more specialized supplier	Unfilled or questionable expectations for a scenario developed to generate the process of outsourcing
Restructuring costs, changing fixed costs by variable costs in terms of the service provider	Changes in the quality for breach of agreements on services, either by the knowledge or capabilities of the supplier company, or errors in definition of the same company
Stimulates local employment through contracts with local firms	Loss of knowledge or skills through transfer to the supplier, where it is more difficult to retain and improve. This happens frequently
Obtaining a rapid budget by selling assets	Loss of control over the externalized functions, source of learning for the internal staff
Improvement of quality, for higher specialization	Dependence on the supplier could cause adverse consequences for the client (investments extraordinary)
Access to outside expert knowledge	Loss of security by staff transferred to the supplier, by hoax and illegal transmission of knowledge and information on the competence

Standardization and access to scale economies	Public and internal opinion on outsourcing jobs to another company
Flushes resources for other purposes	Loss of motivation for staff involved in the service, because it can create a feeling of alienation within the client company and result in the staff feeling that their jobs are valueless
Improves the company focus	
Improves the management of functions difficult to handle	
Optimizing routine tasks	
Sharing risk by flexibility of demand with the supplier company	
Provides legal guarantee for services	
Relationships developed between financial aspects and levels of service	
Starting point for changes in the organization	
Speed through reengineering	

Today's providers of maintenance to industries with complex technical systems (e.g. aircrafts) are facing major challenges. A key problem is to manage the ever-increasing information flow and system complexity. There is an increasing amount of digital product information and design data provided together with hardware and software products from manufacturers, sub-system suppliers and other sources. New technology and innovation drive development and create new needs. The producers and suppliers of maintenance products and customer services are facing challenges of keeping high quality and increasing service levels for complex technical systems with multiple products, suppliers and customers. (Candell et al., 2009)

Different data sources are used in maintenance decision making processes. These data sources are for example failure data, practical experience, results of technical analysis, condition-monitoring measurements and operating data, or a combination of these data resources. The maintenance actions can be performed in the right time, preventing failure if there is relevant, accurate and good data coverage available. There is a big potential to use better maintenance technologies by improving the knowledge, experience and competence of the personnel with training (Al-Najjar, 2007, Al-Najjar and Alsyouf, 2003).

2.2 Uncertainty

The term "uncertainty" has a number of meanings. In preventive maintenance it is used to describe problematic issues in the time-to-failure of equipment. The major problem in preventive maintenance is to define the best time and frequency for repairing. This can affect maintenance costs and also reliability. According to Zimmerman (2000), "uncertainty" means that a person does not have enough information to make right decision in a certain situation. Uncertainties can be categorized as external and internal ones. The decision-maker can control internal uncertainties, but not external uncertainties. These uncertainties can occur because of lack of understanding or knowledge (Cavalcante and de Almeida, 2007).

Zimmermann (2000, p.192) classifies the causes of uncertainty to six categories and he states that "Uncertainty implies that in a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristica." Details of the causes of uncertainty are presented in table 2.

Table 2. Causes of uncertainty (Zimmermann, 2000; modified)

Cause	Description	Impact
Lack of information	Decision maker does not have the information needed.	A situation of uncertainty can be transformed to a situation of certainty by gathering more and better information.
Abundance of information (complexity)	More data is available than a person can digest.	A transfer to certainty cannot be achieved by gathering more data, but rather by transforming the available data to appropriate information.
Conflicting evidence	There might be information available pointing to a certain direction, but some information is available pointing to another direction.	An increase of information does not reduce uncertainty. Checking and deleting wrong information might help to transform the situation to certainty.
Ambiguity	Linguistic information has entirely different meanings.	Ambiguity can be classified also as lack of information because more information helps to move towards certainty.
Measurement	An 'imagined' exact property cannot be measured perfectly.	This can also be considered as a lack of information.
Belief	All information available to the observer is subjective as a kind of belief in a certain situation.	This situation is questionable and it can be considered as lack of information.

3 Methodology

The research process for this paper began with a literature review and building theoretical understanding of the different aspects of lack of data, information and knowledge in the area of maintenance.

This study is qualitative research and the data collection method is surveys. The first survey was carried out with 16 maintenance professionals completing their degrees at Jyväskylä University of Applied Sciences (JAMK). In this group, 10 persons represented customers of maintenance and 6 suppliers of maintenance. These students were "obliged" to take part in the first survey, so the response rate was 100 %. The second survey focused on the members of the Finnish Maintenance Society Promaint. The second survey was sent to 327 members, and the response rate was 20.2 %.

Table 3 shows how the survey respondents belonged to customers or suppliers of maintenance. In survey 2 there was also a group others, to which belonged e.g. entrepreneurs who were not customers or suppliers.

Table 3. Survey respondents broken down into customers and suppliers of maintenance.

	Respondents			
	Customer	Supplier	Other	Total
Survey 1	10	6	0	16
Survey 2	42	16	8	66

The respondents were encouraged to tell little stories about situations where there was some urgent data, information or knowledge missing. The questions were:
- Have you been in a situation where some data, information or knowledge has been missing in maintenance?
- How did you get this missing data or information?
- How did you solve the problem of getting the missing knowledge?
- How did you handle the situation?
- Was the maintenance schedule delayed? Were extra costs caused in maintenance?

The material from the survey was is coded and analysed with NVivo version 10 software.

4 Results

The research was started by the theory-oriented approach using Zimmermann's (2000) classification of six categories of causes of uncertainty. As soon as it was discovered that six classifications were not enough, new material-driven classifications were added. These new classifications were based totally on the material of both surveys. These classifications were not theory-based but only material-driven. More details are shown in table 4.

Table 4. New classification and descriptions.

Cause	Description	Impact
Communication	The customer thinks that the supplier knows everything. The supplier is wondering why the customer does not share information.	Better processes for sharing information are needed.
Attitude	That pump is not working properly. This is not my task. Somebody should fix it.	A transfer to certainty cannot be achieved by gathering more data, but rather by transforming available data to appropriate information.
Limited vision of the whole	The maintenance staff think only of their tasks and the production staff think only of their own processes, and nobody is concerned of the whole.	
Course of action	New processes may have been created but nobody uses them because "we have always done it this way".	Training for processes is needed.

Databases	Maintenance data is saved in different kinds of databases.	Access to databases must be organized.				
Missing knowledge	The needed skills are not available.	Help from a skilled person is needed.				

The coding references in both surveys are presented in table 5. This is the basis of how the research continues.

Table 5. Coding references to the categories.

	Survey 1		Survey 2			
	Customer	Supplier	Customer	Supplier	Other	**Total**
Lack of information	9	2	3	1		15
Abundance of information (complexity)	1					1
Conflicting evidence	7	3	3	1		14
Ambiguity	1					1
Measurement			1			1
Belief						
Communication	11	8	14	2	2	37
Attitude		6	2			8
Limited vision of the whole	6	1				7
Course of action	8	4	9	2	4	27
Database	1		6	2	1	10
Missing knowledge	1	1	4			6

In table 5, the first six rows are Zimmermann's (2000) original classifications. The next rows are new material-driven classifications created by the author. There were no references to beliefs, and also in measurement there was only one reference in the material of the survey. This measurement reference can be handled as a database classification, because in the original text there was a mention about data that was not saved to a database. The reference to abundance of information is very close to the references of conflicting evidence. The reference to ambiguity is also referenced to the classification course of action. Databases are excluded from this research because several earlier studies have focused on maintenance databases and software systems. This research focuses on the seven classifications **bolded** in table 5.

Lack of information

In this research, the notion lack of information is used when information or data is not available at the right time. In the survey one answer described the issue well: *"Typical lack of information is associated with the documentation of equipment. Drawings or other information are not where they should be kept. Usually missing information can be found only by asking somebody who knows."*

According to the two surveys, lack of information is mainly the problem of the maintenance customer. Customers do not get enough information about details, and things like up-to-date documents and drawings are missing. The missing information can be found at least by the manufacturer of the equipment if nobody else can help. Another problem concerns maintenance software. Software is used, but saving data to the system is not properly done. Sometimes information can be misunderstood because the communication is adequate. This issue is also discussed in the communication section.

However, lack of information is not considered a difficult issue because it can usually be solved quite easily by asking somebody. Of course this will take time and may delay the maintenance process.

Conflicting evidence

Conflicting evidence is usually linked to documentation. In different documents there are totally different values, which should be the same in both documents. There situations are very difficult to clarify because it cannot be easily solved which values are the right ones.

In the survey the following kind of answers were given: *"Problems arise especially in ordering spare parts, there are several different spare part lists and instruction manuals for the same device."* If you order a wrong spare part for maintenance shutdown, so you may need to lengthen the maintenance shutdown to get the right spare part. In the worst case the situation comes to attention when a spare part must be installed and it does not fit.

Conflicting evidence is a very problematic issue in maintenance. It is very difficult to solve because if you ask for more information, how can you be certain that this new information is right or the information you need? Also the influence of conflicting evidence can be serious.

Communication

Communication was the most frequently cited issue in the surveys. There are both customer and supplier side gaps in communication. *"The biggest problem is the fact that customers have a lack of staff for the maintenance of an attractive site." "Information cannot be applied at the right place." "The exchange of information does not always go smoothly, the work developer does not see the need to report what has been done and the user of the machine stays unsure of the repair of the property."* There were also mentions about improving communication between the parties: *"Create well-established practices to monitor and improve, as well as for reporting." "A functional and sufficiently tight meeting practice to reduce the information gaps."*

As the above examples show that communication is a difficult issue, and misunderstandings can occur easily. On the other hand, it can be quite easy to organize meetings and create reports to improve the communication between the parties involved.

Attitude

Attitude is quite difficult to measure or observe. Some examples of what might be classified as attitude were found in the answers, however. *"Often, you do not want to provide the requested information, even though they would benefit from the reliability improvement methods." "Plans do exists and sometimes we have been very close to implementing them, but other things have always taken priority."* Sometimes attitude problems can be quite close to the next classification, a limited vision of the whole.

Limited vision of the whole

A limited vision of the whole can be seen as an organizational and management problem. Maintenance may have been outsourced, and so there are many different parties operating in the field of maintenance. *"Distribution of own and outsourced maintenance must be clearly expressed, as distinguished from the everyday maintenance of the project design."*

Another issue is how work is planned to be implemented. Is there enough staff in all the phases, for example in design? *"Preventive maintenance should focus more on resources and enhancing maintenance as well. This could prevent repetitive defects and failures causing excessive costs."*

Course of action

The course of action is also an organization-related issue. *"The operations have not been described as processes, or they are not followed, we do as we have always done."*

Maintenance software systems are seen as a solution helping to act as wanted. *"When the workload increases so easily by individual work, the flow of information is left untreated. In this case, the resources are usually concentrated on the most important work, and the less important may be left with less attention. Knowledge production and transfer is the key to system maintenance." "Sharing information between individuals, deciding which information will remain with one person. Information should be obtained directly from systems automatically."*

Missing knowledge

The problem of missing knowledge is very difficult to solve. Achieving knowledge by training will take a long time. If it is to be achieved by purchasing a service, it may be difficult to find a proper supplier. *"The organizations are fragmented and there are rapid changes, which means that the high turnover of persons in charge causes problems."*

Table 6 contains a summary of the main results of this paper.

Table 6. Classifications of problems and solutions to reducing their occurrence.

Classifications	Solution to reducing the occurrence
Lack of information	The situation is improved by gathering more relevant information from different sources.
Conflicting evidence	An increase of information does not reduce uncertainty. Checking and deleting wrong information might help to transform the situation to certainty.
Communication	Communication problems between people are common. Fortunately meetings are easy to organize.
Attitude	This is a difficult issue to solve, especially when maintenance has been outsourced. Training is needed.
Limited vision of the whole	This is close to the previous and next classifications. More training may be needed.
Course of action	This is quite closely related to attitude and a limited vision of the whole.
Missing knowledge	The needed skills must be acquired.

5 Conclusions

The starting point to this research was to find out whether there is any kind of lack of information or knowledge in the area of maintenance. According to the surveys made in the study, there are quite often situations where some information or data is missing, and sometimes also the needed knowledge is not available.

The theory base was originally Zimmerman's (2000) causes of uncertainty. Uncertainty is a situational property of a phenomenon which is influenced by available and required information. Zimmermann's classifications were used as the basis of classifications in this research. It was soon found that more classifications were needed. The new classifications were:

- communication
- attitude
- limited vision of the whole

- course of action
- missing knowledge.

All these new classifications can be considered as outsourcing problems of maintenance. New processes are created but they are not in use. It is not impossible to solve these problems, the solution is just to pay attention and be aware of the possible problems. However, these problems can appear even when maintenance has not been outsourced.

In the surveys, communication was considered to be a relatively easy problem to solve, what is needed is just organizing meetings and using maintenance software systems properly. Communication was considered the most common cause of lack of information. Communication problems can be managed easily, but communication must be paid attention to. Of course, every time two persons talk to each other, some information will be lost.

The next classifications, attitude, limited vision of the whole, and course of action have similar effects. Information will not be moved properly forwards because the people involved think that forwarding information is someone else's responsibility. Attitude can be an individual or organizational problem. A person can think that this task is not my responsibility. Old methods of doing things may be in use in the organization, even when new processes have been adopted. This can be prevented by training, as well as the next two issues. If a person has a limited vision of the whole of what should be done in the company, he or she can cause serious problems. For example, the person does not report a problem in a machine he has noticed because he does not know to whom or how to report about it. The course of action can be quite a similar issue as attitude at the organizational level. New processes should be used, but nobody uses them because these tasks have always been done in a different way.

Missing knowledge is hard to fill. If the needed knowledge is not available in the company, it may to try to buy it from suppliers. Then there are also timing problems if the needed resource is not available at the right time.

"In my opinion the information gaps are usually due to the company's own actions, as the service provider acts according to the operation model required by the company. The model of knowledge transfer is not documented adequately and it is not a written form of action."
"Information gaps could be avoided by regular exchange of thoughts, and not by making contact when problems have already risen. We should be interested in what the others are doing and share information." According to the surveys, information gaps can be quite easily reduced by regarding the potential problems of data transmission.
Further research is needed to compare the differences between successful data transmission and unsuccessful cases. In this research only unsuccessful cases were included and successful cases were not considered.

Also maintenance and knowledge management research combining information management and maintenance is needed. There are several studies dealing with maintenance software and databases, but not many about information and knowledge management in maintenance.

References

Al-Najjar, B. (2007) 'The lack of maintenance and not maintenance which costs: A model to describe and quantify the impact of vibration-based maintenance on company's business', ScienceDirect, *Journal of Production Economics* 107, pp. 260-273.

Al-Najjar, B. and Alsyouf, I. (2003) 'Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making', *Journal of Production Economics* 83 (3), pp. 81-96.

Candell, O., Karim, R. and Söderholm, P. (2009) 'eMaintenance-Information logistics for maintenance support', *Robotics and Computer-Integrated Manufacturing*, Vol. 25, pp. 937 – 944.

Cavalcante, C.A.V. and de Almeida, A.T. (2007) 'A multi-criteria decision-aiding model using PROMETHE III for preventive maintenance planning under uncertain conditions', *Journal of Quality in Maintenance Engineering*, Vol. 13 Iss:4, pp 385-397.

Crespo Márquez, A. and Sánchez Herguedas, A. (2004) 'Learning about failure root causes through maintenance records analysis', *Journal of Quality in Maintenance Engineering*, Vol. 10 Iss:4, pp. 254-262.

Gómez, J.F., Parra. C., González, V., Crespo, A. and Moreu de León, P. (2009) "Outsourcing maintenance in services Providers", *Safety, Reliability and Risk Analysis: Theory, Methods and Applications – Martorell et al. (eds), Taylor & Francis Group*, London, ISBN 978-0-415-48513-5.

Shyjith, K., Ilangkumaran, M. and Kumanan, S., (2008) 'Multi-criteria decision-making approach to evaluate optimum maintenance stragegy in textile industry', *Journal of Quality in Maintenance Engineering*, Vol. 14, Iss. 4, pp. 375-386.

Zimmermann, H.-J. (2000), 'An application-oriented view of modelling uncertainty', *European Journal of Operational Research, 122*, pp. 190-198.

An Augmented Reality Application to Support Maintenance – Is It Possible?

Rúben Oliveira[1], Torres Farinha[2], Sarbjeet Singh[3] and Diego Galar[4]

[1,2]*CEMUC - University of Coimbra's Mechanical Engineering Research Center*
Departamento de Engenharia Mecânica; Pinhal de Marrocos
3030-788 Coimbra
Portugal

[3,4] *Division of operation and Maintenance*
Luleå University of Technology
Luleå, Sweden

[1]*e-mail: ruben.oliveira@dem.uc.pt*
[2]*e-mail: torres.farinha@dem.uc.pt*
[3]*e-mail: sarbjeet.singh@ltu.se*
[4]*e-mail: diego.galar@ltu.se*

Abstract

Augmented Reality (AR) is a trend technology with many applications for domestic consumers. On the past it was developed significant projects with the objective to introduce AR in industrial environments, but did those projects be succeeded?

AR looks like to be a powerful technology, but can it be applied to industrial environments? And for the Maintenance sector in particular?

This paper pretends to answer the above questions and explain how to overcome restrictions detected on previous projects by presenting some results from a project under development, (Oliveira *et al.,* 2012).

It will also be presented a Computer Maintenance Management Systems (CMMS) called SMIT (Farinha *et al.,* 2008) and its innovations with the integration of modules like active 3D models for technical assets and an AR module.

Machines are enabled to do more and more complex tasks and, consequently, their maintenance is becoming more complex too. This gain of complexity might need new tools to support maintenance interventions and also demands new methodologies to implement for the technicians training in order to perform a better apprenticeship aiming to minimize the cost of each maintenance intervention. AR can give a great contribute to enhance training conditions and technicians capabilities.

1 Introduction

There are several technologies and tools that may help to improve significantly the maintenance sector like oil, thermography, and vibration analysis, among others. These on-condition tools, in conjunction with Computer Maintenance Management Systems (CMMS) help to prevent malfunctions and to diagnose the cause of them.

During an intervention a technician may be supported by checklists, technical handbooks or tools that simulate equipment on a virtual environment to avoid mistakes and showing how to proceed. However, technicians have to visualize instructions on specific supports and identify target components on the real environment. With Augmented Reality (AR) instructions may be given automatically over the real scenario and the technician's focus is kept on equipment. An AR system must be also interactive, which means that the technicians can request more information about components and procedures, and fill reports through an intuitive human-machine interaction that can be achieved through gestures or speech recognition.

Nowadays, AR is a trend on consumer market, but for industry sector, mainly maintenance sector, it represents a high demand and expectation, due the requirements and failing costs on those sectors. While in consumer market the identification of components is made through markers, in most industrial environments the placement of markers is unpractical. An exception is on training sessions where some modifications are allowed.

The AR concept comes from aeronautical industry at ninety decade (Sims (1994)). There are several AR definitions but two are more significantly: the Azuma concept that refers that a system to be considered an AR system should fulfill three requirements (combines real and virtual; interactive in real-time; registered in 3D) (Azuma et al. (2001)); Milgram locates the AR on a diagram between real environment and Virtual Reality (VR) that represents the head of this diagram, in which also includes AR inside Mixed Reality (MR), (Milgram et al. (1994)). According to recent developments and with the objective to avoid misunderstanding about the concept of AR, it may be defined using a combination of both concepts, i.e., a mostly real environment enhanced with virtual features where is possible to interact with the AR scenario.

AR can be experienced directly using an image projector that projects virtual features over the real environment or by an optical see-through head-mounted display, where virtual parts are shown on translucent screens. Alternatively, indirect methods reproduce not only the virtual features but also the real environment on screens, as is the case of tablets, smartphones, computer monitors and video see-through head-mounted displays – usually used for virtual reality.

Equipment are becoming more complex what impose new boundaries to maintenance and to guarantee the best levels of equipment's reliability, what implies to enable maintenance sector with sophisticated tools.

The tendency is to increase the level of integration among systems within the organizations. In this situation it means to integrate CMMS with on-condition predictive maintenance modules, with Expert Systems, with Geographic Information Systems, with Technical Assets 3D models, and with AR modules.

The remaining of this paper is organized: in section 2 are presented previous AR projects on industry; section 3 contains a brief description of the components of an AR system; then, on section 4, the CMMS SMIT is described while results from a project that is being conducted are presented; finally, section 6 contain the conclusions of this paper.

2 Augmented Reality projects

Due to recent developments of AR on consumer market, the concept was spread worldwide very fast. They are known some potentialities of AR but not all of them, neither their limitations. Initially one of AR restrictions was related to the display equipment that reduced the portability of an AR system as well as its size and weight.

A clear advantage of AR is their capacity to superimpose invisible effects on real environment as is the case of air flow or the procedures to (dis)assembly equipment. The hope of new achievements of AR in industrial sectors is enormous, not only for maintenance activity but also for production and project sectors. With the increasing of AR projects and their extension for many areas as is the case of medical ones.

Besides AR projects faced different technological limitations, many of them are related to hardware as stated at (Weidenhausen et al. (2003)). It was achieved significant and promising results and also identified gaps and prospective directions for future AR projects with appliance on industry.

Among the several industrial AR projects implemented, one of them was relevance for maintenance and industrial AR in general, the ARVIKA project, (Weidenhausen et al. (2003)) (Friedrich (2002)). This was a project that congregated strong players from automotive and aerospace industries and also technological centres (Figure 1) with the objective to develop AR solutions for industry; it was developed from 1999 to 2003. The AR systems for this project used speech recognition to interact with the system, markers in order to retrieve equipment's positioning and to identify virtual contents to display, head-mounted displays as output devices and an user interface framework to run on a browser. From ARVIKA project one prototype was applied to real industrial environments, the Intelligent Welding Gun (Echtler et al. (2004)) that requires reflective markers to estimate the pose of components on the scene. Just after the ARVIKA project a new project (ARTESAS) started aiming to solve problems identified on ARVIKA and was developed by the most significant players of ARVIKA.

Figure 1. Players of ARVIKA consortium

Other European project about AR for industrial application with focus on maintenance sector was the STARMATE project, (Schwald and de Laval (2003)) that achieved good results but only validated on laboratorial environment. The AR system developed for training was

composed by two cameras and retro-reflective markers. The use of markers was identified as a clear handicap of the AR systems because they delay the implementation of AR on industrial environments. Despite the limitations of the developed system, AR was identified as a technology with huge potential for maintenance.

For maintenance of defence equipment was developed the ARMAR project, an AR system for training maintenance interventions, (Henderson and Feiner (2009)), (Henderson and Feiner (2008)). It was applied a system to track the user's head in order to indicate the location of target components using different AR output methods and to evaluate the time spent on each method. Due existing restrictions about the use of devices like keyboards to interact with the AR system on some industries, the human interaction with ARMAR system was through gestures recognition using a separate camera. This project is also interesting because it studied the functionality of the Graphical User Interface (GUI) and evaluated the performance of gesture recognition algorithm for a vertical layout of virtual buttons.

Figure 2. Marker on equipment of ARMAR project, (ARMAR project webpage (2013))

Apart from maintenance sector, AR is also being applied on medical environments mainly encouraged by spatial agencies that aim to develop a tool to support astronauts on medical interventions, as is the case of CAMDASS project supported by the European Space Agency (Nevatia et al. (2013)). It is already on market a system that identifies veins on patients that is being validated on several health care facilities, (Phipps et al. (2011)). Besides the target of previous projects is not the maintenance sector, due the criticism of medical equipment those projects must be carefully evaluated in order to identify the methods and technologies used that may be applied on AR maintenance systems.

Although MiRA project is being developed, (EADS (2011)), it is already robust enough to be applied on industrial environments. MiRA is an AR marker based tool used to verify secondary structural brackets and pipes on airplanes fuselage. This AR tool minimize the time spent on checking those attributes from 300 hours to 60 hours and reduce by 40% late discoveries of noncompliance.

Other projects are transversal and may be applied on different industrial sectors. An AR system was implemented on a navigation system to guide technicians in a nuclear power

plant, apart from indicate the right directions the system also issue warnings to advise high pressure and temperature pipes or equipment that are operating and may cause accidents. This system operates based on markers placed along the paths, (Ishii et al. (2007)).

More industrial AR projects can be found at (Fite-Georgel (2011)) in which is presented a survey not only for maintenance AR systems but for industry in general. It is also referred that did not exist yet an AR system fully capable to be implemented in industrial environment. However, other AR surveys present industrial and non-industrial AR system as well as AR equipment, (Oliveira and Farinha (2012)) (van Krevelen and Poelman (2010)) and (Ong et al. (2008)).

The above projects confirm the potential of AR in industry and just because from the majority of those projects did not result a commercial AR system for industrial environments doesn't mean they failed; they have identified technological limitations that were solved or are being solved to be possible implementing in a near future in industrial AR systems.

3 Augmented Reality equipment

An AR system requires a camera to capture the real environment, a processing unit and an output device. Advanced AR systems use also a microphone combined with speech recognition algorithms for human-machine interaction, a sound system to present information and or artificial light system for a better performance of the vision system.

The AR environment is generated by libraries that identify the marker on the scene and retrieve their pose to display the virtual contents associated to each marker, Figure 3. Those contents may be static or dynamic animations that will be superimposed on captured images and they are adjusted to the pose of the marker; if the marker is rotated the animation is shown from a different point of view.
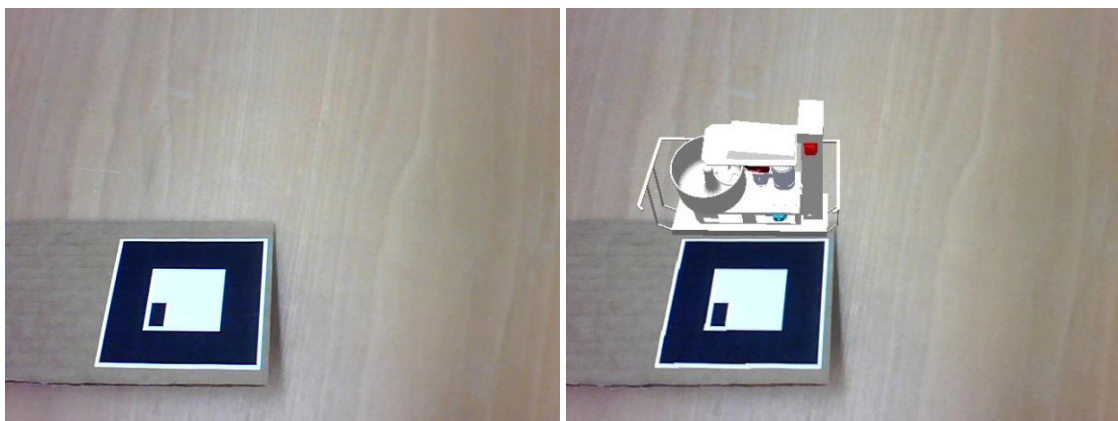
Figure 3. (left) real environment; (right) virtual features on AR environment

All procedures to develop an AR application, since image acquisition until displaying the AR environment are available in AR libraries. The most common library is the ARtoolkit (ARtoolkit (2013)), or other libraries based on this one with specific improvements, like a better algorithm to recognize partially occluded markers. The main steps of an AR library are presented at Figure 4.

A critical component of an AR system is the processing unit; it will depend on the requirements of the system, namely its portability, processing time capacity and remote access. Tablets or smartphones are very interesting because they work as an all-in-one package. However, they have lower processing capacity and did not represent the best solution to deal directly with large amount of data. For more demanding tasks a local computer must be used to manage data. Another alternative is cloud computing, where a local device acquire images from the scene; send it to the server and this return an image with the AR scenario to be displayed. But, this requires fast connections between the final client and the server. The most significant problem with remote access is to ensure the connection security, which is a relevant topic on military aviation (Fransson and Candell (2012)).
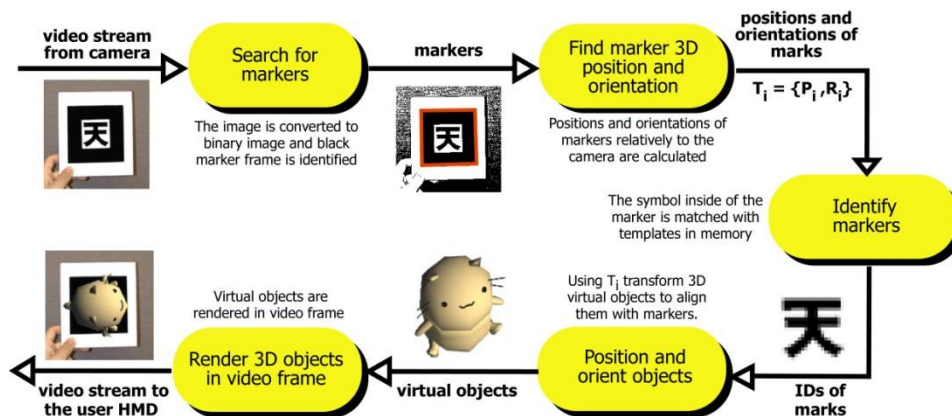
Figure 4. Basic steps of an AR application, (ARtoolkit (2013))

Constant developments on output devices for VR and AR enable the change from big size head-mounted displays to the recent ones that are much more compact, as represented at Figure 5; their development still very active with new patents registered, (Martins (2010)).

Figure 5. EyeD head-mounted display

The development of compact image projectors may enable another way to represent AR environments on AR systems with some demands of portability.

4 CMMS

With the advent of information systems, many aspects of the maintenance activity have evolved, particularly due the increasing of research and development (R&D) carried out and, following this, through the tools available to users, as is the case of CMMS that are of great diversity, but they have many similar aspects, such as those involved in the management of the main areas of operation and maintenance that have many common data that support and feedback the information systems.

Given these characteristics, it is important to understand the structure of an information system for maintenance, with the goal of its potential extrapolation to any other system.

The information system presented here is referred to as SMIT (the Portuguese acronym of Integrated Modular Terology System), which has the following characteristics:

- Integrated Modular System, which means an information system developed in a modular way, integrating the various modules required to manage the maintenance function and the ability to integrate new modules;
- Terology, which is the concept behind it, and which has the following definition:
  - Terology is defined as the combined utilization of operational research techniques, information management and engineering, with the objective of accompanying the life cycle of facilities and equipment. Terology includes the definition of specifications of purchase, installation and reception, and also the management and control of maintenance, modification and replacement of facilities and equipment and their accompanying in service, (Farinha (1997)) and (Farinha (2011)).

Nowadays, SMIT (Figure 6) consists of the following modules:

- Maintenance Objects (MO) – Technical Assets;
- Clients of OM;
- Suppliers;
- Technicians;
- Tools;
- Spare Parts;
- Working Orders (WO);
- Requests for Interventions;
- Maintenance Diagnosis;
- Maintenance Plans;
- Gantt Chart.

Figure 6. Main Logo of SMIT

To implement any CMMS, including SMIT, a prior diagnosis must be performed, with the aim to prepare organizations for the installation and faster entry into production of the CMMS. This step can be the differentiating element in shortening return on investment and rationalization of maintenance costs, (Raposo et al. (2012)).

Additionally, any CMMS ought to have the capacity to communicate with other information systems, as the SAP among others, and the ability to incorporate new modules and new technological tools.

About the communication with other systems, when the capacity of communications with other systems is analyzed, each situation must be managed individually. However, the communication must be done, being directly through direct communication among databases or through specific drivers that direct or indirectly permit the data interchanging and updatability.

These aspects are related to the ability of a CMMS to incorporate new modules and new technological tools, that is one of the strongest capabilities of SMIT.

5 Developments

From the results of previous projects about implementing AR to support maintenance tasks it is clear that AR allows minimizing intervention times, improving the quality of interventions and thus lowering the maintenance costs. However, a constraint was identified on most projects – the use of markers.

Markers represent an easy way to identify the target component and their respective pose on the scene but, on the other hand, it is unpractical to place makers on all assets, (Oliveira et al. (2012)). Furthermore, when using markers it is required that a marker is always visible on the target component, which means that more than one marker per component must be applied.

Identification of components and verification of their quality is a task already done on production lines through image processing techniques where it is possible to control many parameters, applying chambers to control light conditions or even to know the pose of the component. Nevertheless, for field maintenance interventions it is impossible to control all of those parameters.

To overcome the constraint of markers it was already tested an approach based on reference images but, it just works on very restrictive conditions, (Weidenhausen et al. (2003)). In the same paper is mentioned that it is required that an AR system fast and precise, being a possible solution the identifying of the target components by their shape (Figure 7), as proposed at (Oliveira et al. (2012)).
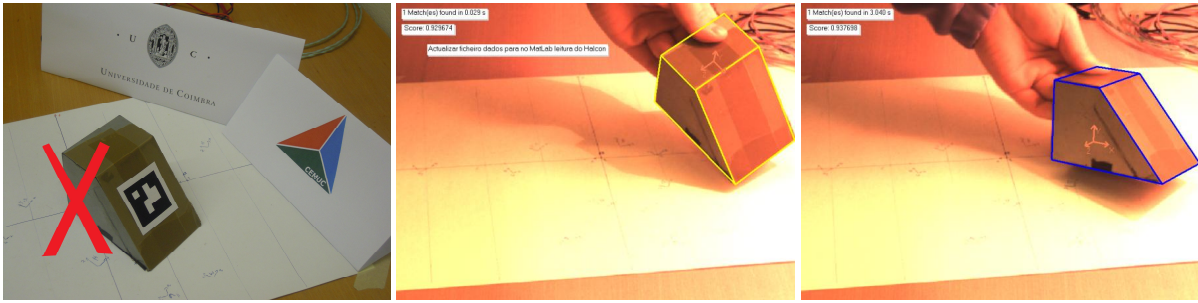
Figure 7. Object's detection without markers

In order to generate an AR environment from real scene images, as schematized on Figure 8, it is used image processing libraries to identify the target components based on their 3D CAD model and to retrieve their pose for a good presentation of virtual contents. It was already verified that it is possible to identify small components on non-ideal conditions (Figure 9), but for large working areas the standard process is too slow for real-time applications. To enhance the response of the system it is being applied prediction methods to reduce the processing times.
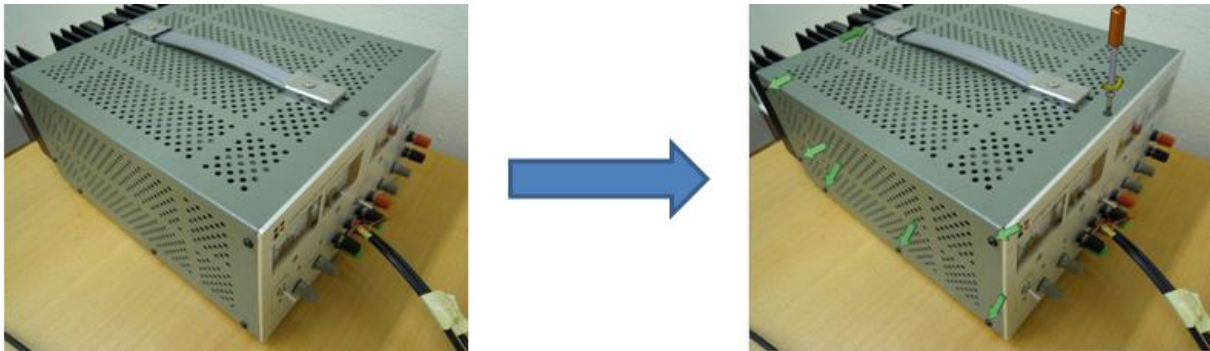
Figure 8. From a real environment to an AR environment
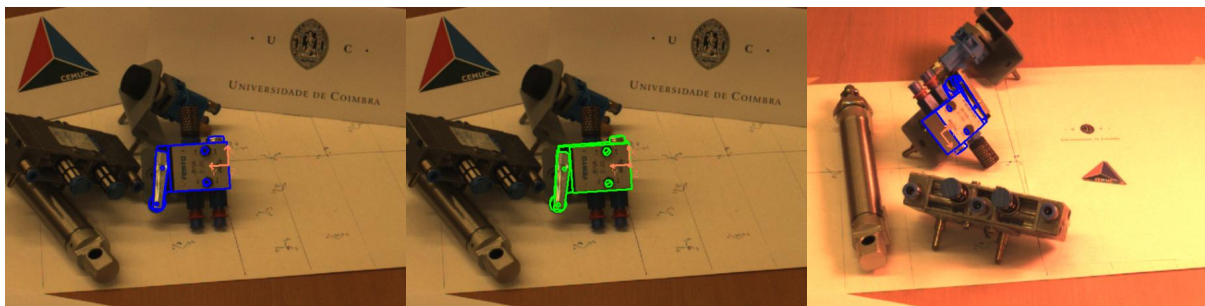
Figure 9. Detection of components on noisy environments

The identification of components by their geometry is being developed at Smart Industrial Robotics and Management group of CEMUC and partial results showed that it is possible to reduce more than 80% the time spent on identification of components by standard solutions and also to avoid mismatching cases when applying prediction methods. Through this method it is also easy to apply changes on equipment and after it to identify the changed components; it only is required to update the system with new 3D models.

An AR system is more powerful when combined with systems like SMIT, where an expert system is available to support technicians solving faults aided by the history of each technical asset.

6 Conclusions

AR will be a daily reality on industrial facilities starting from training environments due their lower restrictions. However, the first AR commercial solutions were developed to this sector and for marketing campaigns, where AR was a success, because even a strange product or brand can be memorized after a good campaign based on this technology.

AR represents a huge potential of improvement even without related technologies fully developed. It requires to overcome the use of markers to enlarge the implementations of AR on industrial context and developed new tools to support maintenance technicians to maintain and repair new and complex equipment.

References

ARMAR project webpage (2013). http://graphics.cs.columbia.edu/projects/armar/index.htm

ARtoolkit (2013), 'http://¬www.hitl.washington.edu/¬artoolkit/¬'.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S. and MacIntyre, B. (2001), 'Recent advances in augmented reality', *IEEE Computer Graphics and Applications* **21**(6), 34–47.

EADS (2011), Eads 2011 coporate responsability & sustainability report, Technical report.

Echtler, F., Sturm, F., Kindermann, K., Klinker, G., Stilla, J., Trilk, J. and Najafi, H. (2004), The intelligent welding gun: Augmented reality for experimental vehicle construction, *in* S. Ong and A. Nee, eds, 'Virtual and Augmented Reality Applications in Manufacturing', Springer London, pp. 333–360.

Farinha, J. M. T. (1997), *Manutenção das Instalações e Equipamentos Hospitalares - Uma Abordagem Terológica*, Livraria Minerva Editora.

Farinha, J. M. T. (2011), *Manutenção - A Terologia e as Novas Ferramentas de Gestão*, Monitor.

Fite-Georgel, P. (2011), Is there a reality in industrial augmented reality?, *in* '2011 10th IEEE International Symposium on Mixed and Augmented Reality', ISMAR '11, IEEE Computer Society, Washington, DC, USA, pp. 201–210.

Fransson, T. and Candell, O. (2012), A handheld maintenance workstation: Information fusion in the aircraft – ground systems gap, *in* 'The 2nd international workshop and congress on eMaintenance', Luleå University of Technology, pp. 33–36.

Friedrich, W. (2002), Arvika - augmented reality for development, production and service, *in* I. C. Society, ed., '1st International Symposium on Mixed and Augmented Reality (ISMAR '02)', pp. 3–4.

Henderson, S. and Feiner, S. (2008), Opportunistic controls: leveraging natural affordances as tangible user interfaces for augmented reality, *in* '2008 ACM symposium on Virtual reality software and technology (VRST '08)', ACM, p. 211.218.

Henderson, S. and Feiner, S. (2009), Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret, *in* '8th IEEE International Symposium on Mixed and Augmented Reality (ISMAR '09)', IEEE Computer Society, pp. 135–144.

Ishii, H., Bian, Z., Fujino, H., Sekiyama, T., Nakai, T., Okamoto, A., Shimoda, H., Izumi, M., Kanehira, Y. and Morishita, Y. (2007), Augmented reality applications for nuclear power plant maintenance work, *in* '19th Australasian conference on Computer-Human Interaction: Entertaining User Interfaces (OZCHI '07)', ACM, pp. 123–130.

Martins, M. (2010), 'Apparatus for head mounted image display (US 20100254017 A1)'.

Milgram, P., Takemura, H., Utsumi, A. and Kishino, F. (1994), Augmented reality: A class of displays on the reality-virtuality continuum, *in* SPIE, ed., 'Telemanipulator and Telepresence Technologies', Vol. 2351, pp. 282–292.

Nevatia, Y., Chintamani, K., Meyer, T., Blum, T., Runge, A. and Fritz, N. (2013), 'Computer aided medical diagnosis and surgery system: Towards automated medical diagnosis for long term space missions'. http://robotics.estec.esa.int/ASTRA/Astra2011/Papers/Posters/FCXNL-11A06-2146056-1-2146056nevatia.pdf

Oliveira, R., Farinha, J. T., Fonseca, I., Ferreira, L. A. and Armas, F. (2012), Augmented reality as a new level for maintenance efficiency, *in* 'The 2nd international workshop and congress on eMaintenance', Luleå University of Technology, pp. 49–55.

Oliveira, R. and Farinha, T. (2012), 'Realidade aumentada – ferramenta de apoio à manutenção em equipamento hospitalar', *Tecno Hospital* (49), 12–16.

Ong, S. K., Yuan, M. L. and Nee, A. Y. C. (2008), 'Augmented reality applications in manufacturing: a survey', *International Journal of Production Research* **46**(10), 2707–2742.

Phipps, K., Modic, A., O'Riordan, M. A. and Walsh, M. (2011), 'A randomized trial of the vein viewer versus standard technique for placement of peripherally inserted central catheters (piccs) in neonates', *Journal of Perinatology* (7), 498–501.

Raposo, H., Farinha, J. T., Fonseca, I., Ferreira, L. A. and Armas, F. (2012), A new approach for the diagnosis of state maintenance, *in* 'The 2nd international workshop and congress on eMaintenance', Luleå University of Technology, pp. 229–234.

Schwald, B. and de Laval, B. (2003), 'An augmented reality system for training and assistance to maintenance in the industrial context', *WSCG* **11**(1), 3–7.

Sims, D. (1994), 'New realities in aircraft design and manufacture', *Computer Graphics and Applications* **14**(2), 91.

van Krevelen, D. W. F. and Poelman, R. (2010), 'A Survey of Augmented Reality Technologies, Applications and Limitations', *The International Journal of Virtual Reality* **9**(2), 1–20.

Weidenhausen, J., Knoepfle, C. and Stricker, D. (2003), 'Lessons learned on the way to industrial augmented reality applications, a retrospective on ARVIKA', *Computers and Graphics* **27**(6), 887–889.

Business Excellence in Maintenance Management - A Comparison of Maintenance Award Schemes

Werner E. Schroeder*

Department of Economics and Business Management
Montanuniversität Leoben
AT-8700 Leoben
Austria
*Corresponding author: Werner E. Schroeder
e-mail: werner.schroeder@wbw.unileoben.ac.at

Abstract

This paper gives an overview of international award-models in the field of industrial maintenance, including a comparison and discussion especially in relation to overall business excellence frameworks. The purpose is to discuss the concept of business excellence in the field of industrial maintenance dealing with existing approaches in the literature. In addition, the paper gives an overview of international awards existing in the field of industrial maintenance. These award-frameworks are discussed and compared. At last the paper shows the concept of the Maintenance Award Austria (MA²), which was initiated by the Austrian Society of Maintenance and Plant Asset Management (ÖVIA) in the year 2011. The underlying maintenance excellence framework, the assessment scheme, the evaluation process as well as practical experiences are shown. The paper is based on a literature review and a two-year case study referring to the framework of the Maintenance Award Austria (MA²).

Key words: Business Excellence, Maintenance Management, Awards, Maintenance Award Austria.

1 Introduction

In general maintenance has a very high economic importance and the role of maintenance in modern manufacturing systems is becoming even more important with companies adopting maintenance as a profit generation business element. Maintenance is viewed as value-adding activity, instead of necessary evil for the expenses (Ben-Daya and Duffuaa, 1995). But many companies do not use the value creation potential of maintenance yet complete.

A maintenance concept generally consists of a framework, which is the supporting structure needed to manage the maintenance function in an organization. Maintenance frameworks incorporate the broader aspects of the business context where finance, operations management and human resource management are combined (Marquez and Gupta, 2006).

Business Excellence frameworks provide guiding schemes also in the fields of operations and maintenance for systematically identifying losses and helping to improve value creation. The use of business excellence models (BEM) has become popular in the last two decades. The existing BEMs have, in most cases, been developed or supported by national organizations as a basis for award programs and for the widespread adaption of principles and methods in the field of business excellence (Dahlgaard, 2013). In this context Business Excellence can be described as results with respect to performance, customers, people and society are achieved through leadership emphasizes the company's strategy, policy, people, partnerships, resources and processes to a high level. Today, more than 80 national awards base their frameworks upon the Malcolm Baldrige National Quality Award (MBNQA) criteria or the European Foundation for Quality Management (EFQM)/European Excellence Award criteria (Mann, 2011). Around 30,000 European organizations were using the European excellence model in 2006 (Heras-Saizarbitoria et al., 2012). Some research indicates that organizations implementing BEM will obtain significant benefits in financial (Boulter et al., 2013; Hansson and Eriksson, 2002; Jacob et al., 2004) and non-financial outcomes (Curkovic et al., 2000).

In recent years an increasing number of Awards in the field of industrial maintenance have been installed, mostly supported by national maintenance confederations or industrial associations, trying to underline the importance and the value creation potential of industrial maintenance. Awards evaluate manufacturing companies, service providers, organizations and individuals through their maintenance activities contribute to the competitiveness of the company and / or increase the safety of the plant(s) to avoid personal and material damage. Many of these award-frameworks also provide best practice approaches and enable companies a benchmarking for further development. This paper gives an overview of the awards existing in the field of industrial management as well as the underlying frameworks.

The research starts by reviewing literature about awards and prizes in the flied of maintenance management. In section 2 different frameworks are pictured and compared. In section 3 a generic model of a maintenance management framework is explained. This framework is the basis for the assessment-scheme of the Maintenance Austrian Award (MA²), initiated by the Austrian society of maintenance and plant asset management (ÖVIA). The ÖVIA is the umbrella organization for maintenance and plant asset management in Austria for more than 28 years. The organization is a networking- and knowledge-platform in the field of maintenance and also interface between science and industry. Section 4 shows the assessment scheme as well as the evaluation process. The paper closes with some practical experiences made since the award was installed.

2 Awards and prizes in the field of maintenance management

Due to increasing importance of maintenance as an entrepreneurial success factor, more and more awards and prizes in the field of maintenance exist, rewarding maintenance management as a whole or recognize best practical solutions. International, in addition to the Japan Institute of Plant Maintenance (TPM Excellence Awards), especially the military and the aviation industry have awards for excellent maintenance. May thus also justified because just in these sectors a high availability and reliability is demanded and also the safety of persons is related directly to these factors. In German-speaking countries there are two awards existing, rewarding an outstanding maintenance management. Beyond that other prices exist, analyzing

maintenance in the course of business excellence assessments. In addition, there are prizes for individuals, performing outstanding in the flied of operational maintenance.

TPM Excellence Awards (TPM)

Total Productive Maintenance (TPM) seeks to maximize equipment effectiveness throughout the lifetime of the equipment. It strives to maintain the equipment in optimum condition in order to prevent unexpected breakdowns, speed losses and quality defects occurring from process activities (Nakajima, 1988; Willmott, 1994) The basic practices of TPM are often called the pillars or elements of TPM (Ahuja and Khamba, 2008). The entire edifice of TPM is built and stands on eight pillars (Sangameshwran and Jagannathan, 2002). TPM initiatives, as suggested and promoted by Japan Institute of Plan Maintenance (JIPM) involve an eight pillar implementation plan that results in substantial increase in labour productivity through controlled maintenance, reduction in maintenance costs and reduced production stoppages and downtimes. JIPM launched the TPM award system in 1964, to 'strengthen the improvement of enterprise constitutions and contribute to the development of industry, by promoting the modernization of plant maintenance and the development of plant maintenance technologies' (JIPM, 2013). Approximately 3.000 plants received the award in Japan and outside over the years. TPM Excellence Awards is under the control of the JIPM. Outside of Japan, JIPM authorised agencies carry out the TPM assessment in accordance with the assessment criteria of JIPM.

Maintainer Awards (MT)

Since 2000 T.A. COOK MAINTAINER grants awards for maintenance projects. The aim of the awards are the appraisal and dissemination of best practice solutions in maintenance as well as the promotion of cooperation and the creation of a communication platform for experts from academia and industry. The importance of maintaining and enhancing the operational efficiency (the cost factor for competitive advantage) is to be brought into focus (Cook, 2012). The award is aimed at industrial companies as well as service providers and service partners. Also innovative applications or products of manufacturers or developers will be awarded. Applications are invited for the categories:

– Project of the Year / industrial companies

– Project of the Year / service provider

– Special Award for innovation

Table 1. Last winners of the Maintainer Award - March 2013 (Cook, 2013)

Category	Company	Project
Project of the Year - industrial companies	Heidelberger Druckmaschinen AG	Training concept with a focus on ensuring the development of the maintenance know-how
Project of the Year - service provider	Aliseca	Multi-site optimization project with the aim to improve the working processes
Special Award for innovation	viasecure	Risk-based approach for the identification of potential risks in turnarounds

Maintenance Award Austria (MA²)

In 2011 the Austrian Society for Maintenance and Plant Asset Management (ÖVIA) launched the Maintenance Award Austria (MA²) reward those companies that have successfully made the change from a classical breakdown maintenance through to a lifecycle-orientated, integrated asset management. The MA² not only assesses the maintenance system as a single-standing organization, but also evaluates the integration in and the interaction with the production system.

The prize is awarded in two categories:

– Maintenance Award Austria - Evaluation of the holistic maintenance management

– MA² Innovation Award - For the most innovative implementation of a single project in the field of maintenance (e.g. service, technology and IT-solution)

Table 2. Last winners of the Maintenance Award Austria - October 2012 (ÖVIA, 2013)

Category	Company	Points [%]
Maintenance Award Austria (MA²) - Winner	SKF Austria	73/100
Maintenance Award Austria (MA²) - Finalist	Palfinger Europe	63/100
Maintenance Award Austria (MA²) - Finalist	ÖBB Technische Services	58/100
		Project
MA² Innovation Award	BOOM-Software	AuDis - Tool for order scheduling

Aircraft Technology Engineering & Maintenance Awards (ATE&M) and Superior Maintenance Awards (SMA)

The nomination for one of the 8 categories (ATE&M Editor's Award for Technology and Innovation, Best OEM for After-market Support, Best Airframe MRO Provider, Best IT Software Provider, Best Logistics Provider, Best Component MRO, Best Engine MRO, Best Spare Parts Provider) of Aircraft Technology Engineering & Maintenance Awards (ATE&M) is only possible for enterprises and service providers related to the aircraft industry. Beside maintenance services as well as the performance in the field of personal safety and the optimization of logistic parameters are assessed. The winner will be chosen by a public audience. The voting process for the nominated companies and service providers is via internet (ATE&M, 2012). The Superior Maintenance Awards (SMA) recognizes outstanding achievements in servicing and maintenance of aircraft by qualified individuals or entities. The assessment categories include knowledge, work ethic and results that directly contribute to the operational readiness of the aircraft (Sikorsky, 2012).

Army Awards for Maintenance Excellence (AAME)

The AAME assess successful maintenance within the U.S. Army, taking into account the compliance of the U.S. Army's maintenance requirements and standards. The awards are designed for maintenance services on stationary equipment or maintenance services for mobile assets such as aircraft carriers, submarines and military aircraft. The award ceremony

takes place annually since 1982 in three categories; "small", "medium" and "large" (AAME, 2012).

Maintenaince Professional of the Year Award (MPA)

The Maintenance Professional of the Year Award (MPA) will be awarded to individuals. As with the ATE&M and the AAME participants are proposed. The application process requires to answer a view questions and to give a brief description of the significant, unique and excellent maintenance service as well as to submit a job description (MPA 2012).

Table 3. Comparison of maintenance award schemes

assessment criteria	TPM	MT	MA²	ATE&M	AAME	MPA	MPE-Index
Production performance parameters	x		x				x
Maintenance performance parameters	x	x	x	x	x	x	
Improvement of performance parameters	x	x	x		x		x
Objectives, strategies	x	x	x		x		x
Organisational aspects	x		x		x		x
Continuous improvement process	x	x	x				
Employee qualification/training	x		x		x	x	x
Impact on micro-economical indicators	x	x	x				
Holistic evaluation	x		x		x		x
Evaluation of a single project		x		x		x	
Qualitative description of results		x		x		x	
Quantification of results	x		x		x		x
assessment process							
Questionnaire	x		x				x
Site-Visit / Audit	x		x				
Jury: team of experts [exp] / public [pub]	exp	exp	exp	pub	pub	pub	exp
Different award categories	x			x			
Comprehensive feedback for participants	x	x	x				
(Industrial) sector	all	all	all	aero	army	all	all
Special prizes			x				
Since	1964	2000	2011	2011	1982	2002	2009

Benchmark studies (MPE Index)

Since 2009, companies have the opportunity to participate in an annual benchmark study. The Manufacturing Performance Excellence (MPE) study as well as the Supply Chain Performance Excellence (SPE) study provides the opportunity to obtain benchmarking data for industrial companies. Again, the focus is on a holistic business valuation. Mainly from the

MPE study a relationship between outstanding production figures and successful maintenance performance can be recognized (Arthur D. Little, 2012).

Additionally the Good Practice Award (GPA), in relation to other maintenance awards, focuses exclusively on safety and health issues. Here one category awards occupational health and safety performance and the contribution of maintenance. A jury of the Agency *Safety and Health at Work* awards practical and innovative contributions promoting safe maintenance practices of companies or organizations (GPA, 2012).

The awards listed in Table 3 assess companies, service organizations and individuals in their maintenance performance. Looking at the different awards, we recognize that the focus is clearly on the evaluation and of plant operators than plant manufacturers or service providers. Especially in the field of plant manufacturing relevant valuation models are still missing.

In the following a generic model of a maintenance management framework is explained. This framework is the basis for the assessment-scheme of the Maintenance Austrian Award (MA²).

3 The Business Excellence Framework in Maintenance Management

There are several frameworks of maintenance management in literature. JONSSON introduces a framework consisting of five components, i.e. goal and strategy, human aspects, support mechanisms, tools and techniques and organization (Jonsson, 1997). A wider framework is proposed by CHOLASUKE et al. by identifying nine elements i.e. policy deployment and organization, maintenance approach, task planning and scheduling, information management, spare part management, human resource management, contracting and outsourcing, financial aspects and continuous improvement (Cholasuke et al., 2004). One of the widest and most recent theoretical frameworks is proposed by PINTELON et al. (Pintelon et al., 2006). It is grounded on an extended maintenance strategy concept including four structural and six infrastructural decision elements.

Maintenance management has to go beyond a purely cost-efficiency dominated orientation including a long-term value system. To ensure a long-term effectiveness of maintenance processes the focus has to be beside the conventional input factors to develop expertise in terms of intellectual capital. So a holistic policy framework is required which reflects maintenance management in a comprehensive way and which includes intellectual capital as a main resource. In the following the requirements of such a management framework will be discussed and set together to a generic model. The content frame should be seen as a basic framework, which can be embellished depending on individual specifications of the operations and maintenance system.

Following the various elements are discussed as well as the necessary definitions are explained. The basic framework (figure 1) is a combined structure-process model which sub summates all aspects of an integrated maintenance management. It contains the essential fields of internal/external entrepreneurial environment, resources/ intellectual capital, maintenance core processes - to convert a certain input into a measurable output (dimension of efficiency) - and the long-term and target-orientated area of impact (dimension of effectiveness). This framework provides the basis for the evaluation scheme of the Maintenance Award Austria (MA²).

Each aspect is described as follows.

Entrepreneurial environment

Here it can be differed into an external and internal entrepreneurial environment. External factors describe the systems' environment in which maintenance (as a supporting cross sectional function in the production system) is embedded. These contain corporate philosophy and corporate goals as well as the pursued production strategy. The internal environment implies the maintenance mission statement, the maintenance target system and the corporate maintenance policy. Both external and internal environment play an important role in managing the maintenance processes, especially for a long-termed success orientation the focus has to be on general principles and corporate goals.
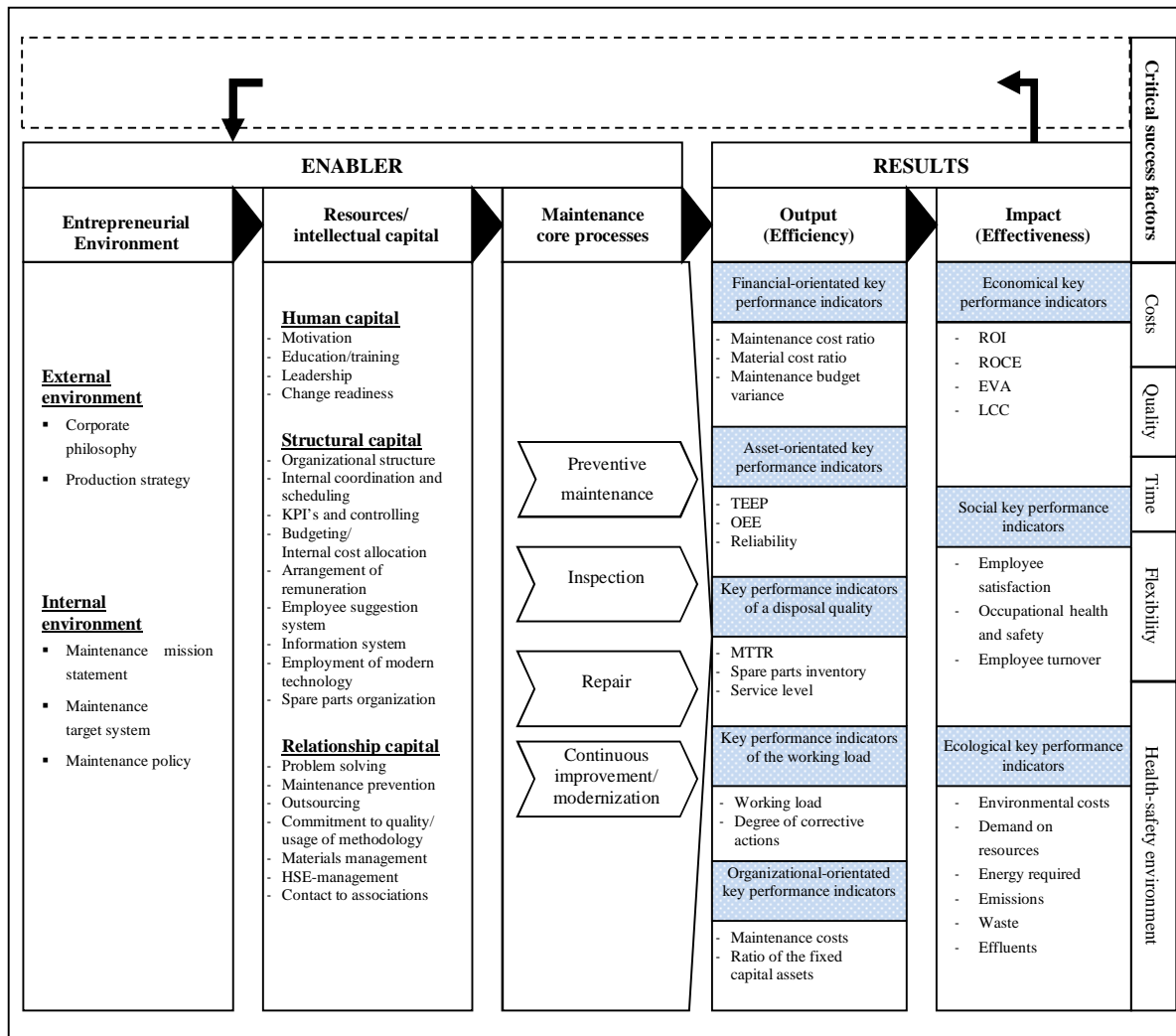
Figure 1. Generic model of a maintenance management framework (Schroeder, 2011)

Resources / Intellectual capital

The maintenance resources form the input for maintenance core processes. Generally the resources and types of capital describe all factors that enable a system to produce a certain output. Intangible inputs have the special feature not to be consumed in course of their use. Rather, it applies them to develop in a meaningful direction to achieve efficiency (output) and effectiveness (impact) gains. Examples are:

– Employees who learn in the course of their work (developing human capital)

- Structures, processes, technologies and methodologies that are continuously improved by permanently passing through and adapting to the situation of the production system and the requirements of plant assets (developing structural capital)
- Relationships and interfaces that are strengthened by cooperation in processes (developing relationship capital)

Human capital (HC)

HC is defined as: "The entire intellectual and physical capital of staff of an organizational unit" (Edvinsson, L., Malone, M.S., 1997). This kind of capital subsumes all skills, abilities and experiences of both the employees and executives. In addition the term also integrates the dynamics of an intelligent organization in a changing competitive environment in sense of a continuous development of skills and abilities. Therefore the organization can only indirectly dispose on their HC so far it is in possession of their individuals. For maintenance this kind of capital describes the attitudes, competencies, intellectual activities and experiences of their employees. Here are all those people carrier of HC that are directly or indirectly connected with maintenance processes. These may be employees of the proper maintenance department, but also production, quality, logistics, purchasing or external staff, which is involved in the maintenance processes. In addition to technical competence there is a strong methodological (problem-solving) and social (leadership) component of competence crucial for HC in maintenance engineering. Further factors include engagement and intellectual agility to HC. This kind of mental flexibility is important for change readiness in transformation processes. Particularly the implementation of new management concepts such as Total Productive Maintenance (TPM) requires a high degree of willingness to change, to break away from classical functional structures and to fix new paradigms. Motivation and leadership are additional factors that influence a positive attitude of the staff in a large scale dimension.

Structural capital (SC)

SC refers to all of a company, which supports the productivity of employees, but remains in the organization "when employees leave the company." SC is in possession of the company and can be used as a tool to develop the employee's knowledge useful. According to SAINT-ONGE, HC is what builds SC, but the better the SC, the better will be the HC. The maintenance SC can be seen in a broad way and includes organizational structures, management-, support-, information- and control-processes, information systems and used technology as well as all other systems of organizational maintenance management services. Also in the area of employee motivation (HC) certain structures, such as the arrangement of remuneration, may not be forgotten. In terms of a continuous improvement the appropriate design of an employee suggestion system, which promotes largely decentralized group proposals, is part of the SC.

Relationship capital (RC)

RC represents the network between all customers, suppliers, internal and external stakeholders with whom maintenance is facing. Regarding to the increasing dynamic of the environment and the associated increase in complexity this kind of intellectual capital has high importance. In particular interfaces that allow the exchange and access to complementary knowledge within and outside of the organizational maintenance structure play a great role. This includes overcoming the work-sharing determined qualification profiles within the O&M system. Here relevant coordination processes have to be institutionalized as well as an appropriate methodological support for knowledge management through learning processes.

The differentiation, in the forms of intellectual capital (HC, SC and RC) is necessary to develop the maintenance management target-orientated. Subsequently the entrepreneurial environment as well as the forms of intellectual capital is sub summated under the umbrella term enabler. They enable the maintenance management to achieve high efficiency and effectiveness.

Maintenance core processes and output

An efficient implementation of maintenance core processes is mainly determined by the environment as well as the used resources and forms of intellectual capital. The more excellent the expression of intellectual capital is, the more effective can be the performance of maintenance services. Beside the classical scopes in maintenance (preventive maintenance, inspection and repair), continuous improvement and modernization of plant assets are getting more and more important in terms of sustainable elimination of vulnerabilities. Here the core processes are not representing a value added chain, but rather constitute the core activities of industrial maintenance. This process orientation allows determining process factors and therefore a statement about the efficiency of input use. Obviously this requires the measurability of outputs in a quantitative sense. Efficiency (output) is therefore usually measured by ratios or at least there has to be a trend behaviour for comparison.

Impact

The impact (dimension of effectiveness) is the long-termorientated outcome of maintenance core processes in context with the given environment and selected targets. In this long-term-orientation the development of the enablers as well as a major stakeholder satisfaction will be aspired. The economic impact mainly refers to the strategic success dimensions: cost, quality, time and flexibility. For example, non-production through plant shutdowns as a result of wrong maintenance strategies will lead to deteriorating delivery performance and subsequently, to possible losses of market share. Intern, longer plant shutdowns are always associated with idle time costs of the production staff. On the other hand measures, which contribute to sustainable improvement of the performance and extending the life-time of plant assets, allow the realization of higher profits and gross margins. These are similar liquidity-related and enable to increase the return on investment (ROI). The environmental and social impact dimension refers primary to measures aimed to ensure health, safety and environment (HSE).

In summary, the outflow or the results of maintenance core processes influence the short-term oriented efficiency dimension (output) and in succession the long-term orientated effectiveness dimension (impact). In figure 1 all dimensions of enablers, processes and results are set together in a generic model of maintenance management. The individual dimensions are not in isolation from each other and have to be seen in a generic context. The long-term coordination of the results with the enablers closes a strategic controlling and learning process and leads to a corresponding development of resources and intellectual capital. The shown efficiency and effectiveness indicators are to be understood as an example. Each company has to decide individually which key performance indicators for measuring the dimensions are most appropriate.
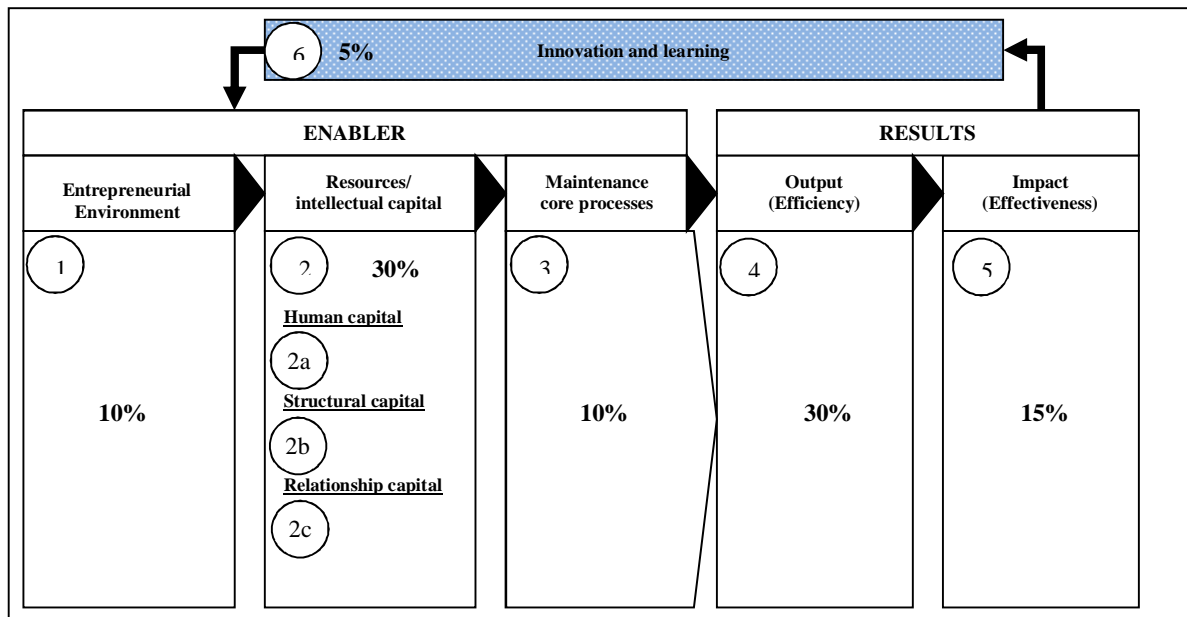
4 Assessment-scheme of the MA²

Figure 2. Points rationing scheme of the MA²-Assessment

To use the model presented in section 3 for evaluation purposes, the framework is based on a points system. Based on the Business Excellence model of EFQM also the division between enabler and results has been made (50% to 50%).

The evaluation process itself is carried out in several stages. Through an online questionnaire, a pre-selection is made. Companies that achieve high performance in this pre-selection will be invited to a site visit. The site visits are conducted by experts from industry and academia. The mainly method at the site-visit is a semi-structured interview technique. Interviews conducted in all company-levels with the focus on the maintenance core- and support processes are made. Results from interviews, as well as data material (e.g. management manuals, process descriptions, documents, statistics ...) serve as basis for the classification in the assessment-scheme, shown in figure 2. The top three companies per year receive finalist status and the winner will be announced in early October as part of ÖVIA maintenance convention.

In addition, each participant receives an evaluation of his assessment as well as anonymized benchmarking data. The participants of the site-visits also serve a potential-profile where points of improvement are identified. The winner is excluded from participating in the award for two years.

Finally some statements from award winners and finalists:

SKF Austria, Winner 2012: "The award is a confirmation that our hard work is bearing fruit. Our greatest strength is the cooperation, the cooperation of production and maintenance."

Constantia Teich, Winner 2011: For us, this award is a great acknowledgment for the many years of effort, to raise the importance of "maintenance" from a "support function" to a significant competitive success factor in our company."

Palfinger Europe, Finalist 2012: "For me as a maintenance manager, the joy is great. It is a confirmation that we are on a good path to maintenance excellence."

4 Conclusion

This paper shows different awards in the field of industrial maintenance. Basically, all awards follow the aim to raise the status of maintenance in the company respectively to honor individual achievements. The explained generic framework of a maintenance management is an approach to focus on intellectual capital as a main resource, because assessing the maintenance management in an integrated view has to go beyond a purely cost-efficiency dominated orientation including a long-term value system. That this model is also suitable for an evaluation of maintenance organizations in various industries demonstrates the use in the Maintenance Award Austria. Based on the Business Excellence framework of EFQM, it has to be attempt to find a balance between enablers and results. The long-term coordination of the results with the enablers closes a strategic controlling and learning process and leads to a corresponding development of resources and intellectual capital.

5 Acknowledgements

References

AAME (2012), http://www.goordnance.army.mil/AAME/aame.html', 2012_04_26.

Ahuja, I.P.S. and Khamba J.S. (2008) 'Total productive maintenance: literature review and directions', *International Journal of Quality & Reliability Management*, Vol. 25 No. 7, pp. 709-756.

Arthur D. Little (2012), 'www.adl.com/MPE', 2013_05_30

ATE&M (2012) 'http://www.ubmaviationnews.com/Publications/Aircraft-Technology-Engineering-Maintenance', 2012_04_26

Ben-Daya, M.; Duffuaa, S.O. (1995), 'Maintenance and quality: the missing link', *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 1, pp. 20-6.

Boulter, L.; Bendell, T.; Dahlgaard, J.J. (2013) 'Total quality beyond North America: A comparative analysis of the performance of European Excellence Award winners', *International Journal of Operations and Production Management*, 33(2), 197–215.

Cholasuke, C.; Bhardwa, R.; Antony, J. (2004) 'The status of maintenance management in UK manufacturing organisations: results from a pilot survey', *Journal of Quality in Maintenance Engineering*, Vol. 10, Nr. 1, 5-15.

Cook, T.A. (2012) 'http://de.tacook.com/fileadmin/files/pdf/Veroeffentlichungen/bewerbung_MT12.pdf', 2012_04_26

Cook, T.A. (2013) http://de.tacook.com/fileadmin/files/2_Events/1_GER/Events_2013/MainDays_2013/Pressem Pressemit_Maintainer2013.pdf, 2013_05_30

Curkovic, S.; Melnyk, S.A.; Calantone, R.; Handfield, R.B. (2000) 'Validating the Malcolm Baldrige National Quality Framework through structural equation modeling', *International Journal of Production Research*, 38(4), 765–791.

Dahlgaard, J.J; Chen, C.-K.; Jang, J.Y.; Banegas, L.A.; Dahlgaard-Park, S.M. (2013) 'Business excellence models: limitations, reflections and further development', *Total Quality Management & Business Excellence*, Vol. 24, Iss. 5-6, 519-538.

Edvinsson, L., Malone, M.S. (1997) 'Intellectual Capital: Realizing your company's true value by finding its hidden brainpower', New York, HarperCollins.

GPA (2012) 'http://osha.europa.eu/en/campaigns/competitions/good-practice-award_2010-2011/index_html', 2012_04_26

Hansson, J.; Eriksson, H. (2002) 'The impact of TQM on financial performance', *Measuring Business Excellence*, 6(4), 44–54.

Heras-Saizarbitoria, I.; Marimon, F.; Casadesus, M. (2012) 'An empirical study of the relationships within the categories of the EFQM model', *Total Quality Management & Business Excellence*, 23(5), 523–540.

Jacob, R.; Madu, C.N.; Tang, C. (2004) 'An empirical assessment of the financial performance of Malcolm Baldrige Award winners', *International Journal of Quality & Reliability Management*, 21(8), 897–914.

Japan Institute of Plan Maintenance (2013), http://www.jipm.or.jp/en/activities/pm/index.html

Jonsson, P. (1997) 'The status of maintenance management in Swedish manufacturing firms', *Journal of Quality in Maintenance Engineering*, Vol. 3, Nr. 4, 233-258.

Mann, R. (2011) 'Awareness and impact of business excellence in Asia', *Total Quality Management & Business Excellence*, 22(12), 1237–1258.

Marquez, A.C.; Gupta, N.D. (2006), 'Contemporary maintenance management: process, framework and supporting pillars', *The International Journal of Management Science*, Vol. 34, pp. 313-26.

MPA (2012) 'http://www.research.net/s/maintpro', 2012_07_26

Nakajima, S. (1988) 'Introduction to Total Productive Maintenance (TPM)', *Productivity Press*, Portland, OR.

ÖVIA (2013) 'http://www.oevia.at/index.php/maintance-award-austria.html', 2013_05_30

Pintelon, L.; Pinjala, S.K.; Vereecke, A. (2006) 'Evaluating the effectiveness of maintenance strategies', *Journal of Quality in Maintenance Engineering*, Vol. 12, Nr. 1, 7-20.

Sangameshwran, P. and Jagannathan, R. (2002) 'HLL's manufacturing renaissance', *Indian Management*, November, pp. 30-5.

Schroeder, W.E. (2011) 'Maintenance Management in Austrian Manufacturing Organizations', *21st International Conference on Production Research*, Stuttgart.

Sikorsky (2012) 'http://www.sikorsky.com/About+Sikorsky/Customer+Awards/Customer+Awards+ Deails?awardvcmid=2ac45981d5898110VgnVCM1000001382000aRCRD', 2012_04_26

Willmott, P. (1994) 'Total quality with teeth', *The TQM Magazine*, Vol. 6, No. 4, pp. 48-50.

Maintenance within Product Service Systems: Is technical knowledge enough to link performance and cost?

Nils E Thenent[1]*, Ettore Settanni[1], Peter Sandborn[2] and Linda B Newnes[1]

[1]*Department of Mechanical Engineering, University of Bath*

BA2 7AY Bath

UK

[2]*CALCE - Center for Advanced Life Cycle Engineering, Mechanical Engineering Department, University of Maryland*

College Park

MD 20742

United States

*Corresponding author: Nils E Thenent

e-mail: n.e.thenent@bath.ac.uk

e-mail: e.settanni@bath.ac.uk

e-mail: sandborn@umd.edu

e-mail: l.b.newnes@bath.ac.uk

Abstract

Availability provision of high value assets is a Product Service System meant to overcome shortcomings of traditional business models. This article deals with the contribution of maintenance performance in this context, particularly in aerospace. The aim is to determine whether quantified knowledge about technical systems is sufficient to characterise successful maintenance, maintenance performance metrics and cost modelling. For this purpose the literature is reviewed to identify supporting propositions. Based on the evidences gathered, it is demonstrated that the type of knowledge applied for measuring maintenance performance and modelling the cost of maintenance match to a large extent. However, in this paper we demonstrate that this type of knowledge is insufficient to capture the conditions for successful maintenance. Finally, directions to address these shortcomings in future research are given.

Key words: Cost modelling; maintenance; performance; aerospace; PSS

1   Introduction

A common business context is one in which an Original Equipment Manufacturer (OEM) has responsibility for designing and manufacturing an asset (such as an aircraft, or a piece of equipment) to certain specifications. The asset or any of its constituent parts failing to deliver their intended function secures the OEM additional revenue streams through after sales support services, or the sale of spares. Models and frameworks developed in this context to address maintenance performance and cost are mostly centred on the assumptions that dependability measures are inherent attributes of a product design (BS EN IEC, 2009; Blanchard, 1992). Cost is in such context a measure of buyer-supplier transactions between organizational structures in place that can be directly and immediately related to a product instance.

More recently, the business focus has shifted from offering individual end-items and then supplementing them with support arrangements to taking responsibility for the customer's capability to attain beneficial outcomes, for example from the utilisation of an asset, hence delivering value '*in use*' (Ng *et al.*, 2011). In principle, the customer procures performance, which is rendered by a network of diverse stakeholders through a combination of activities, resources and competencies. The customer itself is also often involved in the process of generating the outcome. This is usually referred to as a Product-Service-System (PSS), denoting the following (Tukker and Tischner; 2006):

- Products and service outcomes are no longer engineered and offered separately. Rather, the satisfaction or functionality that the user finally wants to realise is integrally taken as a starting point of business development;

- The organisational system that provides this functionality is defined without taking for granted the existing organisational structures and routines; and

- The PSS provider is concerned with the costs of delivering a result.

A particular type of PSS is provided under availability-based contracts. These are a form of long term service agreements with performance guarantees related to the usability of an asset, typically metricised in terms of availability as the ratio between satisfactory operations to downtime (BS EN IEC, 2009). These contracts have are regarded with particular interest in defence aerospace. For example, the UK Ministry of Defence is seeking a substantial move away from traditional support arrangements with industry by means of whole-aircraft availability contracts (Elford, 2011).

The research presented in this paper aims to determine qualitatively whether quantified knowledge about technical systems alone is sufficient in order to characterise successful maintenance, maintenance performance metrics and cost modelling approaches, when the focus is on a PSS to delivering value 'in use' through to fulfil an availability- based contract PSS.

Given the exploratory nature of this study and that the research is still in progress; evidence is gathered from the public domain literature. Additional insight is sought through one of the authors' professional experience as a maintenance technician in commercial aviation, as well as interviews with industrial practitioners. These Interviews have been conducted as part of an

on-going research on what needs to be known to estimate the cost of delivering mission readiness of an aircraft sub-system.
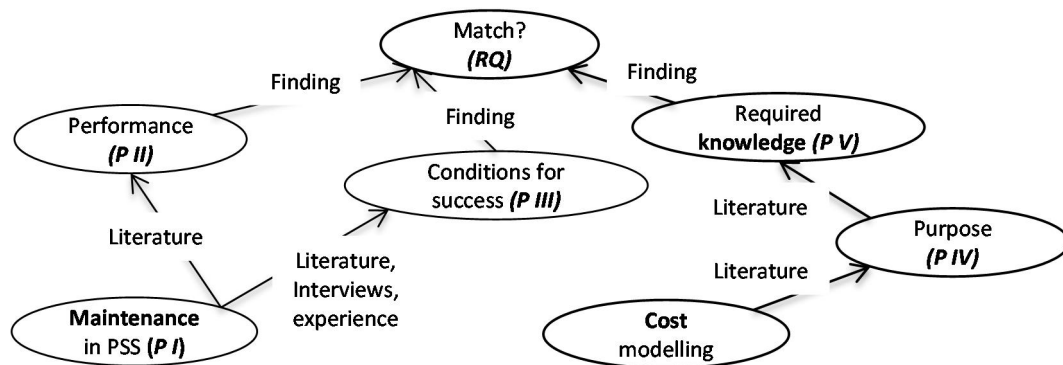

Figure 1 Structure of the paper, with intermediate propositions (P I to P V) leading to answer the research question (RQ).

Figure 1 depicts the steps taken in the reminder of this paper, to answer the research question.

RQ: Does the knowledge required for successful maintenance and for determining the cost and performance of maintenance match?

At each step, propositions are formulated in order to:

   I.   Specify the role of maintenance in PSS;

   II.   Specify what maintenance performance means;

   III.   Identify conditions for successful maintenance;

   IV.   Specify the purpose of cost modelling in PSS;

   V.   Identify on what kind of knowledge cost modelling approaches are based upon.

The concept of technical knowledge employed in this paper is preliminarily defined in the next section.

This paper contributes to the existing literature is in terms of a descriptive argument based on literature and to a lesser extent practitioners' perceptions. The scope of this research is limited to the provision of availability in the field of military aviation.

2   Technical knowledge

In a multi-domain conceptualization of engineering systems the technical system refers to the architectural, physical, nonhuman entities needed to enable the system functions or for use by the stakeholders involved (Bartolomei *et al.*, 2012). Technical knowledge is knowledge employed to develop machinery and equipment by practical application (McCracken, 2012). For support organisations operating within the manufacturing industry, it can be identified with the knowledge about how the technical system can fail, how the production process is designed, and how it functions (Veldman *et al.*, 2011). Technical knowledge is employed here as an overarching concept comprising information and data, as shown in Figure 2.
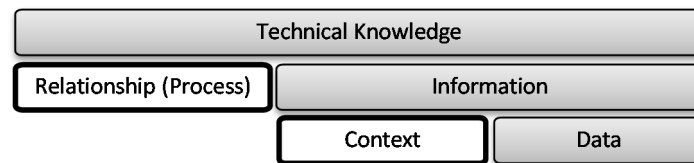
Figure 2 The constitution of "Technical knowledge".

Data is defined as any quantified statement from unknown sources and/or unknown times, whereas the context reflects the environment at a known point in time. Information is based on data that is enriched with context, thus structured and endowed with meaning (Glazer, 1991). From information, technical knowledge is constructed as externalised understanding of the relationships between the inputs and outputs that characterise a process (the internal structure of which is only partly known) for producing a product or service (Bohn, 1994). Table 1 provides illustrative examples of how quantified statements directly related to products and processes can be categorised accordingly.

Table 1 Examples of data, information and technical knowledge.

"Data"	Context leads to "information"	Information and relationships (process) lead to "technical knowledge"
Weight	Specification of component and usage condition.	Failure mechanism, weight translates into acceleration forces depending on usage.
Cost	Specification whether expenditure, internal, or what is charged to a third party.	Relating what has been purchased to what has been achieved; cost is result of a computation.
Failure	Operating condition, way of reporting.	Failure is a result of failure mechanism and, fault isolation practices.

3   Setting the scene for maintenance

Maintenance is typically described as a combination of actions intended to retain an item in, or restore it to, a state in which it can perform a required function (BS EN IEC, 2009; Sandborn, 2013). With reference to aviation, Kinnison (2004) qualifies as maintenance activities those activities carried out for inspecting, overhauling, repairing, preserving, modifying, and repairing technical systems. Maintenance is sometimes referred to as an "art" as well as a "science" (for example, Aubin, 2004; Kinnison, 2004), where *art* is the *"skill of doing something, especially as the result of knowledge or practice"* (McCracken, 2012).

3.1 Maintenance in Product Service Systems

The concept of PSS allows a range of possible deliverables, differing by the degree to which the customer is involved in the achievement of the desired result. Figure 3 illustrates this concept placing at the extremes of the range an aircraft (product) which is maintained by the customer himself, and a successful mission carried out by the service provider. Proceeding from left to right, provider's responsibility shifts towards the delivery of value 'in use' for the customer, increasing the relevance of the intangible features of the delivery over the product-related ones. The provision of availability in a military aviation context, which is the scope of this research, can be placed in the middle of Figure 3: The customer owns the asset and contracts out maintenance through long term service support contracts with performance guarantees.
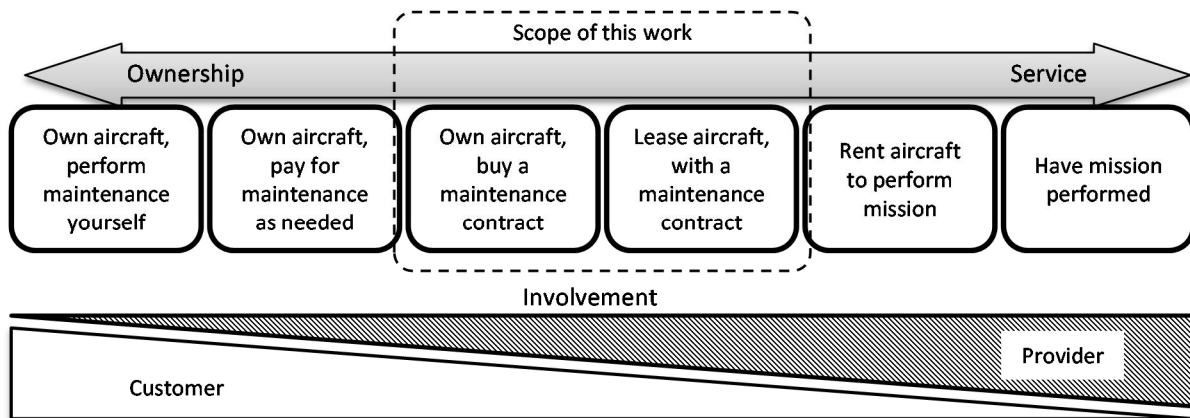
Figure 3 Example of PSS range for an aircraft. (Adapted from Sandborn, 2013; Datta and Roy, 2010)

In such context the service outcome is a technical system being fully mission capable, that is no mission-critical items or sub-systems are in a failed state (Hollick, 2009). Both user and service provider activities, resources and competencies are required for this outcome to be delivered. Figure 4 exemplifies the concept for a military aircraft. The PSS provider's responsibility is answering "Yes" to the question "Aircraft ready?" asked when the customer "wants to fly", all other enabling conditions being fulfilled. In this context, successful maintenance can be reasonably depicted as turning a "no" into a "yes" to meet the customer demand.
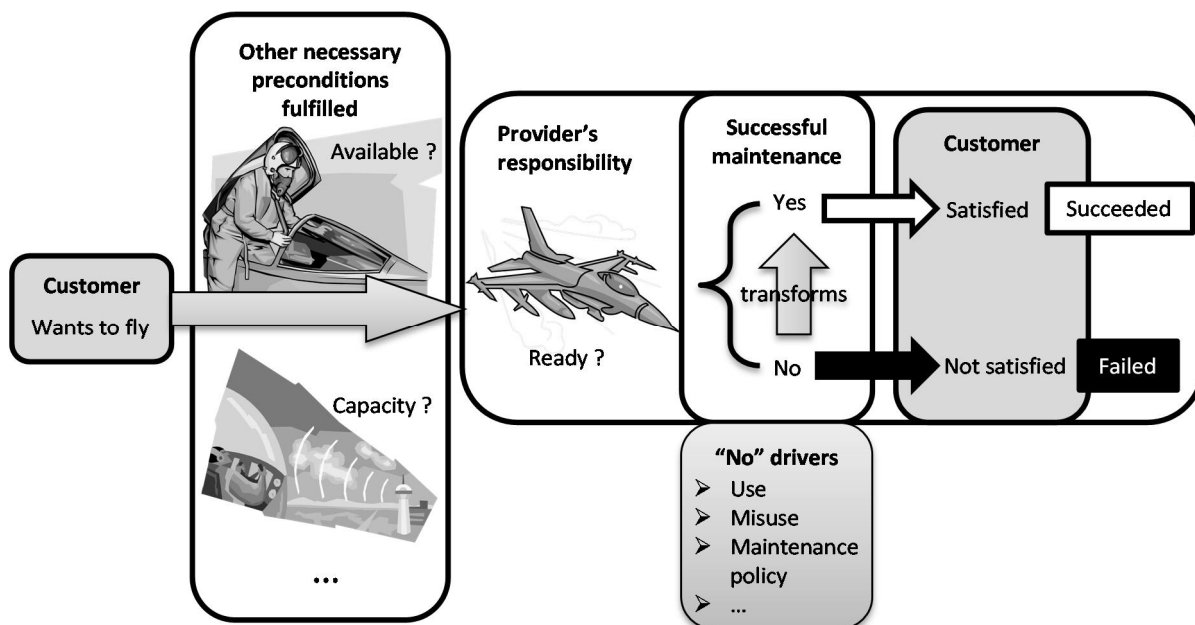
Figure 4 Successful maintenance in the core of providing flyable aircraft.

To achieve the desired delivery multiple intertwined processes in a supply chain of multiple organisations need to be aligned in an efficient way (Aurich *et al.*, 2006). While product-related reliability and maintainability influence the scaling of the supply chain, aircraft availability is ultimately controlled by managing the employed resources (Hollick, 2009). As exemplified by Wilkinson *et al* (2002) an established failure rate will not tell a planner how long a particular piece of equipment will continue functioning. In this light it becomes imperative to understand *how* performance is delivered by these interlinked processes. Ng *et al* (2009) emphasize the importance of behaviours due to the significant human contribution.

However, it is usually not recognised that all processes, involved not only produce the desired output, such as available aircraft, but also undesired outcomes in the form discarded components, or aircraft that may be damaged beyond repair.

Proposition I: In a PSS delivering availability, maintenance is an enabler for providing the desired PSS result. It transforms non-available into available assets at the time demanded by the customer.

3.2 Maintenance performance metrics

According to Neely *et al* (2005) performance is attained through the actions that a business undertakes. The level of performance achieved depends on the extent to which customer requirements are met (effectiveness), and the economical utilization of resources (efficiency) respectively. It is expressed in terms of quantified indicators that are distinguished between leading and lagging. The latter reflect results of events that have happened in the past (for example, machine failures and downtime due to maintenance that have already occurred), whereas leading indicators enable the proactive management of process performance (Smith and Mobley, 2007). Quantification of performance poses a challenge in itself. Therefore, even if appropriate indicators are selected, it is still important to understand *how* these measurements are taken, as subjective judgement can lead to inconsistent recordings (Sumerlin, 1971; Blackwell and Hausner, 1999).

Most of the measures used to quantify maintenance performance are lagging indicators. This is demonstrated by a recent literature review on maintenance performance metrics between 1979 and 2009 (Simões *et al.*, 2011). The authors identify "cost", "overall equipment effectiveness", "availability", "reliability", and "downtime" as the most recurring metrics in the literature. Also, from an asset availability point of view *maintainability* and *reliability*, at times accompanied by *supportability* are widely considered as determinant (Jacopino, 2007; Sandberg and Strömberg, 1999; Crocker, 2010). If considered as designed-in features these characteristics can only be influenced through redesign (Andresen and Williams, 2011). However, unless the asset is deployed, and put into operation none of these metrics reflect any delivered performance in availability provision (Wasson, 2006). Being insensitive to changes in the support environment once established these metrics can be misleading (Blackwell and Hausner, 1999). Similarly, Hollick (2009) cautions about the use of performance metrics that are directly related to the end item, as a diversity of organisations and capabilities contribute to the level of performance that is achieved. Smith and Mobley (2007) stress that it is impossible to manage results in terms of achieved availability or reliability without managing the maintenance process. In this light the findings presented by Simões *et al.* surprise even more. Not only do maintenance organisations rely mainly on lagging indicators, "process performance", "customer satisfaction", "skills", and "resource utilisation" are among the least employed metrics. In particular in a PSS context that requires customer focus and continuous adjustment to changing conditions it is these indicators that seem most appropriate. Parry (2010) confirms that performance measurements are sometimes placed where convenient, not necessarily where valuable.

Proposition II: Performance in maintenance is determined in terms of process performance and product performance. Process-related metrics are further divided into result-oriented, or activity-oriented. The former is expressed by lagging and the latter by leading indicators. Product performance is mainly determined by built-in reliability and maintainability.

3.3 Conditions for successful maintenance

"For the most part, [the Concordes] are kept operational by the loving care and attention of engineers who deal almost exclusively with this aircraft." (Reason, 2000, pp. 310–311)

Successful maintenance is determined by its effectiveness in providing an available aircraft when required, and its efficiency by the use of resources. The latter is affected by the production of undesired outcomes, such as undetected faults or accidents and scrap that use up resources without contributing to the final delivery. Hence, successful maintenance also means safe maintenance, with the literature on safety in aviation providing valuable insights. Reiman (2010) identifies twelve factors, arranged into organisational, social, and individual elements that affect maintenance in a positive way.

Task related knowledge is one of the elements in the latter category, as maintenance always needs to rely on the competency and skill of the personnel, for example an understanding of how a technical system works and not only knowledge about individual components (Goettsche, 2005). Their training, motivation, experience, and working environment form a necessary precondition alongside their attitude, conduct and personality (Simões *et al.*, 2011).

Positive social factors include clear communication, and that embraces communication between different departments in an organisation (Veldman *et al.*, 2011). In the context of PSS this can be translated into the need for a close linkage between all parties involved, including the customer and user. Exchange between technicians and operators is crucial to acquire and enhance understanding of the technical system and to know how it is supposed to be used (Kinnison, 2004; Leney and Macdonald, 2010; Reiman, 2010; Aubin, 2004). Additionally, the importance of data and information from equipment failures, condition monitoring and reliability programs, and service reports is underlined (Kinnison, 2004). During the interviews it has become evident that practices of on-aircraft maintenance, were not favouring the supplier's activities, leading to additional work. Further more, the lack of useful insight from operators or maintenance personnel on other levels has been stated as being hampering for sub-system repair, and for failure analysis. Suwondo (2007) confirms the latter looking at pilot and maintenance reports.

One explanation for field reports providing little insights can be the time pressure maintenance personnel are frequently facing when assessing a situation (Knezevic, 1999). This mandates high maintainability, easing the identification of a failure, and access to the affected components (Fielding, 1999). Built-in test equipment or more sophisticated condition monitoring can significantly reduce the time needed to isolate and rectify a failure (Dabell *et al.*, 2009; Tall, 1971). If such equipment is not reliable it can however have counter-productive effects (Beale and Hess, 2000). In the absence of built-in test provisions adequate test equipment needs to be at hand to avoid false findings (Curry, 1989). The activities following the removal of a functioning unit use in principle the same resources as does a defective unit (Knezevic, 1999). To ensure that actually no fault is found testing can require even more effort than usual (Curry, 1989). An issue that has been raised in this research is that a sub-system that gets send back to the repair provider may only be released back to service when meeting production level test standards requiring additional rework.

One factor for a successful condition monitoring system is the involvement of experienced engineers being knowledgeable about operating conditions (Beale and Hess, 2000). Followell (1995) gives examples of environments that are significant for the reliability of external stores. The environment does not only affect the product-related performance, it is also of

interest for the ability of the personnel to perform their tasks satisfactorily. Even more so when conditions can change, such as during war operations, at an airport gate, or apron (Knezevic, 1999).

It is the maintenance organisation that has to provide all required resources at the right time (Aubin, 2004) in a favourable environment. To do so a maintenance program suitable for the particular needs and conditions needs to be established and to be translated into clear and concise manuals and task descriptions (Ghobbar, 2010; Aubin, 2004). Blackwell and Hausner (1999) show how practices after the identification of a discrepancy impact on the use of resources. Maintenance technicians would remove a defective unit on one aircraft type and send it back to the repair shop. On another aircraft the unit would be aligned by the technician on board the aircraft, not causing a repair. Similarly, availability is affected by practices that allow findings to be deferred, as in commercial aviation or required immediate rectification, as in military aviation (Hockley, 2011).

Proposition III: Successful maintenance depends on individual, social and organisation factors. They need to be supported by appropriate documentation and technical systems in a favourable environment. Essential is the effective communication between all elements (including the technical system).

4   Setting the scene for cost modelling

Sandborn (2013) defines cost modelling as an a priori analysis that maps the characteristic features of a product, the conditions for its manufacture and use into a forecast of monetary expenditures, irrespective from whom the monetary resources will be required (the provider, the customer, etc.). Table 2 summarises some distinctive aspects of cost models.

Table 2 Classification of cost modelling techniques (based on Settanni *et al.*, 2011)

Modelling rational / Concept of cost	Causative models Provide analytical explanatory facilities	Associative models Generate forecast from aggregate past spending outturns
Spending-models One item at a time; Monetary measures directly and immediately relate to it (cash flows and expenditure).	**I** Engineering/Bottom-up (Suwondo, 2007); Feature-based modelling (Evans *et al.*, 2006); Reliability-based modelling (Waghmode and Sahasrabudhe, 2011)	**II** Analogy/ Case-based reasoning (Banga and Takai, 2011); Parametric (Hart *et al.*, 2012); Expert judgement (Emblemsvåg and Tonning, 2003); Artificial Intelligence (Gitzel and Herbort, 2008)
Resource consumption models Multiple activities and deliverables simultaneously; Money is a meta-language for a value representation of the flow of goods and services.	**III** Activity based costing (Emblemsvåg, 2003); Material and Energy Flow Costing (Möller, 2010)	**IV** N/A

4.1 Cost modelling in Maintenance and PSS

Cost is the most occurring performance metric in the literature about maintenance (Simões *et al.*, 2011). However, the approaches adopted to derive such a metric vary, depending on whether the focus of the analysis is

- − The organisational system delivering maintenance services; or

- − The individual technical system sustained.

In the first case, the purpose of assessing maintenance costs is to provide a practical mechanism for planning and controlling the overall maintenance effort, and the efficient use of resources (Kelly, 2006). The maintenance organisation is modelled as a system that contributes to the achievement of the results delivered by a higher organisational system by providing its services to it. Hence, this approach to maintenance cost modelling would fall in quadrant III in Table 2. Examples concerning maintenance in civil aviation include (Mirghani, 1996).

Most maintenance cost modelling approaches have the supported technical system, not the organisation delivering and supporting it, as the point of focus. Given a product's configuration, how it fails (reliability) and is restored to operation (maintainability) is typically described by means of time distributions that are known or can be estimated, whereas its ability to be functional when it is requested for use of operation (availability) results from a combination thereof (Sandborn, 2013). This is particularly common when assessing defence programs at the concept stage (RTO (Research and Technology Organisation), 2007), and more in general to develop trade-off between alternative product designs based on their anticipated reliability (Schor *et al.*, 1989). Some of these approaches fall in quadrant I in Table 2. Typically, the cost composition of a maintenance intervention being known, what needs to be determined is the occurrence of maintenance events (repairs/replacements) over the in-service time of the technical system. By comparison, Engineering approaches employ stochastic processes (see for example Waghmode and Sahasrabudhe, 2011), or simulation (Jazouli and Sandborn, 2011) to determine the number of repairs/replacement that a product unit requires. Other approaches as those in quadrant II consider directly the cost of servicing a technical system as a variable related statistically to some of the technical system's attributes (for example, Curry, 1993).

Current approaches to estimate the cost of a PSS do not present any major discontinuity compared to the methodologies described above, which were developed in the same business context that availability or performance-based contracts are meant to overcome. Datta and Roy (2010) review the literature and outline a framework. However, even though they acknowledge that to model the cost in availability-contracting knowledge about components, including their design, all resources, maintenance and operations is required they eventually suggest combinations of existing cost estimation techniques. Huang *et al* (2012) identify the challenges of adapting these techniques them for the purpose of service cost estimation, but without addressing an autonomous methodology. As a result, most of the approaches to PSS costing tend to focus on a stand-alone asset when modelling the levels of performance a PSS provider is committed to deliver, for example under availability-based contracts.

Proposition IV: The purposes of cost modelling in maintenance are can be twofold:

1. Assessing maintenance costs to provide a practical mechanism for planning and controlling.

2. Provide a monetary counterpart to the occurrences of servicing events.

Even in PSS cost modelling is mostly focused on the second purpose.

4.2 Required knowledge for cost modelling

In this section it is examined what needs to be known for the two identified purposes of cost modelling. Fundamental to the utilisation of the parameters in planning and control approaches is that they are contextualised due to a link to a specific activity (Kimita *et al.*, 2009). Context, namely the activities and their relationships are essential knowledge to build up the model. They are specific for a particular context. Hence, they represent information, and technical knowledge when linking activity input and output.

In models that determine the occurrence of servicing events the specific context has no influence on the parameters that need to be known. While the actual numbers may change, for example when operating conditions are considered by a temperature, the computational structure does not. Taking Proposition IV into account it is therefore concluded that cost models for maintenance in PSS primarily rely on data and information and rarely provide the analytical facilities to translate a monetary value representation of the flow of goods and service that delivers the desired results. Lacking context the applicability to the situation at hand needs to be ensured carefully.

Proposition V: Most cost models rely on data and information. They do not reflect the specific relationships of inputs and outputs based on activities that are undertaken.

5 Findings

To answer the research question the propositions derived from the literature are summarised in Table 3 and the knowledge required for successful maintenance and to measure maintenance performance is examined.

From the point of view of technical knowledge maintenance in PSS has to be considered as a transformation process. It is therefore necessary to understand the context and how the inputs interact to deliver the desired output, namely successful maintenance. How effectively and efficiently this is done is determined by performance metrics. Cost being one of these it is of interest to understand how cost modelling is related to the conditions for successful delivery. It is found that cost models do mostly not reflect the specific context but infer the cost of successful maintenance from product features. Hence, the conditions for successful maintenance are only considered as far as they concern product characteristics, such as maintainability.

Table 3 Summary of propositions

No.	Proposition
I	Maintenance is an enabler for providing the desired PSS delivery. It transforms non-available into available assets at the time demanded by the customer.
II	Successful maintenance depends on individual, social and organisation factors. They need to be supported by appropriate documentation and technical systems in a favourable environment. Essential is the effective communication between all elements (including the technical system).
III	Performance in maintenance is determined in terms of process performance and product performance. Process-related metrics are further divided into result-oriented, or activity-oriented. The former is expressed by lagging and the latter by leading indicators. Product performance is mainly determined by built-in reliability and maintainability.
IV	Two purposes of cost modelling in maintenance are identified: 1. Assessing maintenance costs to provide a practical mechanism for planning and controlling. 2. Monetization of the occurrences of servicing events. Even in PSS cost modelling is mostly focused on the second purpose.
V	Most cost models rely on data and information. They do not reflect the specific relationships of inputs and outputs based on activities that are undertaken.

5.1 Knowledge required to measure performance in maintenance

A closer investigation of performance metrics is undertaken to show that also maintenance performance is determined relying mainly on data and information. To do so the input parameters of selected maintenance performance indicators given by Raju *et al* (2012) are discussed and categorised according to the context and relationship they provide.

Table 4 Examples of performance indices and how the attributes governing them enter their computation.

Index	Attributes governing performance (descriptive input)	Computational input	Technical knowledge category of computational input
As good as new	Benchmark methods, workmanship, quality assurance, expertise; Insulation and grounding.	No of work records; No. of work records meeting new as standard; Per cent residual life; System category.	Computational input only captures the results of the descriptive input. Context is given by system category. Therefore data and information.
Time	Procedures, enterprise resource planning, motivation, focus.	Desired inspection time; extra time.	As above, computational inputs capture the results. No specific context given. Therefore data.

The remainder of the indices are calculated in a manner similar to the examples in Table 4. The majority of input parameters can be classified as data (Table 5). There are six different factors relating that data to the actual context (see Table 5). None of the metrics fulfils the condition for technical knowledge, as there are no specified relationships between the attributes governing the specific performance index and the computational inputs.

Table 5 Required knowledge for maintenance performance metrics (input parameters) (Raju *et al.*, 2012).

Computational input, classified as data	Number of aircraft; Number of days aircraft is serviceable; No. of days aircraft should have been available; Desired uptime; Actual uptime; Desired inspection time; Extra time; No. of breakdowns; No. of breakdowns that should have been prevented; No of work packages; No. of work packages not carried out; No of work records; No. of work records meeting new as standard; Per cent residual life; Signal to noise ratio; Time for correct rectification; Number of snags; Standard value for comfort condition; Prevalent value
Context	Particular squadron; Particular aircraft; Specific task; System category; Time period; Specific condition

5.2 Required knowledge to determine successful maintenance

Table 6 gives examples of technical knowledge for successful maintenance. The availability of data, and communication between professional as well as maintainability, seen from a process perspective can be placed in the given categories. Other conditions, such as the individual, social and organisational factors identified by Reiman (2010) do not properly fit into the scheme of technical knowledge. Maintenance practices, as exemplified by the ability to defer findings are also difficult to describe in terms of technical knowledge, as they are a result of the conditions and the knowledge available. Hence, technical knowledge is insufficient to describe successful maintenance, it should be considered among other conditions.

Table 6 Examples of technical knowledge required for successful maintenance.

Conditions for successful maintenance	Required knowledge		
	Data	**Context**	**Relationships**
Factors identified by (Reiman; 2010)	Not properly captured in the concept of technical knowledge.		
Availability of data	Affected system.	Operating conditions.	Distribution in the PSS.
Maintainability	Number of access panels on an aircraft.	Environment, such as hangar or apron. Are other technicians working on the aircraft?	Over all repair time as a result of the activities from reading the fault report to signing off the paperwork for release to service.
Ability to defer findings	Actual activities, what is required to carry them out and how they are carried out.		
Exchange with other professionals.	Contents related to the appropriate context.		Links between individuals.

5.3 Is technical knowledge enough to link performance and cost?

The above discussion has shown that the knowledge needed to measure maintenance performance and the knowledge employed to model the cost of maintenance are indeed very similar. Both rely mainly on data and information, a subset of technical knowledge. There is however no straight forward "yes" answer to the raised question, as most of the literature considered here suggests. It is found that the knowledge to determine maintenance cost and performance does not match with what determines successful maintenance. Additionally it is found that the conditions that govern successful maintenance cannot be captured by technical knowledge alone.

6 Conclusions & future work

This work has applied the concept of technical knowledge to the literature on maintenance, maintenance performance, and on cost modelling in the context of availability provision through a PSS. It is shown that there is a mismatch between maintenance performance metrics and successful maintenance, in particular for approaches to modelling the cost of maintenance. It is concluded that the contribution of maintenance in PSS is not consistently reflected in such approaches. In the light of maintenance being the determining function for a PSS provision to be successful it is concluded that cost modelling approaches need to be able to incorporate the particular conditions for successful maintenance. Settanni *et al* (2013) suggest an input-output model that is based on a qualitative network representation of the PSS. To capture the conditions for successful maintenance while recognising human and organisational performance variability, as identified by Reiman (2010), the Functional Resonance Analysis Method (Hollnagel, 2012) offers potential for integrating both.

Further more, it has been demonstrated that the concept of technical knowledge alone is not sufficient in the context discussed. As this research is still in progress it is envisaged to extend this concept with the SHEL (Software, Hardware, Environment, Liveware) model to capture constituting elements of a socio-technical system (Cacciabue *et al.*, 2003). Current work includes gathering additional empirical evidence to improve the understanding of maintenance practices and conditions for successful maintenance in PSS and to increase the robustness of the literature-based findings presented here.

References

Andresen, G. and Williams, Z. (2011), "Metrics, Key Performance Indicators, and Modeling of Long Range Aircraft Availability and Readiness", in NATO. Research and Technology Organization (Ed.), *Enhanced aircraft platform availability through advanced maintenance concepts and technologies*, *RTO Technical Report*, NATO, Research and Technology Organisation, Neuilly-sur-Seine CEDEX, France, pp. 7.1-7.12.

Aubin, B.R. (2004), *Aircraft Maintenance: The Art and Science of Keeping Aircraft Safe*, Society of Automotive Engineers, Inc.

Aurich, J.C., Fuchs, C. and Wagenknecht, C. (2006), "Life cycle oriented design of technical Product-Service Systems", *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1480–1494.

Banga, K. and Takai, S. (2011), "Effects of design parameters in cost estimation and cost uncertainty modeling", paper presented at International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 28-31, 2011, Washington, DC, USA.

Bartolomei, J.E., Hastings, D.E., Neufville, R. de and Rhodes, D.H. (2012), "Engineering Systems Multiple-Domain Matrix: An organizing framework for modeling large-scale complex systems", *Systems Engineering*, Vol. 15 No. 1, pp. 41–61.

Beale, J.K. and Hess, A. (2000), "Experiences with A-7E and the AV-8B engine monitoring systems: The good and the ugly", *2000 IEEE AEROSPACE CONFERENCE PROCEEDINGS, VOL 6*, Vol. 6, pp. 221–227.

Blackwell, P. and Hausner, E. (1999), "The redefinition of supportability and its role as a systems engineering tool", *Naval Engineers Journal*, Vol. 111 No. 3, pp. 269–277.

Blanchard, B.S. (1992), *Logistics engineering and management,* 4.ed., Prentice-Hall, Englewood Cliffs,N.Y.

Bohn, R.E. (1994), "Measuring and Managing Technological Knowledge", *Sloan Management Review*, Vol. 36 No. 1, pp. 61–73.

BS EN IEC (2009), *Dependability management. Application guide. Guidelines for specification of maintenance support services* 60300-3-16:2008, BSI.

Cacciabue, P.C., Mauri, C. and Owen, D. (2003), "The development of a model and simulation of an aviation maintenance technician task performance", *Cognition, Technology & Work*, Vol. 5 No. 4, pp. 229–247.

Crocker, J. (2010), "Reliability and Maintainability", in Blockley, R. and Shyy, W. (Eds.), *Encyclopedia of Aerospace Engineering*, John Wiley & Sons, Ltd.

Curry, E.E. (1989), "STEP: a tool for estimating avionics life cycle costs. Aerospace and Electronic Systems Magazine, IEEE", *IEEE Aerospace and Electronic Systems Magazine*, Vol. 4 No. 1, pp. 30–32.

Curry, E.E. (1993), "FALCCM-H: Functional Avionics Life Cycle Cost Model for Hardware", 24-28 May 1993, Dayton, OH USA.

Dabell, B., Gordon, D. and Pompetzki, M. (2009), "Inferential Sensing Techniques to Enable Condition Based Maintenance", *SAE Int. J. Commer. Veh*, Vol. 2 No. 2, pp. 234–244.

Datta, P.P. and Roy, R. (2010), "Cost modelling techniques for availability type service support contracts: A literature review and empirical study", *CIRP Journal of Manufacturing Science and Technology*, Vol. 3 No. 2, pp. 142–157.

Elford, D.G. (2011), "The Evolution of Aircraft Support Concepts Within the UK MoD's Defence Logistics Transformation Programme", in NATO. Research and Technology Organization (Ed.), *Enhanced aircraft platform availability through advanced maintenance concepts and technologies*, *RTO Technical Report*, NATO, Research and Technology Organisation, Neuilly-sur-Seine CEDEX, France, pp. 6.1-6.14.

Emblemsvåg, J. (2003), *Life-cycle costing: Using activity-based costing and Monte Carlo methods to manage future costs and risks*, Wiley, Hoboken, N.J.

Emblemsvåg, J. and Tonning, L. (2003), "Decision support in selecting maintenance organization", *Journal of Quality in Maintenance Engineering*, Vol. 9 No. 1, pp. 11–24.

Evans, D.K., Lanham, J.D. and Marsh, R. (2006), *Cost Estimation method selection: Matching user requirements and knowledge availability to methods*, Paper presented at the 1st ICEC and IPMA Global Congress on Project Management, 23-26 April 2006, Ljubljana, Slovenia.

Fielding, J.P. (1999), *Introduction to aircraft design*, Cambridge University Press, Cambridge.

Followell, D.A. (1995), "Enhancing Supportability Through Life-Cycle Definitions", paper presented at Annual Reliability and Maintainability Symposium.

Ghobbar, A.A. (2010), "Aircraft Maintenance Engineering", in Blockley, R. and Shyy, W. (Eds.), *Encyclopedia of Aerospace Engineering*, John Wiley & Sons, Ltd, pp. 1–13.

Gitzel, R. and Herbort, M. (2008), "Optimizing life cycle cost using genetic algorithms", *Cost Management*, Vol. 22 No. 6, pp. 34–47.

Glazer, R. (1991), "Marketing in an Information-Intensive Environment: Strategic Implications of Knowledge as an Asset", *Journal of Marketing*, Vol. 55 No. 4, pp. 1–19.

Goettsche, L.D. (Ed.) (2005), *Maintenance of Instruments and Systems,* 2nd, ISA.

Hart, C.G., He, Z., Sbragio, R. and Vlahopoulos, N. (2012), "An advanced cost estimation methodology for engineering systems", *Systems Engineering*, Vol. 15 No. 1, pp. 28–40.

Hockley, C.J. (2011), "Maintenance Free Periods of Operation – The Holy Grail?", 23 .1-23-12, NATO, Research and Technology Organisation, Neuilly-sur-Seine CEDEX, France.

Hollick, L.J. (2009), "Achieving shared accountability for operational availability attainment", 26−29 January 2009, Fort Worth, Texas, USA.

Hollnagel, E. (2012), *FRAM, the functional resonance analysis method: Modelling complex socio-technical systems*, Ashgate, Farnham, Surrey, UK England, Burlington, VT.

Huang, X.X., Newnes, L.B. and Parry, G.C. (2012), "The adaptation of product cost estimation techniques to estimate the cost of service", *International Journal of Computer Integrated Manufacturing*, Vol. 25 4-5, pp. 417–431.

Jacopino, A. (2007), "Modelling R&M in performance based contracts - When does risk equal reward?", Jan 22-25, Orlando, FL, available at: http://gateway.isiknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=ResearchSoft&SrcApp=EndNote&DestLinkType=FullRecord&DestApp=WOS&KeyUT=000250381800025.

Jazouli, T. and Sandborn, P. (2011), "Using PHM to meet availability-based contracting requirements", September 25-29, 2011, Montreal, Quebec, Canada.

Kelly, A. (2006), *Plant maintenance management set*, Butterworth-Heinemann, Oxford.

Kimita, K., Hara, T., Shimomura, Y. and Arai, T. (2009), "Cost evaluation method for service design based on Activity Based Costing", paper presented at 7th International Conference on Manufacturing Research (ICMR09), September 8-10, 2009, University of Warwick, UK.

Kinnison, H.A. (2004), *Aviation maintenance management*, McGraw-Hill Companies, Inc, New York, USA.

Knezevic, J. (1999), "Chief mechanic: the new approach to aircraft maintenance by Boeing", *Journal of Quality in Maintenance Engineering*, Vol. 5 No. 4, pp. 314–325.

Leney, D. and Macdonald, D. (2010), *Aérospatiale/BAC Concorde: 1969 onwards (all models) owner's workshop manual*, Haynes, Sparkford.

McCracken, J. (2012), "Oxford English Dictionary. The definitive record of the English language", available at: http://www.oed.com/ (accessed 18 January 2012).

Mirghani, M.A. (1996), "Aircraft maintenance budgetary and costing systems at the Saudi Arabian Airlines: An integrated business approach", *Journal of Quality in Maintenance Engineering*, Vol. 2 No. 4, pp. 32–47.

Möller, A. (2010), "Material and Energy Flow-Based Cost Accounting", *Chemical Engineering & Technology*, Vol. 33 No. 4, pp. 567–572.

Neely, A., Gregory, M. and Platts, K. (2005), "Performance measurement system design: A literature review and research agenda", *International Journal of Operations & Production Management*, Vol. 25 No. 12, pp. 1228–1263.

Ng, I.C.L., Maull, R. and Yip, N. (2009), "Outcome-based contracts as a driver for systems thinking and service-dominant logic in service science: Evidence from the defence industry", *European Management Journal*, Vol. 27 No. 6, pp. 377–387.

Ng, I.C.L., Parry, G.C., McFarlane, D. and Tasker, P. (2011), "Towards a core integrative framework for complex engineering service systems", in Ng, I.C.L., Parry, G.C., Wild, P., McFarlane, D. and Tasker, P. (Eds.), *Complex engineering service systems: Concepts and research*, Springer, Berlin, pp. 1–16.

Parry, G.C. (2010), *Developing Measures for BAE Systems Service Business*, Unpublished report, Bristol, UK.

Raju, V.R.S., Gandhi, O.P. and Deshmukh, S.G. (2012), "Maintenance, Repair, and Overhaul Performance Indicators for Military Aircraft", *Defence Science Journal*, Vol. 62 No. 2, pp. 83–89.

Reason, J. (2000), "A Cognitive Engineering Perspective on Maintenance Errors", in Sarter, N.B. and Amalberti, R. (Eds.), *Cognitive engineering in the aviation domain*, Lawrence Erlbaum Associates, Mahwah, N.J, USA, pp. 309–325.

Reiman, T. (2010), "Understanding maintenance work in safety-critical organisations. Managing the performance variability", *Theoretical Issues in Ergonomics Science*, Vol. 12 No. 4, pp. 339–366.

RTO (Research and Technology Organisation) (2007), *Methods and Models for Life Cycle Costing: Final Report of Task Group SAS-054*, RTO-TR-SAS-054, *RTO Technical Report*, NATO, Research and Technology Organisation, Neuilly-sur-Seine CEDEX, France.

Sandberg, A. and Strömberg, U. (1999), "Gripen: with focus on availability performance and life support cost over the product life cycle", *Journal of Quality in Maintenance Engineering*, Vol. 5 No. 4, pp. 325–334.

Sandborn, P. (2013), *Cost Analysis of Electronic Systems*, World Scientific Publishing Co. Pte. Ltd., Singapore.

Schor, A.L., Leong, F.J. and Babcock, P.S. (1989), "Impact of fault-tolerant avionics on life-cycle costs", 22-26 May 1989, Dayton, OH USA.

Settanni, E., Newnes, L.B., Parry, G.C. and Goh, Y.M. (2011), *Industrial Product Service Systems: what are the methodological repercussions for through-life costing?*

Settanni, E., Thenent, N.E. and Newnes, L.B. (2013), "System modeling: a foundation for costing through-life availability provision", paper presented at PLM13, 6-10 July 2013, Nantes. France.

Simões, J.M., Gomes, C.F. and Yasin, M.M. (2011), "A literature review of maintenance performance measurement: A conceptual framework and directions for future research", *Journal of Quality in Maintenance Engineering*, Vol. 17 No. 2, pp. 116–137.

Smith, R. and Mobley, R.K. (2007), *Rules of Thumb for Maintenance and Reliability Engineers*, Elsevier.

Sumerlin, W.T. (1971), "System operational Considerations and their Relationship to the Test Process", in *Reliability of Avionics Systems*, *AGARD Lecture Series*, Neuilly-sur-Seine CEDEX, France, pp. 9-1 to 9-8.

Suwondo, E. (2007), *LCC-OPS: Life cycle cost application in aircraft operations*, ITB Press, Bandung.

Tall, M.M. (1971), "Cost Effectiveness of Built-In Test Provisions", in *Reliability of Avionics Systems*, *AGARD Lecture Series*, Neuilly-sur-Seine CEDEX, France, pp. 4-1 to 4-8.

Tukker, A. and Tischner, U. (2006), "Product-services as a research field: past, present and future. Reflections from a decade of research", *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1552–1556.

Veldman, J., Klingenberg, W. and Wortmann, H. (2011), "Managing condition-based maintenance technology: A multiple case study in the process industry", *Journal of Quality in Maintenance Engineering*, Vol. 17 No. 1, pp. 40–62.

Waghmode, L. and Sahasrabudhe, A. (2011), "Modelling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems", *International Journal of Computer Integrated Manufacturing*.

Wasson, C.S. (2006), *System Analysis, Design, and Development: Concepts, Principles, and Practices*, John Wiley & Sons.

Wilkinson, C., Pecht, M., Wasson, J. and Condra, L. (2002), "Recommendations for Future Avionics Hardware Development", *SAE Technical Paper Series*.

Improving the efficiency of maintenance actions
CASE: Analyzing the structure of the wet wood chip unloader of a pulp mill

Mirja Tykkälä* and Harri Eskelinen[#]

*Efora Oy
P.O. BOX 5,
FIN-18101 Heinola
Finland

[#] *Lappeenranta University of Technology*
Department of Mechanical Engineering
P.O.Box 20
FIN-53851 Lappeenranta
Finland

*Corresponding author: Mirja Tykkälä
e-mail: mirja.tykkala@efora.fi
e-mail: harri.eskelinen@lut.fi

Abstract

This paper presents a life cycle cost analysis of a redesigned wet wood chip unloader of a pulp mill. The focal point of the analysis is productivity resulting from the effectiveness of maintenance. The key maintenance issue of the unloader was found to be its actual structure, because it was difficult to service and assemble. This paper offers a better mechanical solution to the problem. The scientific viewpoint expressed in this paper emphasizes that too little attention has been paid to the way in which maintenance information could be used at the beginning of the design process. Our results demonstrate how design for manufacturing and assembly (DFMA) aspects can be integrated with maintenance information; such integration makes it possible for a mill to increase productivity and achieve the benefits of maintenance earlier. We also present organizational aspects for improving the efficiency of maintenance actions by utilizing the Responsibility, Accountability, Communication and Information (RACI) role distribution matrix model.

Key words: maintenance efficiency, RACI model, wet wood chip unloader, DFMA.

1 Introduction

Cooperation among design, assembly and installation divisions within a company is generally regarded as an important cornerstone of assembly-friendly construction. However, shouldn't the design division also cooperate with the maintenance and service division? Because the two sides obviously should cooperate, what is the right time for and form of this cooperation? What kind of information is relevant for both sides? Are only failure data and lifetime data pertinent? Which side most needs the cooperation? In this paper, we discuss these aspects and provide options for improving the effectiveness of maintenance actions. We present both the results of an exhaustive literature review and an industrial case example dealing with a redesign project of a wet wood chip unloader of a pulp mill to support our approach. The

redesign followed feedback collected from the maintenance and service division. The case example suits our purposes well because the unloader should be able to be serviced quickly and should have a long lifetime. We present both the old and the new construction of the unloader and analyze the main points of view expressed in discussions between designer and maintenance staff.

Our paper includes a relative wide literature research, which aims to form the basis for our case example analysis. At first, we discuss about the economic aspects of cost optimizing in maintenance actions. At second, we talk about the organizational viewpoints in maintenance and at third, we show options from the literature to integrate these two viewpoints with the engineering design environment. By utilizing simultaneously all these three aspects (economic, organizational and engineering design aspects) it is possible to improve the efficiency of the maintenance actions.

2 Cost models of maintenance actions

Maintenance, cost and optimizing models from the literature are outlined first and then discussed below.

1. Traditional maintenance models based on forecasting of the reasons for possible breakdowns
2. Comprehensive cost models based on e.g. empirically determined indicators
3. Different types of optimizing models and algorithms

Traditional maintenance models are based on *fault diagnosis*, or recognition of the reasons for possible breakdowns beforehand and efforts made to prevent the breakdown from occurring. If it is possible to improve the effectiveness and accuracy of fault diagnosis, this will in turn improve the accuracy of the prediction of the time for maintenance action, which will in turn yield options for decreasing production costs. Al-Najjar (2000) presents an example dealing with effective diagnosis and prognosis when a vibration-based maintenance policy is implemented. Usually traditional maintenance models also include the consequential economic losses incurred by unplanned stoppages.

Komonen (2002) offers one of the most comprehensive cost models of industrial maintenance, the hierarchical system of maintenance performance indicators. This cost model is based on empirically collected data from hundreds of companies operating in various industries. The Komonen model includes important causalities such as these:

1. Impact of the utilization rate of production equipment on maintenance costs
2. Effects of failure rates and repair times on the efficiency of maintenance
3. Maintenance costs in the mechanical wood-processing industry as a function of production equipment
4. Behaviour of maintenance costs as a function of production volume
5. Maintenance costs in relation to production equipment as a function integration level of production

Kennéa et al. (2007) present another comprehensive maintenance cost model, which aims to integrate the cost and reliability aspects through an optimization algorithm. They have

formulated an analytical model for the joint determination of an optimal age-dependent buffer inventory and preventive maintenance policy in a production environment subject to random machine breakdowns. The model takes into account both the effects of preventive maintenance policies and the machine age for optimal safety stock levels. An age-dependent optimization model is utilized based on the minimization of the overall cost function, including inventory holdings, lost sales, and preventive and corrective maintenance costs.

Another classification of models utilized for evaluating or maximizing profits from maintenance comprises different types of models used for planning preventive maintenance actions. These models usually include an option for cost minimizing. Ashayer et al. (1996) present one such example: a mixed-integer linear programming model developed to simultaneously plan preventive maintenance and production in a process industry environment. The model schedules preventive maintenance and production jobs, while minimizing costs associated with production, backorders, and corrective and preventive maintenance. The key function of the model is that it takes into account the probability of a breakdown according to data from the last maintenance period. However, the formulation of this model is so flexible that it can be adapted to several production situations, as Ashayer et al. (1996) have described in their article.

Total Productive Maintenance (TPM), an approach initially developed in Japan, can be regarded as a management philosophy. McKone and Weiss (1998) have discussed maintenance-investment decisions for TPM. Their findings on how to bridge the gap between practice and research in maintenance activities at least partially support our viewpoint.

To briefly comment on the utilization of cost-related models according to the literature, it is obvious that the current trend is the use of more comprehensive life cycle cost models instead of the calculation of single profit gain from specialized maintenance actions. This finding is in line with the opinions of the authors of this conference paper.

3 Organizational and networking models for effective maintenance

It is difficult and even unnecessary to try to distinguish the cost-related aspects from organizational aspects of maintenance actions. If the structure of the organization is functional and if the information for making decisions dealing with maintenance actions is sufficient, remarkable cost savings are generated. Related topics from the literature are first outlined and then discussed below.

1. Required information system features for effective maintenance, such as Computerized Maintenance Management Systems (CMMS)
2. Definition of a good communication system inside a company to ensure efficient maintenance, such as the Responsibility, Accountability, Communication and Information role distribution matrix (RACI matrix)
3. Effective maintenance policy
4. Maintenance concepts in multinational and global environments
5. Decision making processes in maintenance management
6. Logistics of maintenance spare parts

As Arts et al. (1998) have stated, many papers have been written on performance indicators for operational maintenance. Arts et al. (1998) claim that performance indicators of

operational maintenance can help maintenance staff to improve its operations in such a way that the direct and indirect costs of failure processes can be reduced. However, they also support the opinions of the authors of this paper that so far, no consensus has been reached as to which indicators should be used in a particular industry. Arts et al. (1998) try to solve this problem by describing the information system needed for one to draw conclusions about operational maintenance performance in a process industry. The indicators they have proposed focus on determining 1) the most costly equipment from the maintenance perspective, 2) the cost of the current maintenance concept and 3) the major components of maintenance costs. Their key finding is that standards and procedures need to be developed and that adherence to them has to be ensured.

Alsyouf (2006) has developed a strategic maintenance performance measurement system which has been tested at a Swedish paper mill. Based on the key findings of Alsyouf (2006), it was found that in the implementation of the developed framework, it was possible to measure and identify the cause-and-effect relationship of using an effective maintenance strategy, as well as to assess its impact on the company's competitive advantage. For our research purposes, it is important to highlight that Alsyouf (2006) claims that his framework makes it easier for the maintenance and production staff, who are usually technically oriented, to communicate better with top management in terms that managers understand, i.e. in terms of money. Alsyouf (2006) no longer regards maintenance as the cost centre but rather as a profit-generating function. Later, Alsyouf (2007) shows how an effective maintenance policy could influence the productivity and profitability of any given manufacturing process.

Markeset and Kumar (2003) present an approach for design and development of product support and maintenance concepts for industrial systems in a multinational environment. They examine various issues such as reliability, availability, maintainability, and supportability (RAMS), which directly or indirectly affect product support, maintenance needs and related costs. Markeset and Kumar (2003) also emphasize that the strategy for product support should not be centred only on "product", but should also take into account important issues such as the service delivery capability of the manufacturers, service suppliers and the capability of the users' maintenance organization. Markeset and Kumar (2003) claim that product support strategy should not only be focused on the product or on its operating characteristics, but also on assisting customers with services that enhance product use and add additional value to their business processes.

Key to maintenance management is the decision making process: who should make the decisions and when? Pintelon and Gelders (1992) have identified and discussed the most important elements of this decision making environment. The research conducted by Pintelon and Gelders (1992) contributes to the structuring of the maintenance management area and provides the framework for maintenance policy optimization in a business context. Based on Pintelon and Gelder's (1992) results, it is obvious that the organizational development should include at least such topics as system design of maintenance management, issues in maintenance decision making and aiding tools for decision making in the area of maintenance management.

One important area in the global networking maintenance environment is the logistics of maintenance spare parts. According to Huiskonen (2001), the key to success might be for one to recognize the diversity of the operational control characteristics of spare parts and consider these aspects as a basis for supporting the planning and designing of a spare parts logistics system. Huiskonen (2001) discusses four control characteristics of maintenance spare parts – criticality, specificity, demand pattern, and value of parts – in terms of their effects on

logistics system elements – network structure, positioning of materials, responsibility of control, and control principles. Finally, Huiskonen (2001) is able to illustrate distinct operating policies for different types of parts in the spare parts supply chain.

Bruzzo and Eskelinen (2012) raise questions related to organizational communication in maintenance activities. Firstly, Bruzzo and Eskelinen (2012) ask how it is possible to exploit the data provided by the different Computerized Maintenance Management Systems (CMMS) in order to improve the design, manufacturability, and the reliability of the equipment in such a way that manufactures and end-users will benefit from these changes. Secondly, they ask how one can formulate a strategy based on a combination of effective communication techniques, the Role assignation matrix (RACI) model and the Design For Manufacturing and Assembly (DFMA) approach in order to then generate a model allowing the communication gap experienced by designers, maintenance service providers and end-users to be filled. Bruzzo and Eskelinen (2012) have shown that an important characteristic of modern organizations is having a system within the manufacturing company that allows for the inclusion of new improvement proposals or that can be flexible enough to adapt to changes relatively easily. This allows the feedback received from customers to be taken into account in order to maintain the pace and gain ground. More traditional organizations that have failed to do this are gradually disappearing from the market. According to Bruzzo and Eskelinen (2012), in most cases, the foundation of the process lies within the selection of the accountable person in each organization. This must be done in a straightforward manner in order to avoid misunderstandings. In cases where a filtering process is needed, it should be done in the most effective way. To accomplish this task, roles are assigned to the various decision areas by applying the RACI model specifically to the task in question. As companies can have different types of structures and information systems, the following matrix should only be considered as an example. However, an important consideration in all cases is that the matrix must list the key tasks and the titles of the key positions involved in the tasks presented. The RACI model considered for this example is from the end-user side (Bruzzo and Eskelinen (2012)) and is presented in Table 1.

Table 1. Example of Responsibility, Accountability, Communication and Information matrix applied to the user company to implement the DFMA approach in the process (Bruzzo and Eskelinen, 2012)

Decision areas	General Manager	Mainte-nance Manager	Shift supervisor	Production workman	Maintenance Workman
Propose and monitor the scope of the plan	A	C	I	I	I
Audit IT systems and request any needed improvements	C	A	I	I	I
Transmit the filtered information to the other party	I	A	C	I	I
Implement changes and modifications to the machine	I	R	A	C	R
Control operational variables of the machine	I	C	A	R	C

In Table 1, an accountable person is assigned to each task, but in some cases, it is not necessary for the accountable person to actually be the one responsible for the task itself. As Bruzzo and Eskelinen (2012) state, in modern organizations providing detailed job profiles, it might be possible to include the RACI model in the information system and to automate the

manual formulation of the matrix. This conclusion matches the opinions of the authors of this conference paper.

To conclude this organizational discussion, we found that no matter whether computer aided databases or traditional email-based channels are utilized to convey maintenance information to the designer, the key questions are always the same: who needs the information, when and in what form? The presented RACI-model seems to be a promising option for different types of companies and networking environments.

4 Integration of engineering design and maintenance aspects

When we talk about integrating maintenance feedback data with Design for Manufacturing and Assembly (DFMA), we must consider the following questions:

1. What are the weak points of traditional systematic design approaches in general?
2. What is the role of Concurrent Engineering (CE) in the context of maintenance?
3. How can the relevant maintenance data for the designers be identified?
4. How can life cycle aspects of the product be integrated with the overall model of maintenance activities?

These questions are discussed in the following paragraphs.

4.1 Development of traditional design methodologies

One interesting aspect of the field of "developing" DFMA is the criticism directed at some traditional design methodologies. It is likely that most arguments were made against VDI's systematic approach during the 1980's and 1990's. After that, Concurrent Engineering Design was regarded as something of a revolution in engineering, but soon proved not to solve the problems of DFMA.

In systematic design approach according to the VDI 2221 -standard, the functional design of a product and its subsequent modular construction are followed by documentation for manufacturing and assembly. Because these two stages (design and manufacturing) are not synchronized, it is possible that the designer will not attend to manufacturing aspects enough during modularization. According to Miller (1993), this most common design approach, which he calls "step-wise refinement", is good for inexperienced designers and produces designs which gradually improve over time. Miller underlines that the primary disadvantages of this approach are that it tends to have a result which comes from compromises occurring as the process proceeds, and it is difficult to execute many of its small steps concurrently. Concurrency is achieved only by considering variants throughout the design and manufacturability stages simultaneously. This evaluation of multiple variants speeds up the process but creates waste when variants are eliminated. In addition, some components cannot be designed until others are complete. Unfortunately, the decision to go back to an earlier design step is usually encountered late in the process, and an expensive, time consuming restart is required. Since starting over is avoided if at all possible, an average or worse quality of design is usually the result of this approach. When we also factor in the late feedback provided to the designer and linked to maintenance and service actions of the product, we notice that there is obviously an urgent need to improve the efficiency of the traditional systematic design approach.

Nowadays, researchers have no consensus on the most important aspects pertaining to Concurrent Engineering Design (CE), and this leads to different emphases in the handling of the topic. According to Miller (1993), process management is the most important of the CE processes. According to Asiedu and Gu (1998), the point of view of life cycle cost (LCC) is most important in concurrent engineering; therefore, designers need LCC analysis to support their decision making. Hoffman (1998) points out the meaning of quality product-oriented decision making during the CE process. Portioli and Singh (1997) claim that when CE has been used, too little attention has been given to production management issues. According to them, the focus has been too much on the process design. Stahl et al. (1997) suggest that there is a lack of methods supporting the planning of production systems when CE is used. Brookes and Backhouse (1997) claim that the most important challenge in widening the use of CE is the understanding of how to tailor the concept to suit different companies. According to Willaert et al. (1998), CE, in principle, is more a management and engineering philosophy to conquer the market pressure than a design tool.

The authors of this paper are of the opinion that it seems CE in its traditional format can be viewed more as a summary of "best practices" in product development and less as the adoption of a radically new set of ideas for improving DFMA-aspects.

In addition, the authors of this article believe that the DFMA-friendly engineering design process is much more than just a systematic approach or a set of concurrent manufacturing and design stages. If we accept this, then it is possible to also add maintenance feedback or even maintenance-friendly design to the DFMA requirements.

Nowadays, aspects of Life Cycle Cost Analysis (LCCA) have been established as a relevant part of efficient maintenance policy. As Aurich et al. (2006) present, technical services such as maintenance, retrofitting, refurbishing or user training can significantly influence the economic and ecologic performance of high quality investment goods, thus providing new and advanced user benefits. In order to systematically exploit these potentials, the interrelations between (physical) products and (non-physical) services need to be considered proactively, resulting in the necessity for integrating corresponding product and service design processes. For this reason, as Aurich et al. (2006) claim, a process for the systematic design of product-related technical services is introduced, which upon modularization of the product represents a promising starting point for linkage with corresponding product design processes.

Lappeenranta University of Technology (LUT) has established a research team to discover how DFMA aspects could and should be embedded in existing design methodologies. This team has discussed different viewpoints advanced in Eskelinen's recently published scientific research report (Eskelinen, 2012). This conference paper focuses on the viewpoint entitled "DFMA approaches considering feedback from maintenance". According to Eskelinen, the main focus of this viewpoint is the utilization of service and maintenance data to improve DFMA approaches in a global networking environment. The framework for this viewpoint according to Eskelinen (2012) is illustrated in Figure 1.

The interrelation of methods and techniques of the new DFMA model is presented by Bruzzo and Eskelinen (2012) in Figure 2. This novel combination of techniques is integrated into a logical and coherent structure allowing users to take full advantage of each one to accomplish the task of improving the life cycle costs of the activities in question. Bruzzo and Eskelinen (2012) have shown that when the users provide the correct answers to the following

questions, it will be possible to reach an initiation point for a process supported by the DFMA model, which will in turn allow improvements to occur inside the user organizations.

1. When can a case be considered successful enough to be taken into account and communicated to the manufacturing or service company? What are the indicators that would allow the transmission process to be initiated?
2. What information should be conveyed to other interested parties in order to be analyzed and implemented in a conscious way?
3. Is it possible to include the DFMA approach in a computerized system so that the information can be transmitted directly?
4. If the organization has already successfully implemented changes to its processes, what is the added value of these changes, and when should this information be shared with the manufacturers and service companies?

One tool allowing designers to also take service and maintenance aspects into account is virtual modeling (VM). Gomes and Zachmann (1999) have discussed the steps needed to apply virtual reality (VR) to virtual prototyping (VP) in order to verify assembly and maintenance processes in industrial applications. From our perspective, this might open up opportunities for improving the DFMA aspects of the product simultaneously.

Different information flows are crucial to improving the efficiency of maintenance actions in engineering. Kiritsis et al. (2003) have presented a technological solution including 1) product lifecycle models, 2) product embedded information devices with associated firmware and software components and 3) tools for decision making based on data gathered through a product lifecycle. This is done to enable and exploit a seamless flow, and to trace and update information about a product after its delivery to the customer, to its final destination (deregistration, decommissioning) and back to the designer and producer. It is interesting to note from our research standpoint that Kiritsis et al. (2003) were able to present examples of defining a data structure for recording maintainability data during the maintenance operations of a product in order to use them in design for maintainability.
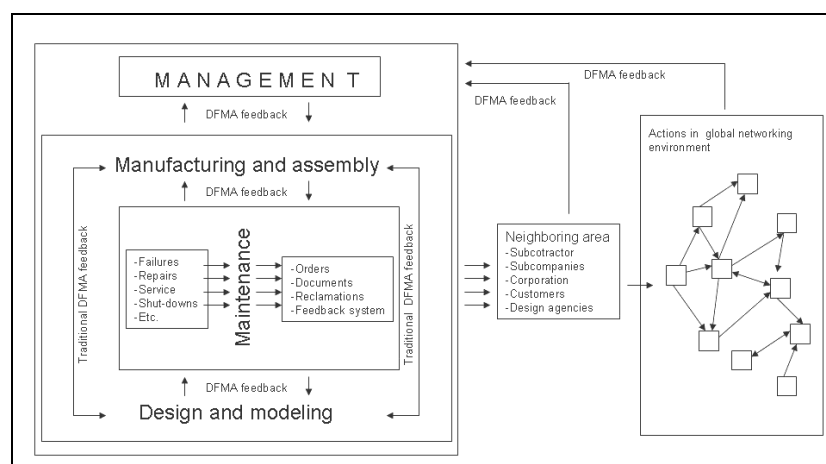
Figure 1. Framework for the utilization of service and maintenance data to improve DFMA approaches in a global networking environment (Eskelinen, 2012).
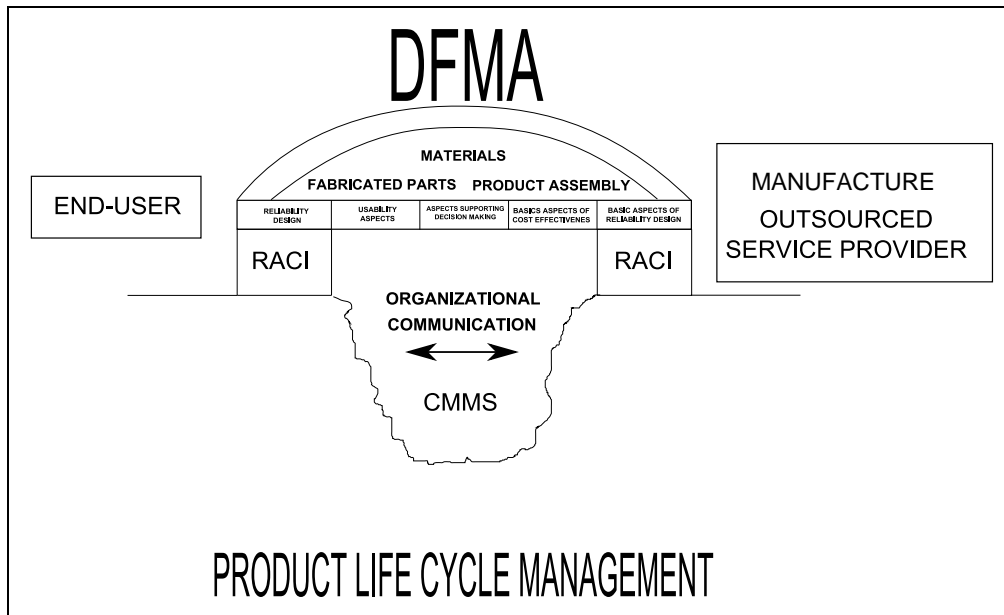
Figure 2. Lappeenranta University of Technology Proposed Model presented by Bruzzo and Eskelinen (2012): Interrelation among the different tools of the model

To conclude this section on design aspects, we observe that the main communication problem is the filtering of relevant information from the maintenance data to be sent to the designer to enable an effective DFMA process. Usually all the information is sent at once to all the actors in the maintenance field, and the designer has to clarify what is possibly missing and what is irrelevant to the design task. The results from our case example dealing with the maintenance and redesign aspects of the wet wood chip unloader of a pulp mill are similar, and clearly support these findings.

5 Case: The wet wood chip unloader of a pulp mill

In analyzing the maintenance history of the wet wood chip unloader of a pulp mill, we could both compile observations dealing with options for improving the efficiency of maintenance actions and generate ideas about how to integrate DFMA aspects with maintenance information. Our ultimate purpose was to show how the mechanical construction of the unloader was modified to make assembly work and maintenance actions easier. Our analysis was based on the maintenance history data of the unloader collected over the past few years. This data also made it possible to analyze the conveyed information flows between designers and maintenance staff. We found evidence of the advantages of the previously described RACI-model especially for effective collaboration between the designers and maintenance staff.

In our case example we focus to discuss about the possibilities to utilize RACI-model to support especially the integration between company's service staff (see chapter 5.2.2) and engineering designers (see chapter 5.2.3). The utilized tool was a client server system and the practical implementation was based on the tuned questions. In this case example we want to show also some numerical evidence about the business-oriented advantages of the functional RACI-model.

5.1 The old construction of the wet wood chip unloader

A photo of the old wet wood chip unloader is presented in Figure 3, and its detailed construction is presented in Figure 4.

Some key features of the old construction are as follows:
1. The installation is in a hanging position
2. The main diameter is 1 m
3. The material of the machine parts in the process equipment is austenitic stainless steel
4. The power of the geared electrical motor is 15 kW and its speed is 80 min^{-1}

The critical process parameters guiding the design of the old construction were that the total flow of material was 400 tn/24 h, and the required efficiency was 90 %. One interesting detail of the old construction was the shaft sleeve, which had suffered from excessive wear. In the new construction, this part was diamond coated to solve the wear problem. Another noted critical component was the gear used in the old construction: it was expensive to change the whole gear every now and then. The third issue of the old construction was oil leaks of the shaft seals.

Figure 3. Wet wood chip unloader (the old structure)
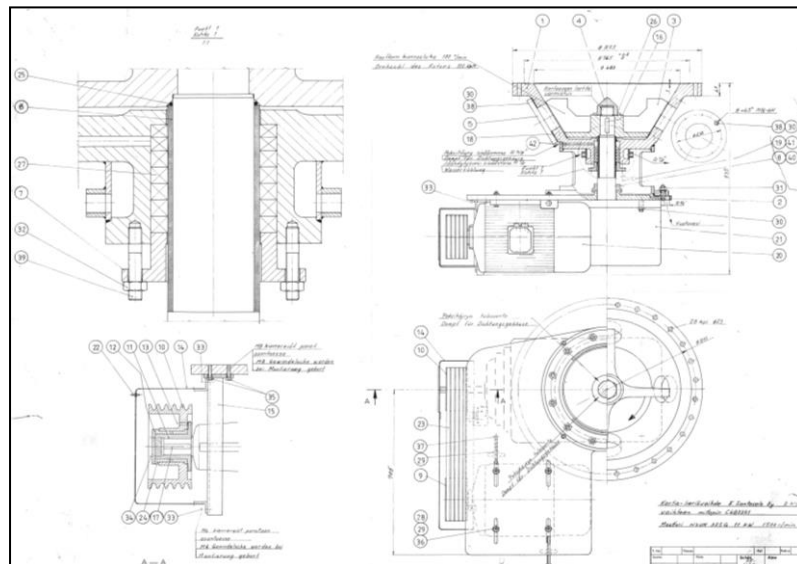
Figure 4. Detailed structure of the old wet wood chip unloader

5.2 The new construction of the wet wood chip unloader

The new construction of the wet wood chip unloader was developed based on the integration of three main DFMA components: process technology, engineering design, and maintenance and service (see Figure 5). We found that in addition to the requirements of the process

technology, maintenance and service aspects should be included in the design phase of the new unloader construction. It was only natural to include in the design, to the extent possible, the assembly aspects based on the observations collected from the mechanics, as they are the ones who had been taking care of the service of the old unloader construction. They had the best information on how to change the required spare parts of the construction. This represented one way to find additional information for DFMA approaches. However, this information came too late, because actually it was merely feedback information, not initial design knowledge.

In the paragraphs which follow, the development of the new construction is discussed from the three following perspectives:

1. The process perspective
2. The maintenance and service staff perspective
3. The designer perspective
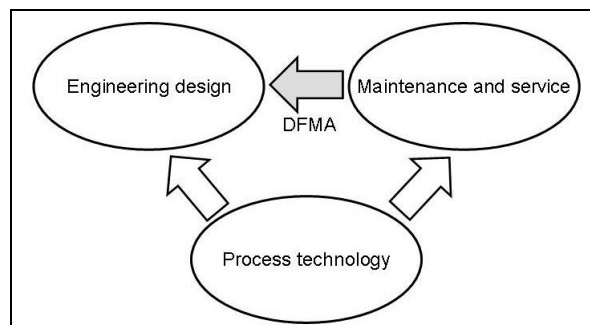
Figure 5. The development of the new construction is discussed from three viewpoints

5.2.1 Development from the process perspective

In order for one to understand the significance of the proper function of the unloader, it is first necessary to recognize its position in the whole pulping process of cellulose (and eventually cardboard). First of all, there are several distinct process phases during which different process parameters play a key role. Pulping may be generally defined as the process of cooking wood chips at a certain temperature and pressure with specialized chemicals. For the cooking process, the temperature of the liquid is typically set at 80° C; its concentration is 65 g SO_2/1 and 76 g NA_2O/1. However, the temperature is elevated to 130° C during the pre-heating phase. The maximum temperature is 180° C during the steam phase cooking. After these stages, the chips drop into the wet wood chip unloader. It is obvious that the components of the unloader suffer not only from the mechanical loading due to rotational motion, but also from the tribochemical effects due to the chemicals and elevated temperature and pressure. This environment thus causes the extensive wear phenomena. The most important questions dealing with the design aspects from the process point of view are these:

1. What is the required process capacity?
2. What materials and chemicals are used in the process?
3. What are the common process parameters, such as those for temperature, humidity, pressure and pH-values and concentrations?

The old construction was designed based only on those aspects of consideration. When the new construction was designed, these points were combined with the following points brought up by the maintenance and service staff.

5.2.2 Development from the maintenance and service staff point of view

The most important questions dealing with the design aspects from the maintenance and service staff point of view are as follows:

1. How could the old construction be changed to enable the assembly of spare parts without disassembling the construction?
2. Is it possible to change the gear transmission system into a belt drive system?
3. How could the oil leaks be avoided?
4. How could the wear resistance of the shaft sleeve be ensured?
5. Could these changes (points 1 to 4) possibly shorten the service and assembly times?
6. Could the same improvements be implemented in other chip unloader constructions of the company?
7. What would be the total costs of the improvements?
8. What would be the costs of the new gear (as compared to point 7)?

5.2.3 Development from the designer point of view

The most important questions dealing with the design aspects from the designer point of view are as follows:

1. Are computer aided models or document files available in any common file format for further development of the construction?
2. What are the allowable costs of the planned improvements to the construction?
3. Are there similar types of problems in other company equipment?
4. Is the reason for the oil leaks found in the seal material?
5. Are there any limitations dealing with the surface coating of the shaft sleeve?
6. Do any parts other than the shaft sleeve suffer from extensive wear?

As illustrated in Figures 6 and 7, the new construction has only two bearings, which are relatively easy to change; moreover, they are crease lubricated, which means there is longer resistance against possible water contact during use of the unloader. The lifetime of the shaft sleeves is extended due to a diamond surface vacuum coating treatment of the wearing surfaces. The wear rate will decrease due to smaller friction between the rotating components.
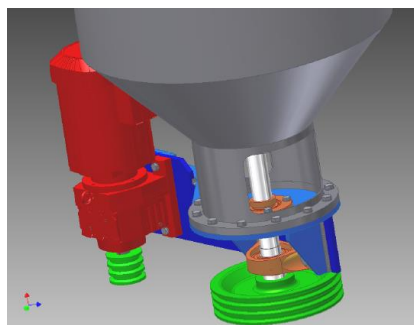
Figure 6. The 3D-CAD model of the new construction

The total number of parts is obviously essentially decreased, which translates into shorter assembly and service times. The power transmission system consists of a directly connected electrical motor and the gear, after which there is a triple belt drive. The problems dealing with the availability of maintenance information were solved by utilizing the SAP system (Client-Server-System; SAP = *Systeme, Anwendungen und Produkte*).
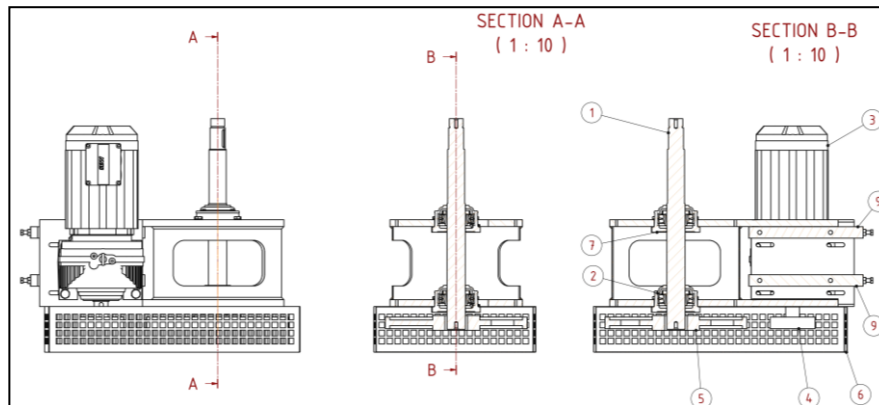

Figure 7. Detailed description of the new construction

The following concrete numerical results from our case show how the efficiency of the maintenance actions was improved based on the introduction of the new wet wood chip unloader.

1. The price of the gear in the old construction was about 3.5 times higher than that of the gear in the new construction.
2. The old construction required an average of 13 service actions/year from 2009 to2012. The new construction has only required 2 services thus far.
3. The maintenance costs of the new construction have decreased to a level which is only 3% of the costs of the old construction.
4. The time needed for service and maintenance actions has decreased by 50% on average due to the new unloader construction.
5. The installation costs of the new construction were only 7% of the total service costs from 2009 to2012.

6 Conclusion

The fresh scientific perspective of this paper emphasizes that too little attention has been paid to how maintenance information could be used at the beginning of the design process of a device. Our purpose has been to illustrate the way in which DFMA aspects could be integrated with maintenance information – which has traditionally only been applied in guiding product improvements. If we succeed in integrating DFMA aspects with available maintenance information, it will be possible to increase mill productivity and realize the benefits of maintenance earlier. In the case described in this paper, aspects of pulping process design were integrated with actual maintenance information of a wet wood chip unloader.

The practical result of this research was the improvement of the wet wood chip unloader, the product in question for this study. The structure of the old unloader had impeded maintenance, because this structure was slow and difficult to handle from the servicing and

assembly perspectives. The wet wood chips had quickly worn down components, especially the shaft sleeves. Also, the delivery time and price of spare parts had increased because the parts were often not repaired fast enough. The improved mechanical solution was based on the utilization of diamond coated shaft sleeves, an easy-to-assemble bearing construction, a new type of power transmission system and a reduction of the total amount of components.

Based on this research work made at Lappeenranta University of Technology and the results of that work presented in this paper together with the observations compiled from the scientific literature, we were able to publish organizational aspects for improving the efficiency of maintenance actions by utilizing a developed RACI model. Together with a functional SAP system, this could offer a good starting point for integrating the maintenance and DFMA aspects of a given product already during the early design stages of the product.

References

Al-Najjar, B. (2000) 'Impact of real-time measurements of operating conditions on effectiveness and accuracy of vibration-based maintenance policy - A case study in paper mill', *Journal of Quality in Maintenance Engineering*, Vol. 6, No. 4, pp.275-287.

Alsyouf, I. (2006) 'Measuring maintenance performance using a balanced scorecard approach', *Journal of Quality in Maintenance Engineering*, Vol. 12, No. 2, pp. 133-149.

Alsyouf, I. (2007) 'The role of maintenance in improving companies' productivity and profitability', *International Journal of Production Economics,* Vol. 105, No 1, pp. 70-78.

Arts, R., Knapp, G. and Mann Jr. L. (1998) 'Some aspects of measuring maintenance performance in the process industry', *Journal of Quality in Maintenance Engineering*, Vol. 4, No. 1, pp. 6-11.

Ashayer, J., Teelen, A. and Selen, W. (1996) 'A production and maintenance planning model for the process industry', *International Journal of Production Research,* Vol. 34, No. 12, pp. 3311-3326.

Asiedu, Y. and Gu, P. (1988) 'Product life cycle cost analysis: state of the art review', *International Journal of Production Research*, Vol. 36, No. 4, pp. 888-908.

Aurich, J. C., Fuchs, C. and Wagenknecht, C. (2006) 'Life cycle oriented design of technical Product-Service Systems', *Journal of Cleaner Production,* Vol. 14, No. 17, pp. 1480-1494.

Brookes, N. and Backhouse, C. J. (1997) 'Variety and concurrent engineering', *Manufacturing Engineer*, Vol. 76, No. 2, pp. 72-75.

Bruzzo, J. and Eskelinen, H. (2012) 'Improving the DFMA aspects in designers and service providers by taking advantage of the maintenance data from end-users' in Eskelinen, H. (Ed.) *Advanced approaches to analytical and systematic DFMA analysis*, Lappeenranta: Acta Universitatis Lappeenrantaensis, 93-104.

Eskelinen H. (2012). *Advanced Approaches to Analytical and Systematic DFMA Analysis*, Lappeenranta: Acta Universitatis Lappeenrantaensis, 15-16.

Gomes de Sá, A. and Zachmann, G. (1999) 'Virtual reality as a tool for verification of assembly and maintenance processes', *Computers & Graphics,* Vol.23, No. 3, pp. 389-403.

Hoffman, D. R. (1998) 'Overview of concurrent engineering', *The Annual Reliability and Maintainability IEEE Symposium*, January, 19-22, 1998, Piscataway.

Huiskonen, J. (2001) 'Maintenance spare parts logistics: Special characteristics and strategic choices', *International Journal of Production Economics*, Vol. 71, No. 1–3, pp. 125-133.

Kennéa, J.-P., Gharbib, A. and Beita, M. (2007) 'Age-dependent production planning and maintenance strategies in unreliable manufacturing systems with lost sale', *European Journal of Operational Research*, Vol. 178, No. 2, pp. 408-420.

Kiritsis, D., Bufardi, A. and Xirouchakis, P. (2003) 'Research issues on product lifecycle management and information tracking using smart embedded systems', *Advanced Engineering Informatics*, Vol. 17, No. 3–4, pp. 189-202.

Komonen, K. (2002) 'A cost model of industrial maintenance for profitability analysis and benchmarking', *International Journal of Production Economics*, Vol.79, No. 1, pp. 15-31.

Markeset, T. and Kumar, U. 'Design and development of product support and maintenance concepts for industrial systems', *Journal of Quality in Maintenance Engineering*, Vol. 9, No. 4, pp. 376-392.

McKone, K. and Weiss, E. (1998) 'TPM: Planned and autonomous maintenance: bridging the gap between practice and research', *Production and Operations Management*, Vol.7, No. 4, pp. 335-351.

Miller, L. C. G. (1993). *Concurrent engineering design, integrating the best practices for process improvement*, Michigan: Society of Manufacturing Engineers, 101-104.

Pintelon, L. and Gelders, L. (1992) 'Maintenance management decision making', *European Journal of Operational Research*, Vol. 58, No. 3, pp. 301-317.

Portioli, A. and Singh, N. (1997) 'Framework for integration of production management issues and concurrent engineering' *International Journal of Systems Science,* Vol. 28, No. 9, pp. 877-881.

Stahl, J., Luczak, H., Langen, R., Weck, M., Klonaris, P. and Pfeifer, T. (1997) 'Concurrent engineering of work and production systems', *European Journal of Operational Research*, Vol. 100, No. 2, pp. 375-398.

Willaert, S. S. A., De Graaf, R. and Minderhoud, S. (1998) 'Collaborative engineering: A case study of concurrent engineering in wider context', *Journal of Engineering and Technology Management*, Vol. 15, No. 1, pp. 87-109.

"Cloud" services for improving production efficiency of industrial enterprises

Anatoly Voronin, Vladimir Kuznetsov, Anton Shabaev* and Ivan Arhipov

Department of Applied Mathematics and Cybernetics
Petrozavodsk State University
Lenin av. 33, 270
185940 Petrozavodsk
Russia
*Corresponding author: Anton Shabaev
e-mail: voronin@petrsu.ru
e-mail: kuznetc@petrsu.ru
e-mail: ashabaev@petrsu.ru
e-mail: iarhipov@petrsu.ru

Abstract

The paper describes research and development of software platform for optimal operation planning of industrial enterprises using "cloud" computing technology. This work is a part of long-term activity carried out by Petrozavodsk State University (PetrSU) in the field of scientific research, software development and customer projects for enterprises of pulp-and-paper and forestry industry. The platform includes advanced mathematical models and optimization algorithms developed by IT-park of PetrSU and is used to develop services for solving planning tasks at different types of enterprises: corrugated packaging production, hardwood sawmills, plywood mills, paper production, as well as transportation companies (or units). Screenshots and mathematical model are provided only for "Sawmill" service, but the procedure is quite similar also for other services.

Key words: "cloud" platform, optimal planning, "cloud" service

1 Introduction

Similarity of production processes on different enterprises allows developing a common platform for production planning for these enterprises. However, using a large amount of locally installed software on geographically distributed enterprises results in additional time and costs needed for the software maintenance. One of the approaches to reduce the maintenance costs is to use "cloud" computing technology. For the implementation of this technology for the production planning tasks it is useful to develop a software platform, which includes a wide range of functional possibilities for software implementation, maintenance, and solving process optimization tasks.

The paper presents description of innovative production planning platform based on "cloud" computing technology. The platform consists of software modules library with optimization algorithms, as well as auxiliary services. Using the platform, several "cloud" services for

production planning and management at different types of enterprises have been developed, mainly in the pulp-and-paper and forestry sectors. Brief descriptions of some of the developed services are provided, including main features of process technology, main functions, economic benefits, and reference lists.

The use of the services allows the mills to noticeably improve efficiency and productivity: reduce the material losses (by 1-3%), to increase the equipment uptime by 3-4%, and shorten the production planning time (by 1.5 – 2 times). Altogether this leads to saving of several hundred thousands euro per year at each mill. The use of the services also allows customer specialists to model and compare side-by-side various scenarios of production and procurement, and select best and justified scenario, thus improving control over production.

2 Cooperation of IT-park of PetrSU with industrial enterprises and organizations of Finland and Russia

Development of software systems for improving production efficiency of industrial enterprises is a part of long-term and diverse activity carried out at PetrSU. A distinctive feature of IT-park of PetrSU is automation of non-typical and complex business-processes by exploiting mathematical methods to solve complex problems such as optimizing planning and resource allocation, trim, and composition. IT-park delivers a broad range of IT services to support manufacturing companies, including:

- Creating mathematical models for solution of complex enterprise management problems;
- Designing algorithms and software packages for optimization problems solution;
- Developing, commissioning and maintaining management information and process control systems;
- Providing management consulting.

IT-park of PetrSU was founded in 2005 and brought together 23 units of the university within 3 departments – ICT, system engineering, and education technologies in ICT. The total number of staff is about 400 people.

The platform development is based on long-term cooperation experience with a wide range of Russian manufacturing enterprises, mainly of the pulp-and-paper and forestry industries, which has been actively developing since 1982. Among the customers are Arkhangelsk, Bratsk, Kiev, Kotlas, Kondopoga, Segezha and Svetogorsk pulp-and-paper mills (which are among 10 largest pulp-and-paper mills in CIS), as well as many other smaller industrial enterprises. Since 1982 more than 150 custom software systems (including since 2005 -- more than 70 systems) have been delivered to industrial enterprises and organizations of Finland, Russia and CIS. Since 2011 this activity has been further intensified by establishment of Opti-Soft Ltd (http://opti-soft.ru) – a small innovative company, which is 100% owned by PetrSU.

Also important expertise was gained in cooperation with industrial customers and partners in Finland, including Metso Corporation (since 1993), Outotec Oy (since 2008), Nokia Research Center (since 2007) and other smaller companies. The joint activities include: mathematical models and software for industrial automation and process control, scientific research, organization of conferences and seminars, and training of specialists.

3 The "cloud" platform for optimal planning

Cloud services are widely used and written in scientific articles. Cloud Computing refers to both the applications delivered as services over the Internet and the hardware and systems software in the datacenters that provide those services (Armbrust and Fox, 2009). Numerous IT vendors are promising to offer computation, storage and application hosting services. Currently, expert developers are required to implement cloud services (Buyya et. al., 2010). Cloud-based applications and new capabilities are emerging daily and bringing with them lower cost of entry, pay-for-use models, greater scalability, improved performance, and improved business continuity (Jamsa, 2011). Cloud computing can help small and medium business to lower their IT costs as the supported functionalities of software are no longer fixed or locked to the underlying infrastructure. This offers tremendous automation opportunities in a variety of computing domains (Wang et. al., 2012).

Practical implementation of "cloud" computing in solving problems of optimal production planning requires development of a platform with a wide range of functionality to simplify and speed up software implementation and maintenance, as well as solution of optimization problems arising at industrial enterprises.

The main components of the platform include (see Fig.1):

- Applications server, whose main part is business logic of software services, describing relevant subject areas,
- Optimization server, including the library of modules for solution of optimization problems,
- File server, managing storing and joint access to files of various types,
- Database server, managing storing, filling and changing data, as well as for providing information in response to the application server requests,
- Audit server, managing complex monitoring of activity of various modules.
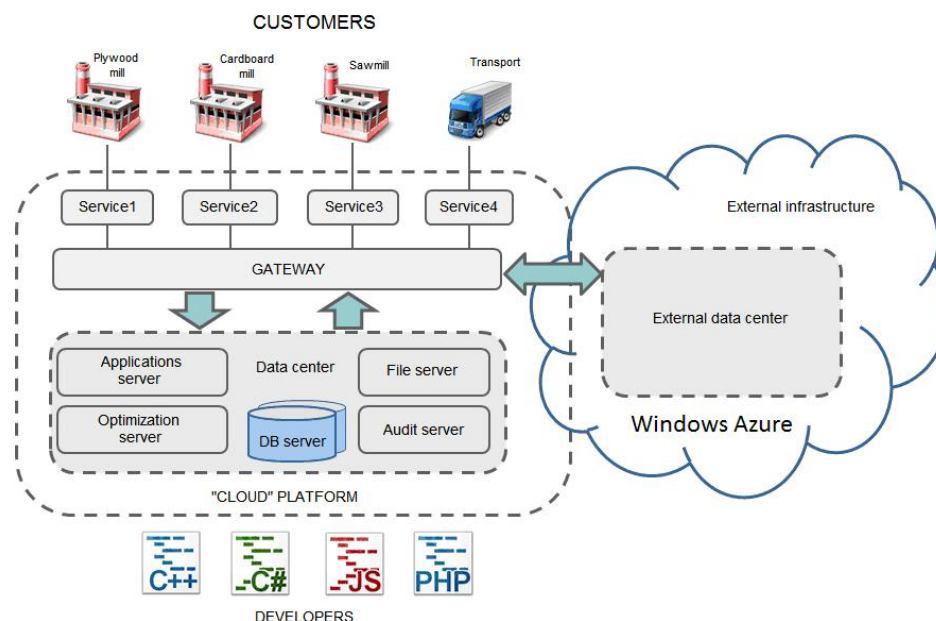
Figure 1. The main components of the platform

All platform components are integrated into MS Visual Studio.NET and can be freely and uniformly used together with standard methods and components of MS Visual Studio.

On the basis of the platform, "cloud" services for optimal planning and management of complex production processes of industrial enterprises are developed. This is possible and efficient, because such services typically use quite similar set of menus, forms, tables, dialog boxes and other components, as well as optimization algorithms.

The main component of user interface of each "cloud" service is a web browser, which generates visual representation of the product and exchanges data via "gateway" layer with servers of the platform (typically using encrypted channel to protect the customer and the Platform from unauthorized access).

The optimization algorithms are based on earlier developed in PetrSU mathematical models and methods for solving a wide range of optimization problems. In particular, they cover operations of cutting, collecting and transporting materials, quite typical in planning and management of pulp-and-paper and forestry industry enterprises (Kuznetsov et. al., 2008). Several optimality criteria are used when solving optimization problems – profit maximization, minimization of the production costs and resource consumption, and other, as well as mixed criteria.

The specialized library ("universal" solver") is one of the main distinctive features of the platform (Kuznetsov et. al., 2008). It has been developed based on 30 years of experience in customer projects for companies and enterprises of Russia, and Finland. Algorithms for effective solution of complicated cutting problems, including linear and nonlinear optimization problems, high-dimension problems, problems with combined criteria, etc. are implemented based on the versatile solver. The library also includes a special module ("matrix constructor") for increasing efficiency of constructing, storing and using constraints matrix.

The hardware is currently provided by own data-center of IT-park, but can also be moved or combined with external infrastructure, e.g. Windows Azure or other.

4 "Cloud" services for optimal planning at industrial enterprises

On the basis of the platform, a spectrum of specialized "cloud" services have been developed for optimal management of several types of enterprises, including the following:

– "Corrugated cardboard" – for corrugated cardboard plants operation
– "Sawmill" – for sawmills operation
– "Loading" – for optimal loading of transportation facilities (trucks, trains and ships)
– "Trim optimization" – for trim optimization during paper machines operation
– "Plywood" – for plywood mills operation

Development of each service is based on quite deep study of the process technology, otherwise planning results would not be efficient (and sometimes even not useful). Integration of the services into existing ICT ecosystem at Customer enterprises is possible.

Description of each service follows. Due to lack of space, screenshots and mathematical model are provided only for "Sawmill" service, but demos are available at http://opti-soft.ru/

4.1 "Corrugated cardboard" service

The line of corrugated cardboard is cut into rectangular pieces at the speed of 160m/min. The pieces are used for making boxes. The task of the mill management is to ensure the production of required number of boxes made of several rectangles of different size. As the number of boxes types exceeds 100 per week, and the number of boxes of each type is less than 1000, the material losses increase to 5-6%, planning time – to several hours, etc. The service uses mathematical methods and optimization algorithms to decrease the material losses and planning time, and increase the equipment uptime.

The target of the service – production of balanced amounts of rectangles of cardboard for making boxes with minimal material losses, considering the production capacity and re-tuning time of equipment, order scheduling and priorities.

The main functions of the service include:

- Generation of all feasible cutting orders according to specified types of boxes
- Finding the cutting order, which ensures production of required number of boxes, including the warehouse stock
- Production optimization according to material losses
- Monthly planning of plant operation (target figures may be loaded from other systems)
- Price calculation for each type of box
- Tracking the effect of each additional type of box on total plant material losses
- Documentation, reporting and archiving
- Integration with other systems, including accounting systems, ERP systems, process control systems (e.g., BHS, Dücker, Signode) and other.

The "local" software system and the "cloud" service have been *successfully installed* at 15 enterprises, including the following main ones:

- OJS "Arkhangelsk pulp-and-paper mill" (Arkhangelsk, Russia)
- OJS "Kiev pulp-and-paper mill" (Obuhov, Ukraine)
- "Naberejno-Chelninsky cardboard-and-paper mill" Ltd. (Naberejnye-Chelny, Russia)
- CJS "Gotek" (Zheleznogorsk, Russia),
- "Nizhkarton" Ltd. (Nijny Novgorod, Russia),

The use of the service enabled the mills to reduce the material losses from 5-6% to 2-4%, which amounts to saving of several hundred thousand euro per year, and also has noticeably reduced the production planning time – by 1.5 – 2 times.

Consideration of re-tuning of the finishing equipment while planning the cutting equipment operation remarkably reduces the number and duration of finishing equipment downtime periods. As a result, the total production line uptime is increased by 3-4%.

In 2008 the "local" system received Certificate №№1640 of the Foundation of algorithms and software of the Russian Federal Agency for Education. In 2012 the web-based service was registered by Russian Federal Service for Intellectual Property, Patents and Trademarks (Certificate №2011618457). In 2009 the System has won **Golden medal** in nomination "The best innovative and R&D project of the year" of St.-Petersburg Technical Fair.

4.2 "Sawmill" service

The aim of the sawing process consists in processing round wood into sawn lumber, as well as technological wood chips. Typically a sawmill receives logs of various grades and diameters and sawn lumber is also divided according to sorts and sizes. The problem of sawing patterns calculation consists in specification of sizes and number of lumber to be cut from each log of given quality, length and diameter. As a rule, monthly plans cover more than 10 grade groups of logs and the number of produced sawn lumber grades is 50 or even 100.

The plan contains quantity and size-qualitative structure of logs to be sawn and the lumber produced by applying each sawing pattern, taking into account all features, limitations and parameters of process equipment, as well as of raw material and production orders. The use of the service also improves the efficiency of calculating and correcting the operational plans.

The target of the service – with the use of advanced mathematical models and optimization algorithms of own development to solve a series of sawmill operation planning tasks for any number of orders and any configuration of process equipment.

The main functions of the service include:

– Calculation and selection of cutting patterns
– Calculation of optimal plan, ensuring production of given specification of lumber from available (or expected) wood – either by maximal profit from the lumber, or by minimal use of wood
– Calculation of profitability of new orders in combination with existing production plan, and with possible new orders
– Calculation of optimal limits for log types (diameter groups) for sorting lines
– Calculation of optimal calendar plan in order to maximize the use drying and finishing equipment

The developed mathematical model takes into account all known essential features, limitations and parameters of process equipment, of raw material and production orders.

Parameters of equipment:

– The number and saw cut width for saws of 1st and 2nd row for each saw bench
– Relation between maximal diameter of log, which can be cut on the saw bench, from maximal height of the cut and maximal width of the cutting pattern
– Productivity of saw bench per shift depending of diameter and length of logs
– Minimal width of the two-edged cant (separate for each log diameter), because smaller width leads to increased waste
– Minimal production volume per each cutting pattern, because each retuning of saw bench leads to waste of time
– Minimal width of central part of the cant, minimal difference between width of cant and side part
– Maximal width of side part, maximal number and width of side boards, maximal number of different types of sawn timber in the cutting pattern
– Many other, depending of the sawmill equipment parameters.

Parameters of orders:

– Minimal and maximal production volumes for each type of sawn lumber

- Minimal and maximal length of lumber, and cutting steps (which reduces the output)
- Required moisture content after drying
- Quality of lumber (A, B, C and other)
- Priority of an order (to ensure delivery performance)
- Requirements regarding positioning of lumber relative to log axis:
  - in cant part only, i.e. only from two-edged cant
  - in side part only
  - in central part
  - 2 Ex-Log, i.e. 2 boards in central part (without central board)
  - 2 Ex-Log not side board, i.e. 2 boards in central part with other boards in the two-edged cant
  - 3 Ex-Log, 4 Ex-Log, 5 Ex-Log, 6 Ex-Log – similarly
  - Not in the center
  - 2,4,6 Ex-Log, i.e. in central part, without central board (but for large diameters (e.g. over 30cm) this constraint can be skipped)
  - Maximal share of lumber from side part (for Ex-Log; e.g. not more than 20%).

The system has friendly and flexible user interface and can be easily modified to handle new customer-specific requirements.

The use of the system allows to increase overall mill productivity, output of high-quality grades of lumber and better matching the production specification. Overall increase of profitability – by 1-2%. More details are provided in next section.

The efficiency of the system has been confirmed during 2011-2013 on real production data of 4 sawmills in North-western Russia: OJS «Medvezhegorsky sawmill», OJS «Segezhsky sawmill», OJS «Sokolsky DOK», CJS «Solomensky sawmill».

In 2012 the System was registered by Russian Federal Service for Intellectual Property, Patents and Trademarks (Certificate №2010617003). Also in 2012 the System has won **Silver medal** in nomination "The best innovative and R&D project of the year" of St.-Petersburg Technical Fair.

4.3 "Loading" service

The paper rolls are transported in train carriages, trucks, and ships. The vehicle must be loaded according to strict rules, the violation of which results in quality degradation and customer complaints. As the number of different types of rolls grows, and vehicle internal geometry becomes complicated, the order or loading of rolls into a vehicle may become relevant. As a result, the vehicle may carry less load than it could. The order of loading of rolls into a vehicle depends on vehicle geometry (the center of the roof of a railroad carriage is always higher than the walls), size and location of the gates (front or side), load balancing, etc. The number of possible combinations of rolls is inconceivable.

The service uses mathematical methods and different combinatorial, linear, dynamic and integer optimization algorithms to load more cargo into a set of vehicles, decrease the number of vehicles used, as well as to provide graphic presentation of cargo inside the vehicle.

The *use of the service* in many cases enables to increase by 5-10% the total weight of paper rolls loaded in a transportation vehicle. This enables to use less number of railroad carriages, trucks and containers. Also the planning time is noticeably reduced – by 1.5 – 2 times.

The software system had been *successfully installed* at OJS "Bratsk pulp-and-board mill", OJS "Kondopoga pulp-and-paper mill", OJS "Kotlas pulp-and-paper mill" (all – in Russia).

In 2008 the "local" system received Certificate №№1644 of the Foundation of algorithms and software of the Russian Federal Agency for Education. In 2013 the web-based service will be registered by Russian Federal Service for Intellectual Property, Patents and Trademarks.

4.4 "Trim optimization" service

Roll sets are produced by the winder from the parent reel. The "trim" (the width of the parent reel exceeding the width of the roll set) is a waste. With parent reel widths up to 10m, roll widths down to 50cm, and production orders including many different roll widths, there are thousands of ways to cut the parent reel to obtain the required rolls. Usually, there are 3-4 PM with different speed, parent reel width and density, and possibly paper quality. The production targets are set for entire mill, and paper grade change results in bad paper and lowers the total mill production. The service uses mathematical methods and optimization algorithms to plan the operation of several PMs to meet the production targets and minimize waste. Also the planning is simplified for the operators.

The target of the service – calculating the optimal distribution of orders between several paper machines for the purposes of increasing the productivity in given conditions, closest matching of production targets, decreasing of trim losses, decreasing of amount of down-graded paper.

The automation system has been installed at OJS 'Kondopoga' – one of 10 largest paper mills in Russia. The use of the system results in saving of 1.2% of paper per year. Considering the tons-per-year of paper production from a modern paper machine, even savings of 0.5% make this type of process control economically profitable. The other significant advantage is reduced time for production planning.

In 2008 the "local" system received Certificate №№1641 of the Foundation of algorithms and software of the Russian Federal Agency for Education.

4.5 "Plywood" service

Plywood is made from thin sheets of wood veneer (plies), which vary in thickness 2.5-4mm. Usually, 3, 5 or 7 plies of dimension 1.2×2.4m are glued together at right angles to each other to form the plywood panel, which can then be refinished. 4-5 quality grades of panels exist.

With hundreds of production orders received, thousands of plies already available (as well as timber logs for making new plies, if needed), there are thousands of feasible ways to obtain the sheets of required quality. Due to various limitations on the equipment operation, the planning must be made very carefully to meet the production and economical targets. The service uses mathematical methods and optimization algorithms to increase production by cost or volume (on average, by +1.5% per month) by using existing plies more efficiently, as well as to simplify the planning procedures for the operators.

In 2008 the "local" system received Certificate №№1642 of the Foundation of algorithms and software of the Russian Federal Agency for Education. In 2013 the web-based service will be registered by Russian Federal Service for Intellectual Property, Patents and Trademarks.

5 The mathematical model and the service for sawmill optimization

Due to lack of space, screenshots and mathematical model are provided only for "Sawmill" service, but the procedure is quite similar also for other services, presented in this paper.

5.1 The main model

Initial data:

L – set of timbers (enumerated)
W – set of sorting groups and kinds of wood (enumerated)
M – set of sawing lines (enumerated)
C – generated set of sawing patterns (Tyukina, Y. and Makarova, N. (1988))
$d_{i,j}$ – share of timber $i \in L$ in sawing pattern $j \in C$. $d_{i,j} \in [0,1]$
$g_{w,j}$ – 1, if sawing pattern $j \in C$ involves wood kind $w \in W$, 0 otherwise
$h_{m,j}$ – 1, if sawing pattern $j \in C$ involves sawing line $m \in M$, 0 otherwise
v^d_m – minimal total wood volume, sawn at sawing line $m \in M$
v^u_m – maximal total wood volume, sawn at sawing line $m \in M$
r – minimal sawing pattern volume (only for selected patterns)
v^s_w – volume of wood kind $w \in W$ at the warehouse
v^p_j – minimal production volume of timber $i \in L$
v^q_j – maximal production volume of timber $i \in L$
z_i – unit penalty for deviation from constraint on minimal production of timber $i \in L$
y_m – unit penalty for deviation from constraint on minimal sawing volume at line $m \in M$

Unknowns:

x_j – total wood volume, sawn using sawing pattern $j \in C$
f^l_i – deviation from constraint on minimal production volume of timber $i \in L$
f^u_i – deviation from constraint on maximal production volume of timber $i \in L$
f^m_m – deviation from constraint on minimal sawing volume of sawing line $m \in M$
f^r_m – deviation from constraint of maximal sawing volume of sawing line $m \in M$

Then the main optimization problem looks as follows:

$$\sum_{j \in C} \sum_{i \in L} d_{i,j} x_j \to \max$$

$$v^p_i \leq \sum_{j \in C} d_{i,j} x_j + z_i (f^u_i - f^l_i) \leq v^q_i, \quad i \in L$$

$$\sum_{j \in C} g_{w,j} x_j \leq v^s_w, \quad w \in W \qquad (*)$$

$$v^d_m \leq \sum_{j \in C} h_{m,j} x_j + y_m (f^r_m - f^m_m) \leq v^u_m, \quad m \in M$$

$$x_j \in \{0\} \cup [r, +\infty)$$

The main unknown variables are volumes of logs to be cut according to each sawing pattern, which uniquely defines the order and places of cuts, as well as thickness, width and length of sawn lumber produced. The main solution algorithm of the problem (*) is presented on Fig.2, where v – vector of dual estimates for each constraint of the problem (*), A_j – j-th column of main matrix (Fig.3), c_j – j-th coefficient of goal function of the problem (*) $c_j = \sum_{i \in L} d_{i,j}$, $j \in C$.
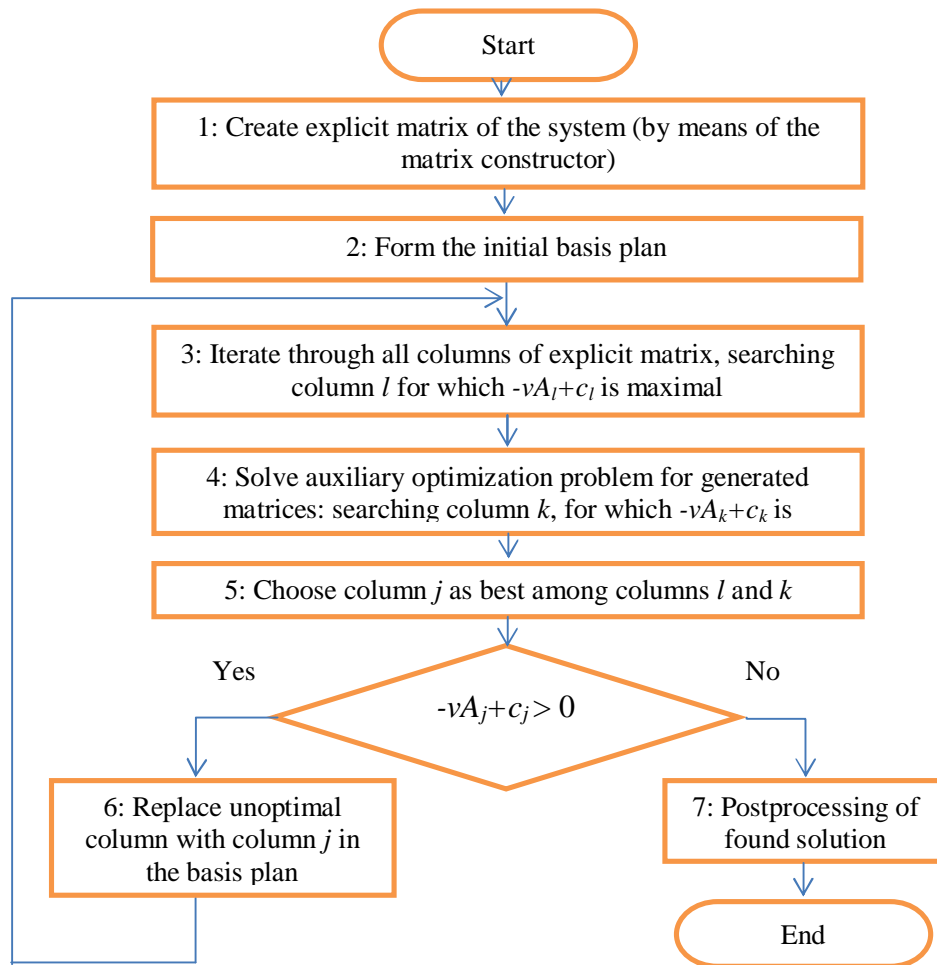
Figure 2. The main solution algorithm for sawmill optimization problem

The structure of the main matrix of problem (*) is presented on Figure 3 below. IT-park research and project experience shows that constraints matrices in practical optimization problems typically have large dimension and distinctive block structure. Therefore, a special data structure was developed («the matrix designer»), which increases the efficiency of storing and using explicit constraints matrix by splitting it into sub-matrices.

It should be noted that set of all sawing patterns C only rarely can be provided explicitly, because there can be millions of feasible combinations of timbers, sorting groups, kinds of wood and sawing lines, each of which would've been a column in corresponding matrix C. Instead, the new column to be added to the basis plan at step 6 of algorithm on Fig. 2 is computed using solution of auxiliary optimization problem (step 4 of algorithm on Fig. 2).

On Fig.3: MDS – square diagonal matrix with equal elements on main diagonal (typically, 1 or -1), MS – any matrix with all elements equal, M – any other matrix.

		L	L	M	0	1	1	3		N		
cost		M (1xL)	M (1xL)	MS (1x1)		MS (1x1)				M (1xN)		
up bound												
L	M (Lx1)	≤	MDS (LxL)	MDS (LxL)							≤	M (Lx1)
W										C	≤	M (Wx1)
M				MS (Mx1)							≤	MS (1x1)
1	MS (1x1)	≤			MDS (1x1)							
1						MDS (1x1)					=	MS (1x1)
low bound												

Figure 3. The main matrix of the problem (*)

The main method for solution of optimization problems is the columns generation method (Dantzig, 1963; Kantorovich and Gorstko, 1968). Its major difference from other methods is that optimality of a solution is checked not by using explicit matrix, but by solving an auxiliary optimization problem. The standard columns generation method was improved to efficiently handle constraints that are typical for practical optimization problems – upper and lower bounds on production volumes, several identical production units, proportional dependence between variables, etc.

5.2 The auxiliary optimization problem

Initial data

N – set of timbers;

W – set of sorting groups and kinds of wood;

t_j, w_j – thickness and width of timber $j \in N$ accordingly, in mm;

b_j – sign that timber is basic (1 – basic, 0 – otherwise), $j \in N$;

u^b – minimal share of volume of basic timbers, $u^b \in [0,1]$

u^s_j – maximal share of timber $j \in N$ from side part, $u^s_j \in [0,1]$

v^l_j – dual estimate of timber $j \in N$;

v^w – dual estimate of current wood $w \in W$;

v^b – dual estimate of constraint on the minimum share of basic timbers;

v^s_j – dual estimates of constraints on the maximum share for timber from side part, $j \in N$;

V^w – volume of a log of wood $w \in W$;

c^w – cost of 1 m^3 of wood $w \in W$;

c^l_j – price of 1 m^3 of timber $j \in N$;

s_1, s_2 – thicknesses of saws at the first and second pass accordingly.

Unknowns:

P^b – set of positions for placement of timber in cant part of a log.

P^s – set of positions for placement of timber in side part at the first pass.

z^b_p – index of timber in p-th position in cant part, $p \in P^b$, $z^b_p \in N$

y^b_p – distance from the center of sawing pattern to timber z^b_p in cant part (in mm). For central timber of the pattern $y^b_p = -\dfrac{t_{z^b_p}}{2}$.

l^b_p – length of timber in position $p \in P^b$ in cant part

z^s_p, y^s_p, and l^s_p – defined for side part similarly;

W^b – width of received two-edged cant: $W^b = \max\limits_{p \in P^b} \left\{ w_{z^b_p} \right\}$

W^c – width of central part of two-edged cant: $W^c = 2 \max\limits_{p \in P^b} \left\{ y^b_p + t_{z^b_p} \,\middle|\, w_{z^b_p} = W^b \right\}$

q_p – 1, if $y^b_p = -\dfrac{t_{z^b_p}}{2}$, 2 otherwise $(p \in P^b)$

g_p – 0, if $w_{z^b_p} = W^b$, 1 otherwise $(p \in P^b)$

Constraints:

- Timber belongs to group $D_{2 \cdot k}$ (requirement "2 k Ex Log", $k \in \{1,2,3\}$):

$$\forall \, j \in D_{2 \times k} \Rightarrow \begin{cases} y^b_1 = \dfrac{s_1}{2}, \quad z^b_1 = z^b_2 = \ldots z^b_k = j, \\ \sum\limits_{p \in P^b,\, z^b_p = j} q_p = 2k. \end{cases}$$

- Timber belongs to group D_{nm} (requirement "Not in the center", e.g., for Japanese timber "Mabashira"):

$$\forall \, p : z^b_p \in D_{nm} \Rightarrow y^p_b \neq \dfrac{s_1}{2} \,u\, y^p_b \neq -\dfrac{t_{z^b_p}}{2}.$$

- The maximum total width of side part in cant part is not more than W^{sm}:

$$\max\limits_{p \in P^b} \left\{ y^b_p + t_{z^b_p} \,\middle|\, w_{z^b_p} < W^b \right\} - \min\limits_{p \in P^b} \left\{ y^b_p \,\middle|\, w_{z^b_p} < W^b \right\} \leq W^{sm}.$$

- Thickness of each timber in side part in cant part is not more than t^{sm}:

$$\forall \, p \in P^b : w_{z^b_p} < W^b \Rightarrow t_{z^b_p} \leq t^{sm}.$$

- The total difference between cant part and side part is no less than D^{cs}:

$$W^b - \max\limits_{p \in P^b} \left\{ w_{z^b_p} \,\middle|\, w_{z^b_p} < W^b \right\} \geq 2D^{cs}.$$

- Other constraints.

These and other constraints are graphically illustrated on Fig. 4. In the service it is implemented as a form for input of corresponding parameters, which makes their meaning intuitively very clear for users with relevant technology background. More similar forms can be created for input of other parameters.
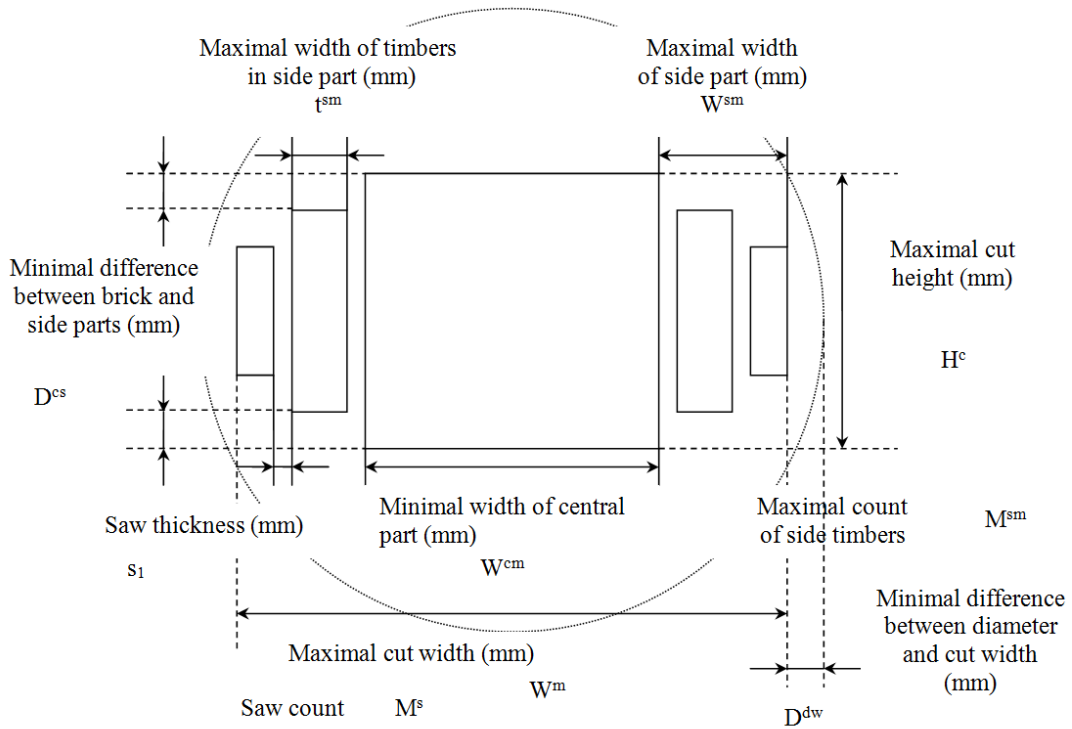
Figure 4. Graphical presentation of main sawing pattern parameters

Goal function:

$$\sum_{p \in P} \frac{l_p q_p t_{z_p} w_{z_p}}{V^w} \left(-v^l_{z_p} + 1 + v^b \left(u^b - b_{z_p} \right) + v^s_j \left(g_p - u^s_{z_p} \right) \right) + v^w + v^m \to \max .$$

This auxiliary optimization problem is solved in quite complicated way using dynamic programming (Bellman, 1957), but full description is beyond the limits of this paper. Formulation of all technology requirements and limitation in mathematical form, suitable for applying optimization methods, requires considerable effort and mathematical qualification.

5.3 User interface

This model and corresponding solution algorithms have been implemented in web service of optimal planning of sawmill operation. The service has been implemented using modern Kendo UI and Stimul Report components on ASP MVC 3 platform. One of the user forms is presented on Fig.5. The user interface can be modified to according to customer requirements.

5.4 Economical benefits from using the service

The economical benefits from using the service are summarized in Table 1. For each sawmill the values in "before" columns were obtained by existing optimization routines, and in "after" columns – by the service. Technical feasibility of all plans calculated by the service have been in every case confirmed by mill staff.

The first use case was to produce fixed specification of lumber from smaller volume of wood (material savings) during planning period equal to one month. The corresponding figures for each sawmill are averages for 4-10 months (depending on the mill). The use of the service allowed to increase the share of lumber (in raw wood) by 1.1-1.6 % (1.2% on average), and to decrease raw wood consumption by 1.2-2.5% (1.9% on average) during a month.
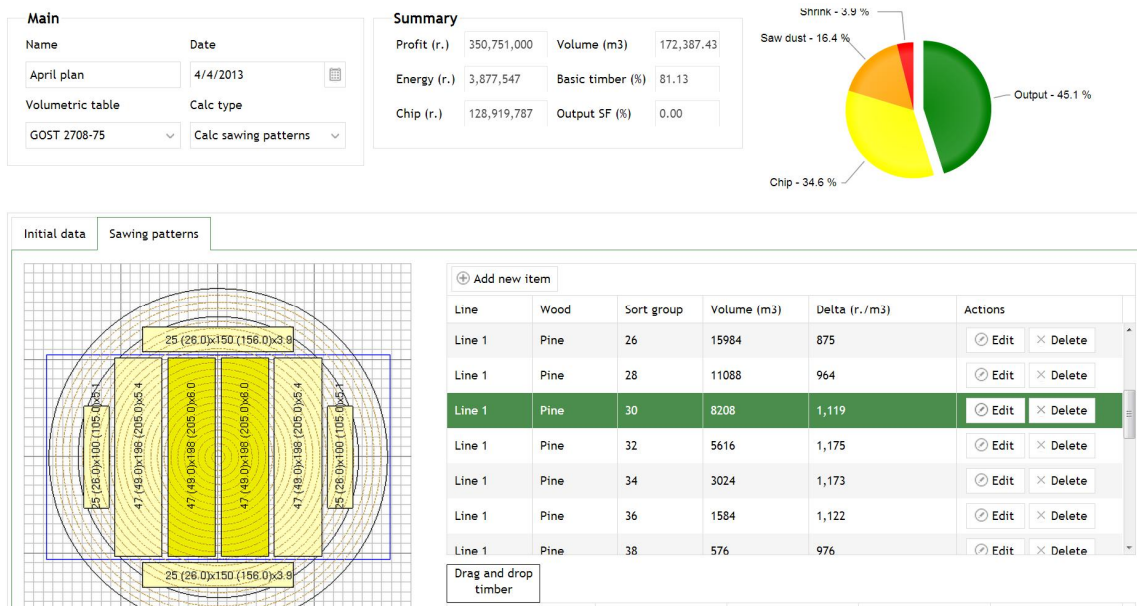
Figure 5. Graphical presentation of main sawing pattern parameters

The second use case was to find the most profitable production specification using all available wood during planning period equal to one month. For some types of lumber the production volumes were fixed (e.g., 1000 m^3), and for some – were given in limits (e.g., 800-1200 m^3). In this case the use of the service allowed to increase the "delta" (difference between the price of lumber and the cost of raw wood) by 1-1.5% (on average 1.1%) during a month. The absolute values of "delta" (in rubles) can not be published.

Another advantage of using the service is reduced time for calculating and correcting the plans – by 1.75-2 times every month. The additional "free" time can be used for more detailed analysis of mill operation. Overall, the payback period of the service is less than 3 months depending on orders portfolio and other specifics of the mill and planning period.

Russian sawmills seldom use optimization software by foreign providers, because it does not allow to take into account essential features of their production processes. However, authors are willing to compare optimization abilities of the service with similar optimization software.

Table 1. Summary of economical benefits from using the service

Company	Share of lumber, before	Share of lumber, after	Wood consumption (m3), before	Wood consumption (m3), after	Increase of "delta"	Calculating plans (hours), before	Calculating plans (hours), after
"Medvezhegorsky sawmill"	49.3%	50.4%	15 765	15 367	N/A	10	5
"Segezhsky sawmill"	45.0%	46.2%	18 194	17 976	N/A	6.5	3.5
"Sokolsky DOK"	46.4%	48.0%	16 294	15 996	N/A	8	4.5
"Solomensky sawmill"	48.3%	49.3%	22 096	21 642	1.10%	7.5	4
Average	47.3%	48.5%	18 087	17 745		8	4.25

6 Conclusion

The number of successfully implemented "cloud" projects for small, medium and large businesses is steadily growing. "Cloud" services are being offered by many IT companies, including Microsoft (Dynamics AX), 1C, SAP, Oracle, thus acknowledging the relevance of research and development in this area.

IT-park continues improvement of existing "cloud" services for optimal planning at industrial enterprises, presented in this paper, as well as develops new services. IT-park specialists are also ready to customize them to specific demands of each Customer. The use of unique mathematical models, methods and algorithms combined with modern software development platforms and methodologies enables IT-park specialists to offer products, which improve the productivity and profitability of key production processes of its Customers.

The use of the services enables the Customers to reduce material losses, increase the profitability, and also reduce the production planning time, which leads to significant economic benefits as has been confirmed by Customers.

5 Acknowledgements

References

Armbrust, M. and Fox, A. (2009) 'Above the Clouds: A Berkeley View of Cloud Computing', University of California at Berkeley
(http://www.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-28.pdf)
Bellman, R. (1957) 'Dynamic programming', Princeton, N.J.: Princeton University Press.
Buyya, R., Broberg, J. and Goscinski, A. (2010) 'Cloud Computing: Principles and Paradigms', John Wiley & Sons
Dantzig, G. (1963) 'Linear programming and extensions', Princeton, N.J.: Princeton University Press.
Jamsa, K. (2011) 'Cloud Computing:SaaS, PaaS, IaaS, Virtualization, Business Models, Mobile, Security and More', Jones & Bartlett Learning.
Kantorovich, L. and Gorstko, A. (1968) 'Mathematical Optimal Programming in Economics', Moscow: Science (in Russian).
Kuznetsov, V., Pechnikov, A. and Shabaev, A. (2008) 'Multifunctional system of applications development for solution of material cutting and composition operations', Automation and modern technologies, Vol. 11, pp.10-14 (in Russian).
Tyukina, Y. and Makarova, N. (1988) 'Technology of sawing and woodworking', Moscow: Higher school (in Russian).
Wang, L., Ranjan, R. and Chen, J. (2012) 'Cloud Computing: Methodology, Systems, and Applications', Taylor & Francis Group

Condition monitoring of the disconnectors in the electric power transmission grid with temperature sensors

Per Westerlund, Patrik Hilber
Department of Electromagnetic Engineering
School of Electrical Engineering
KTH Royal Institute of Technology
Teknikringen 33
SE-100 44 Stockholm
Sweden
e-mail: per.westerlund@ee.kth.se

Tommie Lindquist
Svenska Kraftnät
Swedish National Grid
Box 1200
SE-172 24 Sundbyberg
Sweden

Abstract

In the electrical substations there are disconnectors, which can be opened to disconnect equipment from high voltage parts. As the disconnectors are normally closed and transfer current owing to their often critical positions in the power grid, it is difficult to maintain them. The purpose is to develop a new online method to monitor disconnectors and a new theory for their ageing, in order to schedule the maintenance better.

Increasing resistance in the contacts could cause high temperatures and eventually failure. Nine IR temperature sensors have been placed on each of six disconnectors together with reference sensors. After cleaning and interpolation of the data, two regressions are made, first between a sensor at a contact and the reference sensor, then adding the square of the current. The method is promising since it explains most of the variation in temperature with a sensor dependent parameter.

Keywords

electric power transmission, reliability, disconnector, condition monitoring, temperature measurement

1. Introduction

1.1. Electric transmission system

The electric transmission system consists of overhead lines and cables and transmits electric energy across a country, with connections to other countries. The lines and cables connect
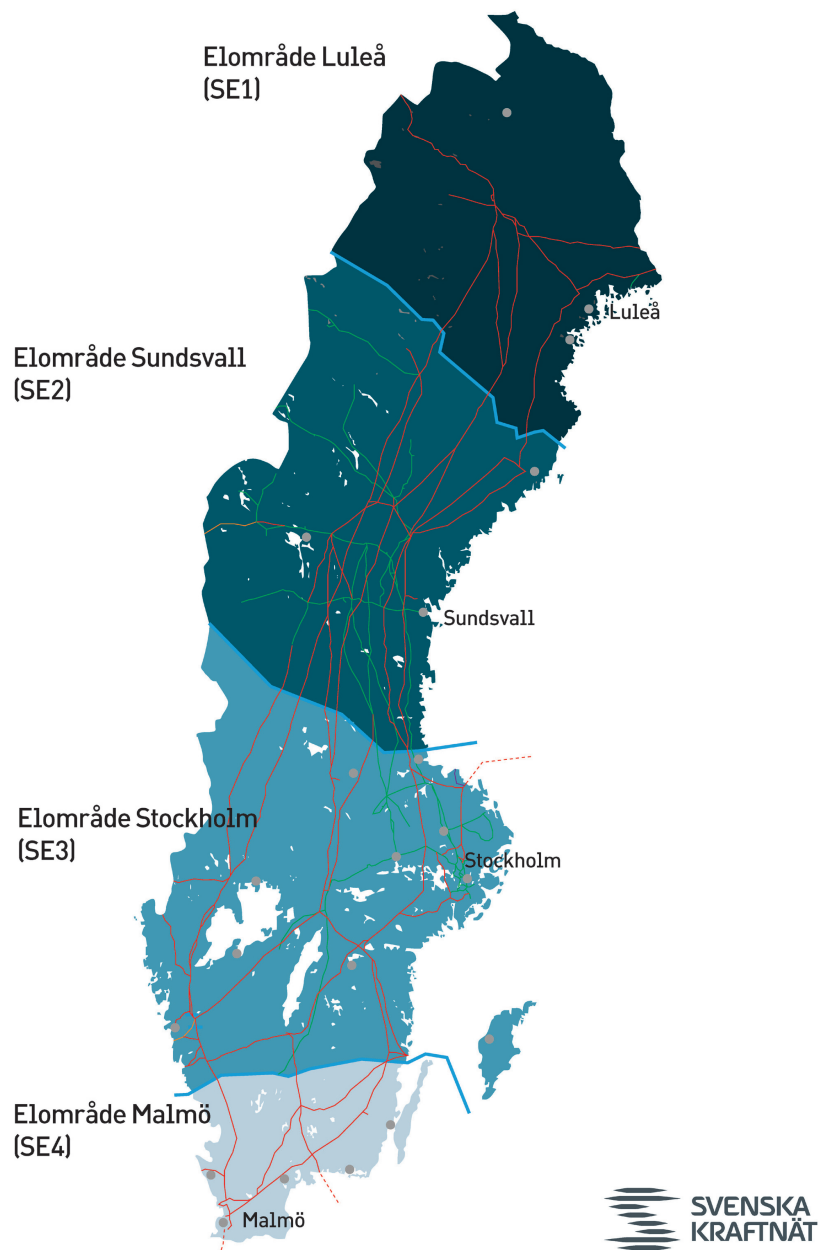
Figure 1. The Swedish electric transmission system, which is divided into four price areas based on the bottlenecks in transmission capacity. The red lines represent 400 kV lines and the green ones 220 kV lines. (Reproduced with permission from Svenska Kraftnät)

at substations, which serve to lower the voltage and to direct the flow of electric power. The transmission system is meshed, which means that there are several paths between two points, and it uses the highest voltages, in Sweden 400 kV and 220 kV (kilovolts). Figure 1 shows the Swedish transmission system, which consists of 15 000 km lines and about 150 substations. [sta, 2013] The distribution systems transport the electric energy to the customers and they use lower voltages (from 0.4 kV to 30 kV) and they are operated radially, so only one line or cable delivers power to a customer, even though there could be some alternative feeder. There are also regional networks between the transmission and the distribution networks with intermediate voltages and some redundancy. The electric grid is shown schematically in figure 2.
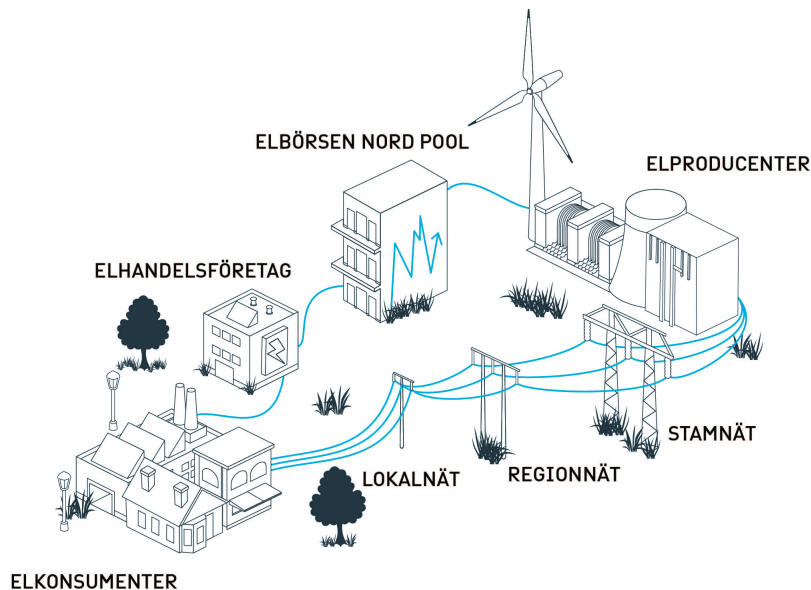
Figure 2. This is a schematic view of the electric grid. The three different networks are at bottom, going from producer to consumer with a decreasing size of the poles in the order transmission, regional and distribution network. The companies involved are at the top: Nord Pool Spot, which run the market for electric energy in the Nordic countries, and the retailer, that sells to the customers. (Reproduced with permission from Svenska Kraftnät)

1.2. Equipment at the substations

In the substations there are transformers, which lower the voltages for example from 400 kV to 220 kV. There are also switches, of which there are two different types: disconnectors, also known as disconnect switches or isolator switches, and circuit breakers. The purpose of the disconnector is safety, to isolate certain equipment from high voltages and it is only opened when there is no current.

The studied disconnectors are so called centre-break and they consist of two arms, which can rotate around one a ceramic insulator. The ends that are not connected to the insulators join
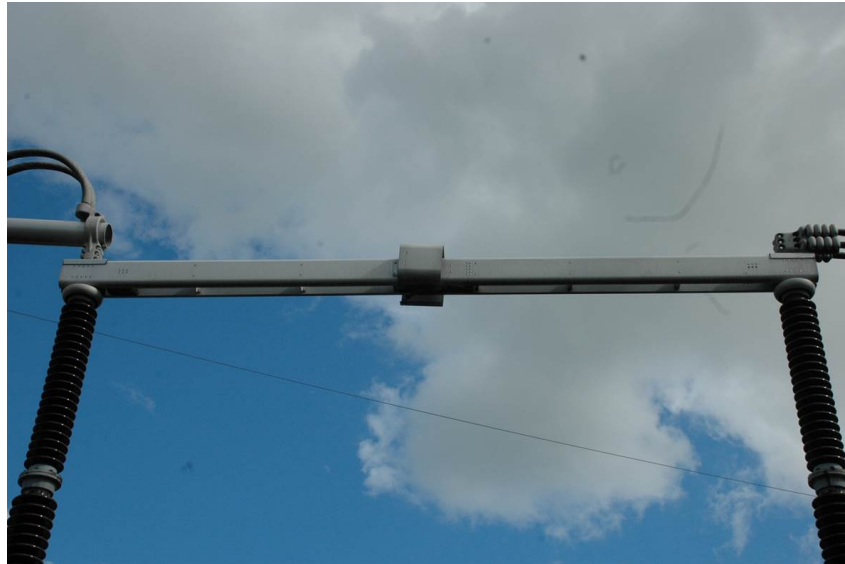
Figure 3. Example of a disconnector. Photo:Svenska Kraftnät.

each other when it is closed. Figure 3 shows how the disconnector is constructed. Mostly the disconnector is closed and carries current and it is only opened a few times each year, during maintenance or installation of some other apparatus at the substation.

The circuit breaker is the actual breaker of the current. Since the current tends to continue even though there is no contact, as it creates an arc between the two conductors that are being separated from each other, there should be a device to extinguish the arc. Similar arcs might also appear between a train and the overhead line if there is a small gap between the line and the pantograph on the roof of the train.

1.3. Contact resistance in disconnectors

A cause for failure is a high resistance in the contacts points, both the main contact between the two arms and the contact between the moving arms and the connecting cables. A high resistance causes high power losses according to Joules law ($P = R \cdot I^2$ where P is the power, R the resistance and I the current). With high power losses the temperature of the conductor will rise, which could cause damages in the material. The contact resistance could be regarded as a condition to monitor.

A possibility to measure the resistance R is to use the definition, that is, voltage V divided by current I, a variant of Ohm's law $R = U/I$. The problem is that the disconnector has to be without voltage, which normally means that the whole line to the substation should be disconnected at the other end. As it will decrease the transmission capacity of the grid, it can only be done with a long interval such as every five years. Also the voltages used at that kind of measurement are quite low, so the measured resistance might differ from the actual resistance at a normal current that passes the disconnector. There are also instruments that can measure the voltage drop across a contact with live equipment, but they do not withstand the high voltages in the transmission network.

Then there are indirect measurements of the resistance, for example by measuring the increase of temperature. This can be done by temperature sensor or by thermography, using a camera that captures infrared radiation. As it requires that somebody goes there to measure, it is possible to make the measurements when the current is low, which gives a low accuracy. [Lindquist *et al.*, 2005] Also it is difficult to get an absolute temperature value, since it should be used at the same spot and with the same angle to get repeatable measurements. Thermography is good for comparison between different parts of a substation at a given time.

A novel way to measure the temperature is to put IR (infrared) sensors direct at the points to be measured, since the sensors have become cheap and have a long battery life due to low power consumption. Then there is no different in position or in angle between different measurements, since they are fixed. There is no problem with image processing, as the contacts only look at one point and they are cheap enough to be placed at many points. They can of course measure the temperature continuously. The IR sensors are a good complement to thermography since they measure the temperature more often and thus they can get measurements with higher loads than with thermography. The drawback is that the IR sensors only measure at specific points. [Lindquist, 2011]

1.4. Other conditions in disconnectors to be monitored

Another possibility is a failure when the disconnector is to be opened, which is done by an electrical motor. Monitoring the currents in the motor it is possible to estimate the mechanical deterioration, since with more resistance of rotation higher currents are needed. It is also interesting to follow the condition of the insulators, since they should support the rotation of the arms. This can be done by ultrasound. These two possible causes of failure will be handled in a coming project.

1.5. Condition monitoring in the reliability chain

In the two most northern electric areas of Sweden, where a large amount of hydropower is produced, it is challenging to plan outages in order to carry out maintenance or to connect new equipment, since the network capacity is fully used. [per, 2013, p 61-67]
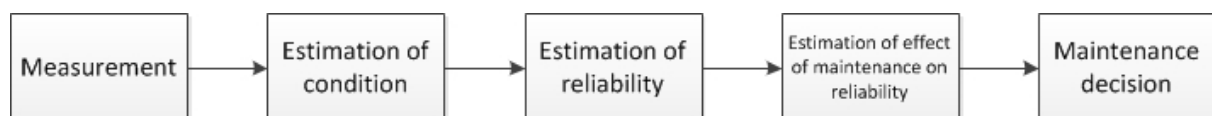

Figure 4. The reliability chain

That circumstance is a reason to monitor disconnectors in order to plan their maintenance more carefully. Also the measurements could provide enough data to improve the ageing model of disconnectors. Thus the maintenance plan for the disconnectors that are not monitored could be made more accurate. In order to make good maintenance decisions, it is needed to advance along the reliability chain in figure 4. The purpose of this study is to find a model for the reliability when the condition of a disconnector has been estimated, so at least two steps on

the reliability chain should be covered. A strategy for inspection with thermography has been developed. [Lindquist & Bertling, 2007]
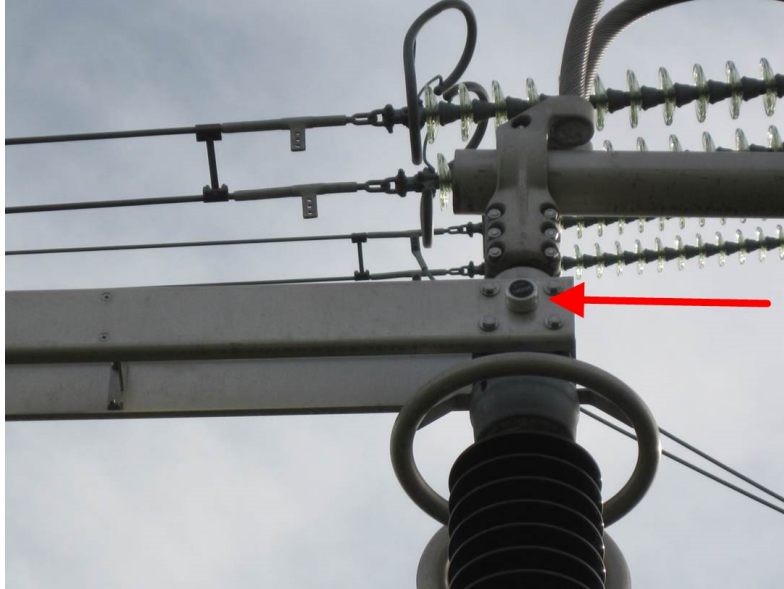
2. Measurements

Figure 5. Example of a disconnector with a sensor placed on the arm above the insulator as shown by the red arrow. Photo: Svenska Kraftnät.

The objects of this study are six disconnectors for 400 kV at two substations in Sweden. Nine temperature sensors have been placed on each for the project. There are three sensors along each of the three phases, two at the contact between the two moving arms and the respective support and one at the contact between the arms as in figure 5 and 6. There are also reference sensors at each substation in order to record the outdoor temperature. The temperature is transmitted every eight minutes to a base station at the substation by a radio protocol, so there are no cables to the sensors, which is good as the sensors are placed on surfaces that are at high voltages. An insulated pole has to be used to place them. The sensors have a battery that should last ten years. The accuracy is ± 0.5 degrees centigrade.

3. Data analysis

Values near the absolute zero were removed. The data has to be cleaned from unreasonable values, i.e. near the absolute zero. That was due to error in the devices. Also there are time intervals, where there is no data, due to some communication problems. Furthermore some sensors sent data 15 times as often as the others. Finally the data has to be interpolated since the sensors are not synchronized. The interpolation is linear. Figure 7 shows data from two sensors with a detailed view in figure 8, where the temperatures drop during three winter days.
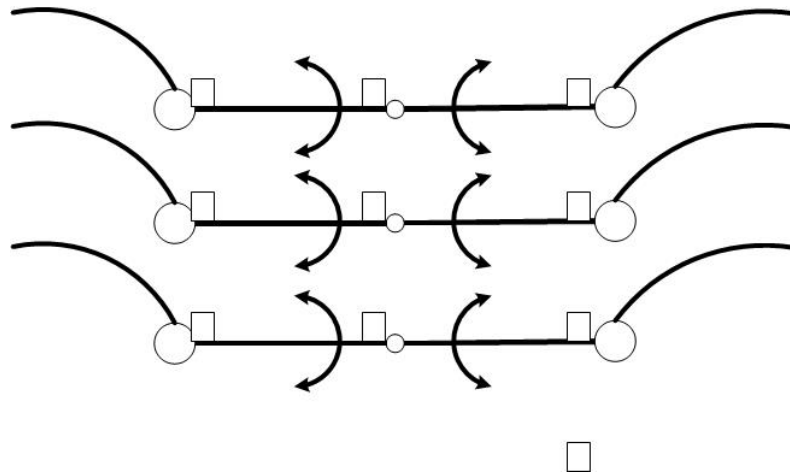
Figure 6. Placement of the sensors (small squares) on a disconnector, three on each phase and a reference sensor close to the ground.
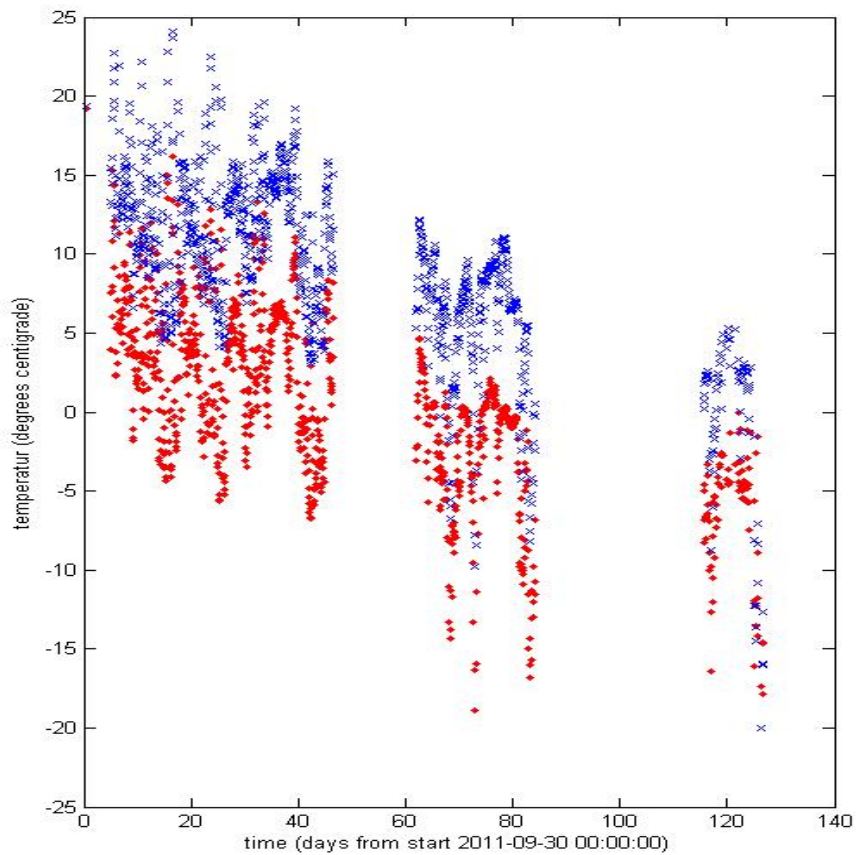

Figure 7. Example of time series. The blue crosses in the upper part are from the sensor at the centre contact of phase 1 and the red dots below from the reference sensor.
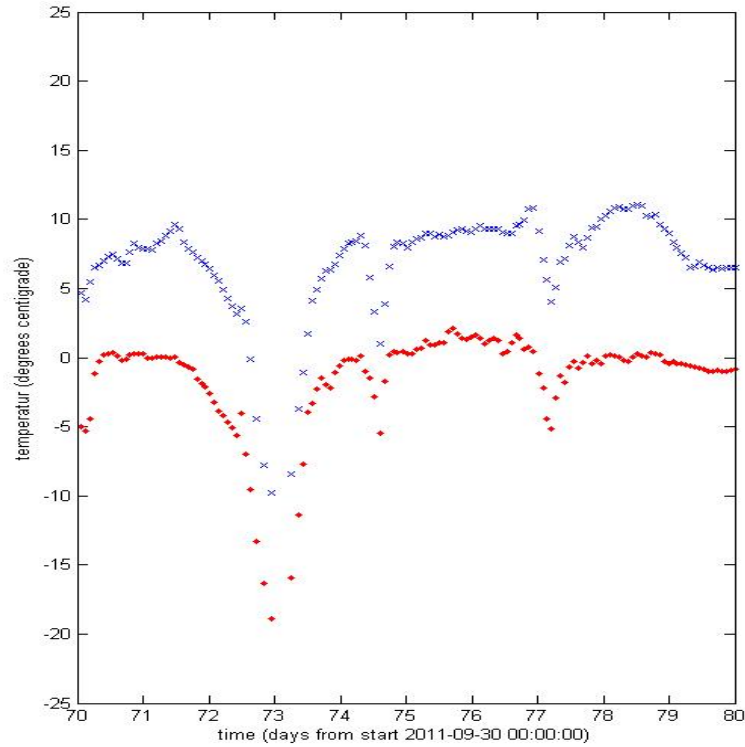
Figure 8. This graph represents only 10 days of the graph of figure 7 with blue crosses for the sensor at the centre contact of phase 1 and red dots for the reference sensor.

3.1. Linear regression of temperature

In order to get a relation between the temperature at the two sensors, the time series should be plotted against each other as in figure 9. In all figures the data comes from two sensors on the same disconnector, one is called phase 1 centre and it is at the contact between the arms, the other is called reference and it measures the outdoor temperature. A basic first step is to make a linear regression, i.e. to fit a equation:

$$T_2 = b_0 + b_1 T_1$$

where T_2 and T_1 are the temperatures at the two sensors at the same time and b_0 and b_1 are two parameters to be determined.

The linear regression is a way to explain the variation of one sensor with the variation of the other. Since there are more than two temperature pairs, let it be n, the system of equations is over determined and the solutions are given by a least square algorithm, to get the solution that minimize the square of the errors for all of the pairs. That is, the equation system to be solved is:
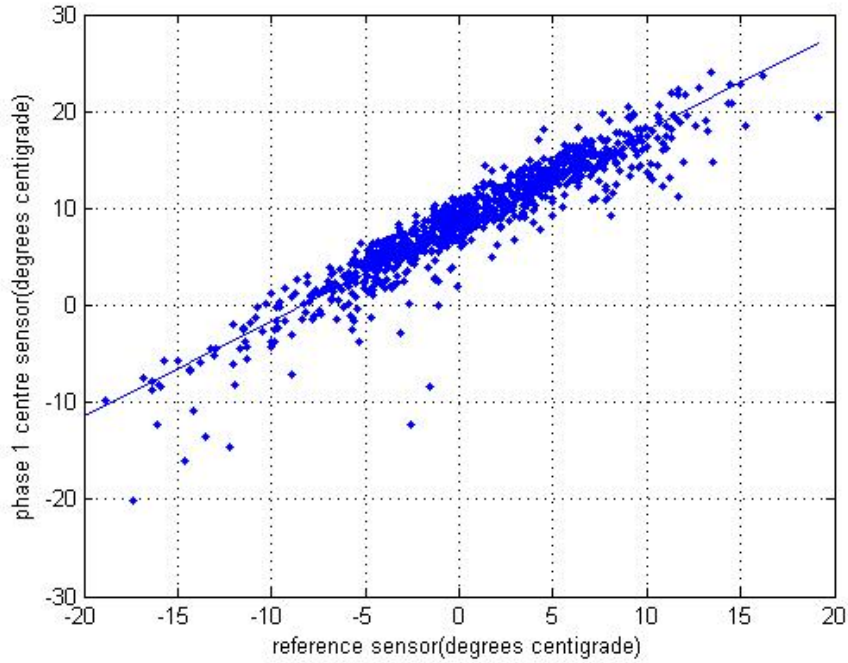
Figure 9. Scatter plot of two time series of temperatures. The line comes from the regression of the phase 1 centre sensor against the reference sensor, T_2 respective T_1 in the formula.

$$T_{2i} = b_0 + b_1 T_{1i} + \epsilon_i$$

for i going from 1 to n and the sum of all ϵ_i should be minimized. [Hogg & Tanis, 1993, p 488-509] The ϵ_i is called residual for each pair, that is, what remains to be explained. It is always interesting to study the residuals to find out how the regression was carried out. It is also interesting to divide the variance of the residuals by the variance of T_2 and subtract this from 1, since this value indicates how much of the behaviour of T_2 that is still unexplained. It is called R^2 and amounts to 0.88, which is quite good, since it lies between 0 and 1 and the close to 1 the better. [Sen & Srivastava, 1990, p 14]

The histogram of the residuals is shown in figure 10. The skewness is -2.22, which means that the left tail is bigger than the right tail. A symmetrical distribution has a skewness of 0. The kurtosis or excess is 14.3, which means that the distribution is much taller than the normal distribution around its mean. The skewness is calculated as the sum of the third power of the deviations from the mean and the excess as the fourth power. Both are normalized by the standard deviation. [Cramér, 1945, p 183-184] Thus the distribution of the residuals reveals that there should be some more factors to investigate. In the following table are the results from one disconnector. The sensors are regressed against the reference sensor.
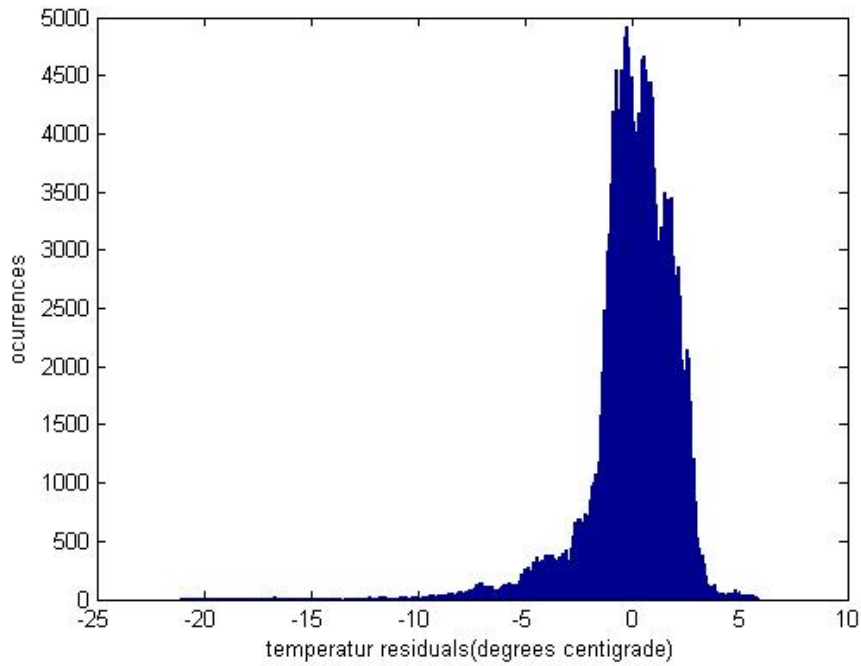
Figure 10. Histogram of temperature residuals.

Sensor	$b_0(°\mathrm{C})$	b_1	R^2
Phase 1 right	7.6193	1.0216	0.9492
Phase 1 centre	8.2093	0.9813	0.8764
Phase 1 left	7.0730	1.0102	0.9236
Phase 2 right	7.5445	1.0426	0.9413
Phase 2 centre	7.5218	1.0277	0.9358
Phase 2 left	7.6581	1.0174	0.9443
Phase 3 right	8.3229	0.9691	0.9267
Phase 3 centre	8.3496	0.9993	0.9399
Phase 3 left	6.5685	1.0168	0.8971

The sensors at the contacts are about 7 or 8 degrees warmer than the reference sensor according to the coefficient b_0 and when the reference sensor gets warmer their temperature increases about the same. This is due to that b_1 is about 1. These regressions explain between 0.88 and 0.95 per cent of the variation in the sensors at the contacts.

3.2. The influence of current

Figure 11 shows the variation of the current, which is given as an hourly average, well below the maximum permitted current, about 3000 amperes. The values of the current should thus also be interpolated, which is also done linearly. Then the temperature residuals should be plotted against the current to judge the influence of the current on the temperature. Since the
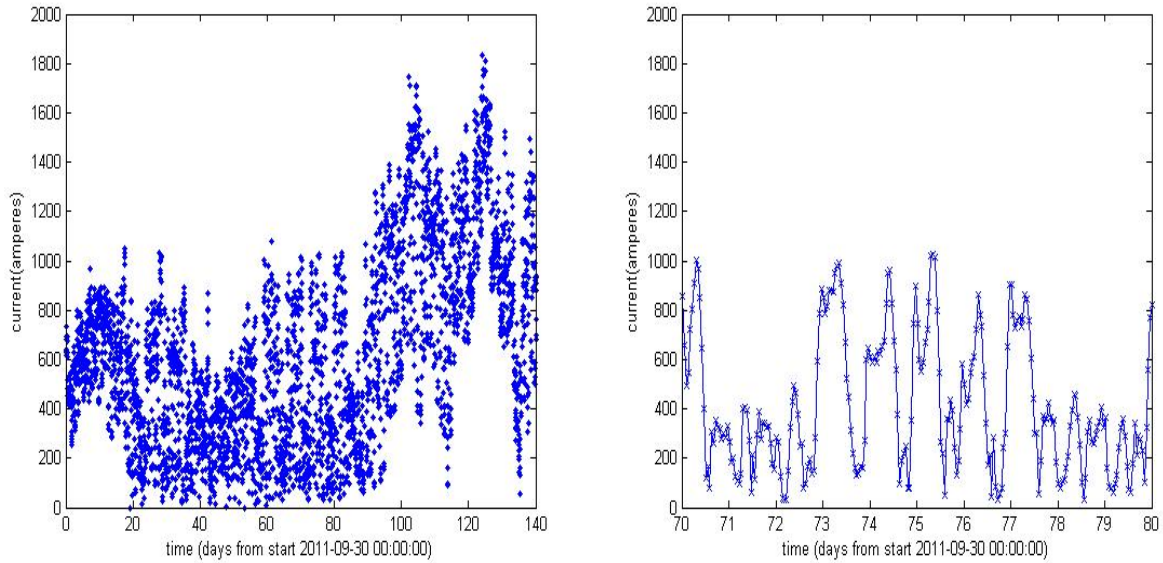
Figure 11. Variation of the current in one of the disconnectors. The graph to the right represents only 10 days of the graph to the left.

dots in the plot could be overlapping, it is necessary to calculate a two-dimensional histogram. It is also normalized for each current value and plotted in colour, so the most common temperature residual has the reddest colour. The curves look quadratic as in figure 12.

According to Joule's law, $P = R \cdot I^2$ where P is the power, R the resistance and I the current, the power losses increase with current and so does the temperature. Hence a regression is made to get the parameters b_0, b_1 and k in the equation:

$$T_2 = b_0 + b_1 T_1 + kI^2$$

The following table shows these parameters putting the different sensors on the same disconnector as in the preceding section as T_2 and using the reference sensor as T_1:

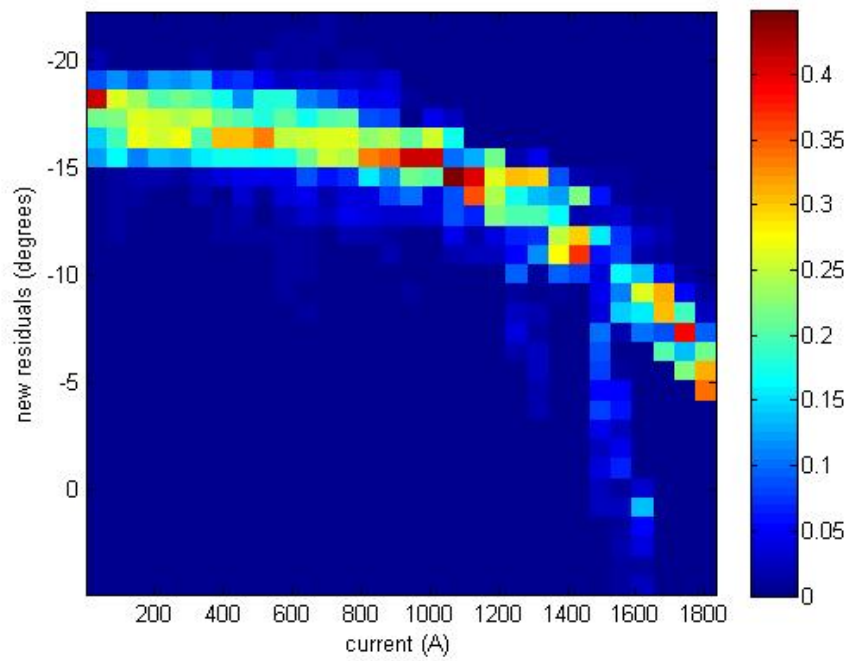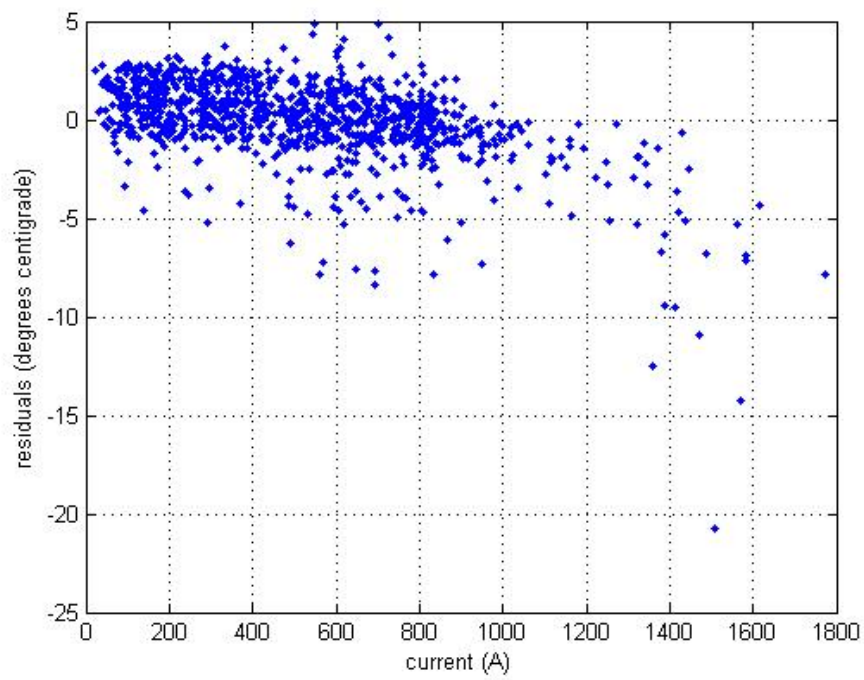| Sensor	$b_0(°C)$	b_1	$k(°C/kA^2)$	R^2
Phase 1 right	8.9212	1.0417	-2.9192	0.9757
Phase 1 centre	9.3575	0.9356	-2.9750	0.9214
Phase 1 left	8.6937	1.0388	-3.6220	0.9649
Phase 2 right	9.0317	1.0575	-3.2050	0.9747
Phase 2 centre	8.5103	1.0268	-1.8185	0.9477
Phase 2 left	8.8045	1.0309	-2.5494	0.9652
Phase 3 right	8.9436	0.9740	-1.5805	0.9299
Phase 3 centre	9.1516	1.0043	-1.7228	0.9497
Phase 3 left	8.6219	1.0527	-4.5555	0.9598

Figure 12. To the top a scatter plot of temperature residuals versus current and to the bottom a coloured normalized histogram of the same.
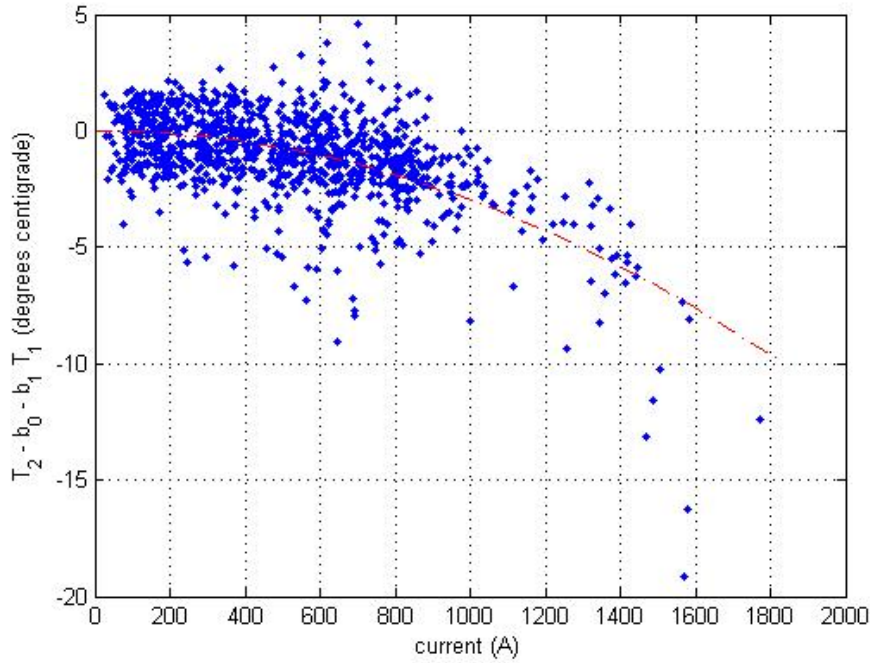
Figure 13. Explanation of the effect of the current. The dash-dotted line is the best quadratic adaption of the current for the regression of phase 1 centre sensor against the reference sensor.

In figure 13 $T_2 - b_0 - b_1 T_1$ is plotted against I^2 and the curve kI^2 shows a fairly good agreement. The parameter b_0 has increased to between 8.6 and 9.4 since now high currents lower the temperature at the contacts as k is negative, which has to explained physically, for example by using the theories in [Holm, 1967]. The biggest variation is in k, which could be regarded as a condition of the contact, instead of measuring the contact resistance. The parameter b_1 remains the same, about 1. The amount of explanation, R^2, has increased to between 0.92 and 0.98.

4. Conclusion and future work

The measurement system with IR sensors fixed at the contact in disconnectors to measure their temperature continuous is interesting. With a straight forward regression it is possible to rank the contacts of a disconnector, which will allow for maintenance of the most degraded contacts first. In addition disconnection of healthy components can be avoided, resulting in a total system performance improvement. By using extrapolation it can be investigated if it is likely that a disconnector will exceed temperature fault criteria at nameplate rating currents. Hence it is possible to indicate faulty disconnectors before a failure event takes place.

In this paper we have studied disconnectors and presented a measuring system, which can estimate the condition. We have worked with the two first steps on the reliability chain for disconnectors. The first step, measurements, is working and we have started on the next one,

condition estimation, aiming to estimate the reliability. A future task is to understand how the parameters determined by regression change with time. The measurement period may be too short in order to observe changes in one disconnector. Another possibility is to compare the disconnectors, since they are from different decades.

Acknowledgment

References

[per, 2013] 2013 (April). *Perspektivplan 2025 - en utvecklingsplan för det svenska stamnätet (Perspective plan 2025 - a plan for the development of the Swedish electrical transmission system)*. Tech. rept. Svenska Kraftnät.

[sta, 2013] 2013. *Stamnätet (the transmission grid)*. http://www.svk.se/Om-oss/Var-verksamhet/Stamnatet/. retreived 30th May 2013.

[Cramér, 1945] Cramér, Harald. 1945. *Mathematical methods of statistics*. Uppsala: Almqvist & Wiksell.

[Hogg & Tanis, 1993] Hogg, Robert Vincent, & Tanis, Elliot A. 1993. *Probability and statistical inference*. 4 edn. New York: Macmillan.

[Holm, 1967] Holm, Ragnar. 1967. *Electric contacts, theory and applications*. 4th edn. Springer-Verlag.

[Lindquist, 2011] Lindquist, Tommie. 2011. Wireless sensors VS Thermography — Comparing accuracy and applications. *In: SC A3 Colloquium*. Cigré, Vienna.

[Lindquist & Bertling, 2007] Lindquist, Tommie, & Bertling, Lina. 2007. A method for calculating disconnector contact availability as a function of thermography inspection intervals and load current. *In: Cigré Symposium on System Development and Asset Management under Restructuring*.

[Lindquist *et al.*, 2005] Lindquist, Tommie, Bertling, Lina, & Roland, Eriksson. 2005 (June). Estimation of disconnector contact condition for modelling the effect of maintenance and ageing. *Pages 1–7 of: IEEE Russia Power Tech*.

[Sen & Srivastava, 1990] Sen, Ashish, & Srivastava, Muni. 1990. *Regression analysis. theory, methods, and applications*. Springer.

The conception of use of space oriented models in maintenance management of the selected classes of technical means

Andrzej Wieczorek*

Institute of Production Engineering
Faculty of Organisation and Management
Silesian University of Technology
ul. Roosevelta 26 – 28
41 – 800 Zabrze
Poland
*Corresponding author: Andrzej Wieczorek
e-mail: Andrzej.Wieczorek@polsl.pl

Abstract

The article includes the state of art and perspectives within the use of space oriented models in maintenance management, particularly for decision-making in this area. The concept of a complex model (composed of GIS model, model – taxonomic method and the model used for the purposes of time-series-cross-section analyses) was also proposed. This model will be used in carrying out the calculations, but also simulating and predicting the values of efficiency, reliability and performance of selected classes of technical means. The last part of the article proposes an application of the model in terms of the chosen strategies and maintenance philosophies (including RCM, TPM, BCM, Human Centred Maintenance) for decision – making in maintenance management of technical means of the selected classess.

Key words: maintenance management, spatial models, forecasting, simulation

1 Introduction

In the rational exploitation (using and maintenance) of technical means (machines, devices, systems, etc.) it is reasonable to assume that effects of their work, observed based on values of effectiveness and reliability measures strongly depends on time and space of exploitation of these means. It is a result of existence of using and maintenance conditions, varying in time and space that affect the functioning of both the technical means and their environment. Therefore, decisions in maintenance management of technical means should be made by the application of methods and techniques, which take into consideration space aspects in these decisions. They have to enable to indicate maintenance strategy for selected technical mean, exploited in the selected geographical locations, maintenance organizational, decision – making and information structures and activities within planning, organizing, motivating and controlling. Decision making in maintenance management in accordance with the proposed approach requires having data, information and knowledge on technical means, maintenance events (failures, maintenance tasks start and finish, etc.), processes and maintenance workers and geographical locations in which they are.

Therefore, the article includes the state of art and perspectives within the use of space oriented models, including: data and spatial models in maintenance management, particularly for decision-making in this area. The concept of a complex model was also proposed; this model consists of GIS model, whose components are selected thematic layers (theses layers contain information about the objects and their users and maintainers, as well as the impacts, which might affect the system: man – machine system), model – taxonomic method and the model used for the purposes of time-series-cross-section analyses in which the particular sections of data are assigned to selected geographical locations in GIS map. This model will be used in carrying out the calculations, but also simulating and predicting the values of efficiency, reliability and performance of selected classes of technical means. The last part of the article proposes an application of the model in terms of the chosen strategies and maintenance philosophies, including Reliability Centred Maintenance, Total Productive Maintenance, Business Centred Maintenance, Human Centred Maintenance for decision – making in maintenance management of mobile and stationary technical means mainly used for military purposes, but also of civil ones (in the second case under consideration they will be used in maintenance of city – buses and water and sewerage supply network).

2 Space oriented models in using and maintenance management of technical objects – state of art and perspectives

Decisions on the organization management recently need to have appropriate data set, so the right methods of its collection and processing. All of these methods use appropriate models of the real world, reflected in the databases of computer systems (data models) and also data processing models (spatial models), stored in these databases. The concept of modeling real world by Bernhardsen is shown in Figure 1.
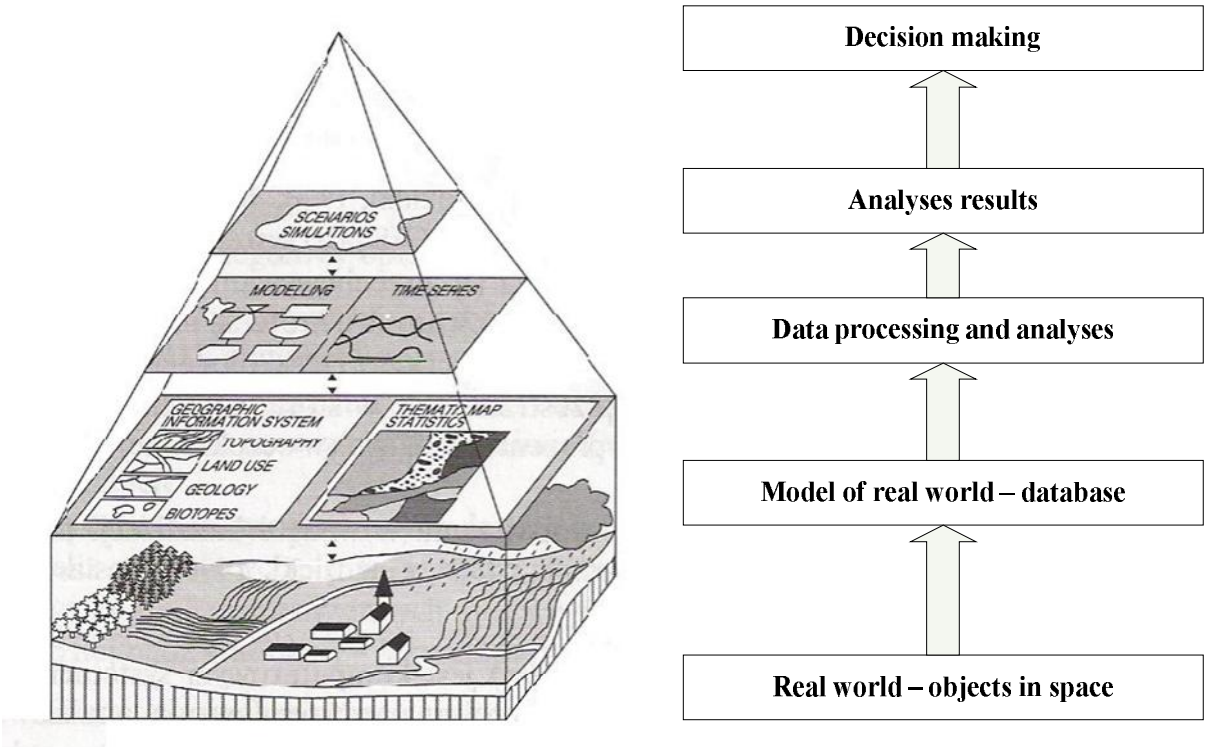

Figure. 1. An example of modeling real world (Bernhardsen, 1992)

This concept involves the use of spatial data models as a way to describe data. These models have been implemented in GIS (Geographic Information Systems). By (Longley at al., 2008) the following data models can be distinguished:

– *CAD, graphical and picture model*; first mentioned model is used in CAD (Computer Aided Design) systems. The CAD system real objects are represented symbolically in the form of a vector by points, lines and polygons. Graphical model is derived from the computer mapping, whose main task in the 60s of the twentieth century was the automated production of paper topographic maps and creation of simple thematic ones. In the case of the image model the data source for this model are scanned aerial photographs and digital satellite images. Thus, these systems use raster or regular grid layout to represent objects on the Earth's surface,

– *raster model* – raster data model uses the matrix elements, also known as pixels to represent objects. In the halftone cells the attribute values can be stored, for example, categories, integers or floats, which are dependent on the adopted coding system,

– *model vector* – raster model is related to the conceptual model of continuous fields, and vector data model is closely related to the notion of discrete objects,

– *object model* – object – oriented models in GIS focuses on the collection of spatial objects and their inter – relationships.

The upper mentioned models, as a components of GIS, in accordance with the current knowledge about them, included in Report of research project: 'Integrated, intelligent system of monitoring and management of exploitation of water network on the area of the activity of Water and Sewage Supply Ltd. in Rybnik' can be used to manage the using and maintenance of technical objects for the following purposes:

– identify failure reports of technical objects and the classification of work related to their removal,
– planning work, such as repairs, inspections, maintenance,
– planning detailed tasks in the failure removal and repair works,
– providing technical, material and personnel necessary to perform the tasks,
– organization of breakdown and planned maintenance,
– long – term planning of maintenance tasks,
– financial, time and material accounting and accounting of occupation of terrain of work execution,
– control of objects through the use of such monitoring of selected parameters of their work or inspection.

Data models as components of GIS can be used for maintenance management of stationary systems, which are such network systems (networks: water, sewage, heating, gas, electricity), but also mobile technical objects. Examples of the use of the GIS in first mentioned case is shown in (Kwietniewski, 2008; Karolewski, 2006) and the use of GIS, in supporting maintenance of the water supply system is shown in (Wieczorek, 2010; Kaźmierczak et al., 2012; Loska and Dąbrowski, 2011).

Model of the real world, with its reflection in GIS layers and database will be used in data processing and analysis (see: picture 1), conducted by the use of spatial models. There are the following spatial models (Longley et al., 2008):

– static models,
– dynamic models.

Another classification assumes classification of spatial models including (Longley et al., 2008):

– *analog models*, examples of such models can be paper maps, that are symbolic replicas of the natural environment, shown in scale,
– *digital models*, these models reflect the occurrence of spatial phenomena. Geocomputation term is associated with these models.

Based on research conducted by the author of the paper it is justified to say that the problem of the use of spatial models in maintenance management of technical objects is weakly present in the world literature. An answer for this problem could be quantitative spatial models, which are dealt with discipline, which is econometrics. The examples of spatially oriented models, which are the subject of its interest, may be time-series-cross-section that allow for data analysis, associated with both the time domain and space one.

In addition to these models we can distinguish the spatial econometrics models, among which it is possible to indicate (Suchecki et al., 2010):
– methods of time-series-cross-section analyses,
– methods of spatial econometrics.

The spatial econometrics applies a number of methods, models and measures. Among them it is possible to distinguish (Suchecki et al., 2010):
– Lorenz curve and Gini's index for spatial data,
– another measures of spatial concentration: traditional indexes of spatial concentration, Herfindahl – Hirschman index, classical divergence index, Isard's index, Krugman's concentration index, indexes based on entropy measures, GE(1) index – Theil's index, GE(2) index, square index, Chi – kwadrat index, Gibbs Martin index, concentration indexes based on probability and correlation of location choice (Ellison and Glaeser index, Maurel and Sédillot index),
– regional location index (for example: Krugman's specialization index),
– methods of structural geographical analyses (classical methods of shares alterations (SSA), stochastic models of weighted regression (SSANOVA), dynamic models and panel models of shares alterations (methods of Barff – Knight variable weights, method of Esteban's competitiveness changes, SSANOVA panel models, spatial method of shares alteration (SSSA)),
– models of new geographical economy and special models (cause – effect models of new geographical economy, models of surface trend, models of spatial diffusion, models of gravitation, potential models),
– spatial regression models (SAR – spatial auto regression models, models with spatial auto regression of random component, SCM – models with spatial filtration of explanatory variable, mixed models).

The research, conducted by the author of the article, including studies, in which the author participated in a project carried out under the 'Innovative Economy' Operational Programme, activities: 1.4 – 4.1 under the title: 'An integrated, intelligent system of monitoring and management of exploitation of water network on the area of the activity of Water and Sewage Supply Ltd. in Rybnik' shown that there is a need to support decision – making in maintenance management of technical objects, taking into account the spatial aspects. Therefore there are a number of problems need to be resolved. Among the current challenges that should be the subject of further research it is reasonable to indicate:
– modelling of objects, events and using and maintenance processes that occur, when the "classic" using and maintenance philosophy (RCM, BCM, TPM) is realised, as well as new and another ones, taking into account time and space aspects,
– modelling the functioning of the system: human – technical object – the environment in conjunction with the selected geographic locations where the features of not only technical means and the environment, but also human ones are important,

– modelling using and maintenance systems whose "practical" representation are structures: information and computer, organizational and decision – making structures,
– modeling, taking into account time and space aspects, oriented to using and maintenance measures calculation, the first approach to this problem is shown in a publication (Wieczorek, 2012b),
– modelling of impacts on technical objects as a function of time and space, it is envisaged to undertake research in this area with the use of spatial econometrics methods,
– solution to the problem of integration of different solutions for time and space models, both at the level of methodology and tool, as highlighted in (Savic, D. et al., 1997),
– methods of measures selection for decision – making based on time and space models,
– culture of data acquisition for the analysis which are the subject of discussion.

3 The concept and the possibility of using the original model for the use in maintenance management of the selected technical means

3.1 Description of the proposed model for use in maintenance management of technical objects

Due to the needs, indicated by upper – mentioned studies, described above, there is a necessity to develop model solutions that would result from methodological integration of described above solutions of data and spatial models. An example might be a concept of the complex model that includes:
– method of maintenance objects analysis (taxonomic method),
– method of time-series-cross-section analysis
– GIS model.

Method of maintenance objects analysis (taxonomic method)

This method was developed as a result of a research project under 'Innovative Economy' Operational Programme, activites: 1.4 – 4.1 under the title: 'An integrated, intelligent system of monitoring and management of exploitation of water network on the area of the activity of Water and Sewage Supply Ltd. in Rybnik' and described in a report on its execution and in (Loska, 2013). A usage this method in practice consists of three successive stages:
– ranking technical objects,
– classification and selection of technical objects,
– analysis of assessments and values of using and maintenance measures.
The purpose of the ranking according to report of upper mentioned project is ordering of equivalent technical objects from a point of view of their exploitation, based on the history of unintended events (failures, breakdowns, catastrophes) and intended ones (maintenance, repair), resulting from the on–going maintenance and repair work, together with all the circumstances. For the purposes of the ranking of technical objects, a method of evaluation, taking into account the maintenance key indicators was developed. A practical use of measures to assess the maintenance of technical objects and using and maintenance processes, carried out with their participation justifies to indicate several key features that include:
– technical condition, which is a measure of the potential of using of object at a particular time,
– reliability describing the technical object availability to act in terms of statistics,
– the quality of ability of an object to satisfy stated or anticipated needs,

–   functionality describing the object in the field of human interactions,
–   efficiency describes the object in terms of performance,
–   maintainability describing susceptibility of an object to perform maintenance,
–   diagnosing susceptibility describing the vulnerability of an object to extract about technical condition.

These features should be considered more as groups, rather than a single sizes. To each group, it is possible to include the measures (indicators) describing and evaluating some exploitation (using and maintenance) aspects of objects / technical systems, as well as the functioning of the maintenance services. In practice, these measures should be an effective tool to:
–   evaluate characteristic values for the quantitative evaluation of technical objects and maintenance services,
–   compare between the organizational cells / departments of company in specific time intervals,
–   undertake improvement actions, based on the results of analyzes using values of measures.

In practice, there are many exploitation mathematical models underlying the quantitative evaluation of exploitation of technical objects and functioning of maintenance services. In particular, the analysis of various industries showed that the most commonly used measures are ones under three general models:
–   reliability model,
–   exploitation effectiveness model OEE (Overall Equipment Effectiveness),
–   technical organizational model KPI (Key Performance Indicators).
In this case a measures selection and arrangement were made in three main categories:
–   economic measures (indicators), expressing the cost value of a selected exploitation aspect,
–   technical measures (indicators), expressing the diagnostic and reliability value of a selected exploitation aspect,
–   organizational measures (indicators), expressing the time or out-of-exploitation value of a selected exploitation aspect.

The selected measures of performance describe the various aspects quantitatively, and thus are expressed in different units, mutually not comparable. The basic assumptions of the method is equivalent treatment of all the necessary measures, in other words, these measures must be reduced to the same rating scale. In addition, we are dealing here with both stimulants (for which high values of characteristics are desired, e.g. mean time between failures – MTBF), and destimulants (for which low values of characteristics are desired, e.g. cost of emergency work). It is therefore proposed to perform a normalization process, including unification of values, taking into account:
–   expression of the value of assessment in relative terms (related to the maximum and minimum measure values, obtained in the entire history of measuring in the organizational and technical system),
–   expression the value of assessment in the range <0 , 10>, which will allow to reduce individual measures from the appointed form (e.g. €/m3) to the not appointed form in one range (from 0 to 10), thus possible to compare,
–   establishment of a uniform trend of the indicators values (according to the (Loska, 2012), a better solution is a positive trend – stimulants – greater value is better).
Based on the above criteria, you can determine the value of assessment for exploitation measures:

– for the measures of a positive trend – stimulants:

$$OC_i = \frac{10 \cdot m_i}{m_{i\,max} - m_{i\,min}}$$

(3.1)

OC_i – selected (i – th) exploitation assessment,
m_i – selected (i – th) exploitation measure,
m_{imax} – maximum value of exploitation measure in the whole history measuring in the given organizational and technical system,
m_{imin} – minimum value of exploitation measure in the whole history measuring in the given organizational and technical system,

It is assumed that for all measures considered here, the minimum $m_{imin} = 0$, so:

$$OC_i = \frac{10 \cdot m_i}{m_{i\,max}}$$

(3.2)

– for measures on negative trend – stimulants – destimulants:

$$OC_{id} = 10 - \frac{10 \cdot m_i}{m_{i\,max} - m_{i\,min}}$$

(3.3)

for $m_{imin} = 0$:

$$OC_{id} = 10 - \frac{10 \cdot m_i}{m_{i\,max}}$$

(3.4)

The determined values of exploitation assessments can be ordered in a table of exploitation measures, see: table 1.

	Economical ratios weight k_1	Technical ratios weight k_2	Organizational ratios weight k_3
Level 1 weight p_1	a_{11}	a_{12}	a_{13}
	$OC_{E1},...,OC_{Em}$ (sum of weights equal to 1)	$OC_{T1},...,OC_{Tm}$ (sum of weights equal to 1)	$OC_{O1},...,OC_{Om}$ (sum of weights equal to 1)
Poziom 2 weight p_2	a_{21}	a_{22}	a_{23}
	$OC_{Em+1},...,OC_{En}$ sum of weights equal to 1)	$OC_{Tm+1},...,OC_{Tn}$ sum of weights equal to 1)	$OC_{Om+1},...,OC_{On}$ sum of weights equal to 1)
Poziom 3 weight p_3	a_{31}	a_{32}	a_{33}
	$OC_{En+1},...,OC_{Ep}$ sum of weights equal to 1)	$OC_{Tn+1},...,OC_{Tp}$ sum of weights equal to 1)	$OC_{On+1},...,OC_{Op}$ sum of weights equal to 1)

Table 1. Table of exploitation assessments

where:

OC_{Ei} – exploitation assessment of economic type,
OC_{Ti} – exploitation assessment of technical type,
OC_{Oi} – exploitation assessment of organizational type,
.

Table 1 takes into accounts:
- types of exploitation assessments (economic, technical and organizational ones), for which sum of weights must be equal to 1 ($k_1 + k_2 + k_3 = 1$),
- decision – making levels, whose weights have the following values: $p_1 = 4$, $p_2 = 2$, $p_3 = 1$.

Based on data in the tables it is necessary to determine:
- exploitation assessments matrix:

$$W = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (3.5)$$

where:

$$a_{ij} = \sum_{i=1}^{N} OC_{ij} \cdot g_i \quad (3.6)$$

$$\sum_{i=1}^{N} g_i = 1 \quad (3.7)$$

where:
a_{ij} – standarized weighted sum of exploitation assessments, calculated for the object, weight value relative to the single assessment,
OC_{ij} – exploitation assessment,
g_i – weight value referred to a single assessment.

- vector of tasks categories:

$$K = \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} \quad (3.8)$$

where:

K – the set of weight related to the category (economic, technical, organizational),
k_i – weight of the i – th category.

Vector of category enables you to define weights for certain types of assessments. This allows the proper definition of the importance of company maintenance. For example:
- high value of economic category weight at lower value of technical and organizational category weight may point to carry out maintenance activities with particular emphasis on the resulting cost,

– high value of technical category weight at lower value of economic and organizational category weight means the implementation of maintenance activities, reliability and efficiency improvement with less emphasis on cost and number of man hours.

The values of the category vector can be shaped arbitrary, with the assumption that:

$$\sum_{i=1}^{N} k_i = 1 \qquad (3.9)$$

– vector of decision – making levels:

$$P = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} \qquad (3.10)$$

where:

p_i –   weight of the i – th organisational level of the organization:
p_1 –   weight of organization level,
p_2 –   weight of technical department level,
p_3 –   weight of maintenance department level.

Vector of decision – making levels allows you to emphasize these assessments that in the decision making process have a specific meaning in relation to company maintenance policy This role results mainly from maintenance strategy as well as organizational and decision making structures, that are built on the basis. In particular, the vector includes:
– weight of company level (p_1) – taking into account the strategic decisions and the associated assessment, taking into account the strategic decisions and the associated assessment directly related to operational policy and the functioning of the maintenance department as a whole,
– weight of technical department level – taking into account decisions and the related assessment of the planning and implementation of maintenance activities,
– weight of maintenance department level – taking into account operating decisions and the related assessment of the specific ways of implementing of maintenance tasks.

The hierarchical nature of the levels of decision – making and responsibility for specific maintenance tasks allow to determine the value of vector of decision – making levels, applying the principle that the weight of the higher level is a multiple of the weight directly to a lower level:
$p_3 = 1$,
$p_2 = 2$,
$p_1 = 4$.
The values of the vector of decision – making levels are contractual in nature and can be differently shaped in relation to another company.

Based on pre – defined and designated matrices and vectors rank of the object is calculated, as a result of aggregation:

$$R = (W \cdot K) \cdot P^T \qquad (3.11)$$

Particularly:

$$R = \left(\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \cdot \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} \right) \cdot \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}^{T} \tag{3.12}$$

$$R = \begin{bmatrix} a_{11} \cdot k_1 + a_{12} \cdot k_2 + a_{13} \cdot k_3 \\ a_{21} \cdot k_1 + a_{22} \cdot k_2 + a_{23} \cdot k_3 \\ a_{31} \cdot k_1 + a_{32} \cdot k_2 + a_{33} \cdot k_3 \end{bmatrix} \cdot \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}^{T} \tag{3.13}$$

$$R = [(a_{11} \cdot k_1 + a_{12} \cdot k_2 + a_{13} \cdot k_3) \cdot p_1 + (a_{21} \cdot k_1 + a_{22} \cdot k_2 + a_{23} \cdot k_3) \cdot p_2 +$$

$$(a_{31} \cdot k_1 + a_{32} \cdot k_2 + a_{33} \cdot k_3) \cdot p_3]$$
$$\tag{3.14}$$

Rank determined on this basis is exploitation value of the object in relation to other ranking objects.

The step: classification and selection of technical objects of usage method of maintenance object analysis is to order and select from large group of these objects that have the greatest adverse impact on the functioning of the maintenance staff. In particular, this step includes:

- arranging objects in ascending order – on the basis of the designated ranks of objects, their ordering in ascending take place, where according to the previously adopted positive trend in the method, the least values require the most attention,
- selection of significant objects to the analysis – the developed method of exploitation analysis of objects assumed that ranking is simultaneously subjected to a large number of technical objects, and therefore it is advisable to select those that are most important in the overall outcome of the company in the field of maintenance services. In this case, as a basis for the selection, the Pareto method was assumed. It enables to prioritize factors, influencing investigated phenomenon, that is, by adopting a rule that 20% of the objects causes 80% of the problems (events), for further analysis we select 20% of objects arranged in ascending order in accordance with designated ranks.

Basing on an arrangement and objects selection the table of meaningful objects assessments is prepared. An example of such table is presented as a table 2.

Object	OC_{E1}	OC_{E2}	...	$OC_{T1}n$	OC_{T2}	...	OC_{O1}	OC_{O2}	...
Object 1	5,8298	2,8381	9,2601	8,4817	6,6827	5,9054	9,6167	1,9592	1,2903
Object 2	8,5672	9,5137	7,8592	2,8477	5,215	5,5156	8,8301	6,7208	7,4659
Object 3	8,7513	8,3331	8,1491	4,9275	9,6247	5,3423	2,3966	6,0476	0,5653
...	5,5166	0,1955	4,9398	7,8234	9,2348	8,8092	2,4353	6,715	1,4519

Table 2. Table of meaningful object assessments

The last step of described method is to analyse assessments and values of using and maintenance measures. This step includes an appropriate analysis and formulation of conclusions that are base for corrective activities.

Method of time-series-cross-section analysis

The above described method of maintenance analysis of technical objects (taxonomic method) was carried out under the assumption that it will be the basis for the calculation of weights and measures based on current and historical data on objects, events, and using and maintenance processes. The collected data on values of the indicators, obtained for the following moments / periods of time make it necessary to conduct research on their basis. Objective of the analyses as tasks in this research will be to evaluate the organization (technical objects and their environment) in the selected (current or future) time / selected (actual or future) period of time, and to take appropriate decisions when unfavourable results of these analyses will be obtained. In addition, due to the need to undertake certain exploitation activities in the future and plan ahead by preparing medium – and long – term plans it is necessary to obtain, not only actual but also future data on using and maintenance measures. Therefore, for this purpose it is proposed to use time – series – cross – section analyses methods that take into account not only time, but also the spatial aspect of the using and maintenance processes of technical objects. In the proposed approach the time – series – cross – section will be created by the time series of G variables – using and maintenance measures, describing K objects – geographic locations. The matrix of exploitation measures can be written as block matrix, where every block includes multi – dimensional time series, which characterize k geographic location (Cieślak et al., 2005):

$$M = \begin{bmatrix} M^1 \\ ... \\ M^K \end{bmatrix} \qquad (3.15)$$

where:

$$M^K = \begin{bmatrix} m_{11} & m_{12} & .... & m_{1n} \\ m_{21} & m_{22} & ..... & m_{2n} \\ .... & .... & .... & .... \\ m_{G1} & m_{G2} & .... & m_{Gn} \end{bmatrix} \qquad (3.16)$$

where:

m_{Gn} –   g measure in the moment or interval; this measure in the moment or interval t (g = 1, …, G; t = 1, …, n)

Due to the above needs the two types of tasks should be distinguished. These are:
–   trend or trends detection of data series in the particular data sections of time – series – cross – section, conducted for the determining the specific changes in the organization, which is the subject of evaluation,
–   forecasting, conducted for the determining future values measures, appearing changes in organization,
–   simulation with the use of "what – if?" analyses.

Trends detection for example can be conducted with the use of methods, described in (Cholewa and Kaźmierczak, 1992). They are:
–   'series test' method,
–   Spearman's rank correlation coefficient,
–   ARI (AutoRegressive Integrated) model.

Following these methods will allow to identify specific geographical locations, among k locations, in which there are technical objects for which the occurring trend would indicate

the need to take certain actions, consisting of verification of the correctness of selection of the adopted exploitation strategy, carrying out specific maintenance, repair, etc. Forecasting of measures values could be conducted with the use of (Cieślak et al., 2005):

- simple extrapolation,
- algorithm of expotential smoothing,
- Hellwig's method,
- method based on use of auto regressive models of time series (AR/ARI) and auto regressive and moving average (ARMA/ARIMA) models.

Significant problems that arise when there is need to use the time –series – cross – section is:

- choice of time step (interval between moments of time when measurements of values of measure were conducted),
- constancy of time step; when time step is not the same, there is a need to apply interpolation techniques, which might let to determine values of measure in moments, resulted from the principle of time step constancy without obtained values.

GIS model

An element of the proposed complex model will be GIS one. Its role is to deliver map qualitative and quantitative data for using upper described data processing models, that will be used in decision – making in maintenance management. It is be composed of thematic layers. Each layer contains first of all data on exploited technical objects, but also data on impacts (forces) on technical object / its components. These influences are resulted from appearing selected maintenance conditions in technical object environment (where environment is created by elements of animate and inanimate matter, including people – users and maintainers of technical mean). The concept of the use of GIS model as a component of complex model is shown in Figure 2. Each layer in this figure contains the information stored with the following models:

- spot (examples: bus stops/parkings, trees, traffic signs),
- linear (examples: installations of different type, roads etc.),
- field (examples: mining damages, temperature, humidity of air, solar radiation, wind, fog, storm, rain / snow/ hailstorm, flood, an earthquake, the drought).

Technical objects that affect or do not affect the values corresponding to each force should be assigned to individual layers of the proposed GIS model. The examples of objects contributing to appearing forces on object can be:

- traffic signs (speed limit, values announcing threats, on which driver of vehicle on road is deciding on change of parameters dynamic vehicles),
- buildings,
- green (their localization influences meteorological parameters wind),
- bus stops/parkings (their appearing is contributing change of values parameters describing conditions transport- stop of the vehicle).

All objects on the map have their own characteristics, which are called attributes. There are the following attributes:

- *spatial attributes*; they determine the location, size and geometric shape of the objects and their spatial (topological) relationships,
- *descriptive attributes* define the no – spatial properties and relationships of objects.
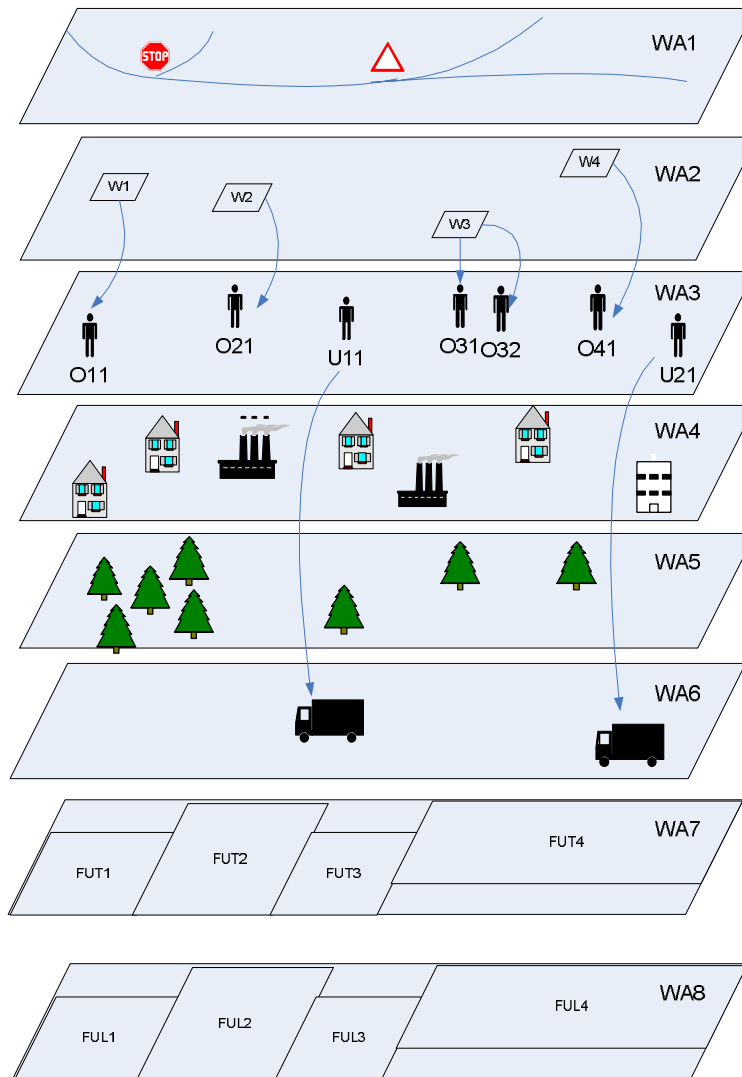
Figure 2. Layers of proposed GIS model (Wieczorek, 2012):
WA1 – layer „Roads", WA2 – layer „Workshops" (where: W1…W4 – elementary workshops), WA3 –
layer „Workers" (where: U11…UNM – users (1…M) assigned to 1…N workshops and O11…UNM –
maintainers (1…M) assigned do 1…N workshops, WA4, WA5 – layers „Forces", WA6 – layer „Technical
means", WA7 – layer „Function of human" (where: FUT1…FUT4 – functions realized by human), WA8 –
layer "Function of technical means" (where: FUL1…FUL4 – functions realized by technical means)

3.2 Possibilities of using proposed model im exploitation management of the selected classess of technical means

It is assumed that the proposed model will be used for the evaluation of the effectiveness, efficiency and reliability in an organization focused primarily on the planning and execution of maintenance tasks of technical means. It was assumed that these tasks will be planned and executed in accordance with RCM strategy (Reliability Centred Maintenance). The plan of tasks to be executed in the future, according to this philosophy, including the tasks relating to specific geographic locations will be obtained, inter alia, as a result of the analyzes of trends in time series data in different sections of measures of assessment of the organization (technical objects and their environment) in time-series-cross-section analyses. The values of parameters to assess trends related to the selected assessment measures of organization if exceed the limit values will be the basis to indicate the geographical location, in which operational tasks should be carried out. For the purpose of the execution of RCM philosophy,

using the model in question there should be considered an extra layer in the proposed GIS model, which is a component thereof. In this layer, on the basis of the specific interactions there will be designated areas of specific functions to respond to the first question of RCM methodology (in accordance with SAE standard) (see: picture 2). Implementation of *TPM philosophy (Total Productive Maintenance)*, using the model in question should include additional measures specific to this philosophy in a set of indicators to assess the organization, in particular the rate of *Overall Equipment Effectiveness*. Implementation of *BCM (Business Centred Maintenance) philosophy*, proposed by Anthony Kelly should also take into account the data and information specific to this philosophy.

Exploitation of technical means in accordance with *Human Centred Philosophy*, as described in (Wieczorek, 2012a) is based on protecting the interests of all participants of the system: human – technical mean – environment. This philosophy assumes that there is a need to reach a compromise between the needs of the organization, expressing itself in ensuring adequate levels of efficiency, productivity and reliability of exploited objects, on the other hand, needs, abilities and limitations of human (user and maintainer) of these objects, and dangers in relationships: human – technical mean. Management within this philosophy will be to make decisions on the basis of measures, among which there will be not only measures of the organization assessments (technical means and their environment), but also a measures of the human. GIS model that will be used in decision – making in terms of this philosophy will have a layers, to which there will be attributed not only the data and information about the objects and the effects on the objects, but also data and information about individuals – users and maintainers of these means. Examples of methods and techniques within described philosophy are shown in (Winkler T. et al., 2013) and (Michalak et al., 2013).

An important issue in activity for using and maintenance of technical means is to consider technical, organizational and economic aspects of decision – making. Particular attention in organizations is increasingly paid to the social aspects of the implemented solutions; more often, therefore, there is the concept of *Technology Assessment*. Subject of interest of the article's author is the issue related to using and maintenance of technical mean. Social needs in the using and maintenance of technical means change themselves not only in time, but they are different for different geographical locations. Therefore it is reasonable to use standard solutions described in the article at the stage of decision – making.

It was assumed that the original model of the organization assessments, as proposed in the article, using the methods of series analysis across the board – the time will be used for the analysis of processes and systems of exploitation of stationary technical means as well as stationary one. First of all, it will be used in the operation of military facilities – vehicles, but also machines of production lines which are necessary in the production of these vehicles.

4 Conclusions

Rational decision making on core activities (manufacturing and services) and secondary (including maintenance) requires a data and information which may be static, but also may change. There is often a need to track these changes and if the values reach a certain value, it is necessary to make these decisions on the basis of them. For this purpose it is necessary to have the appropriate methods and techniques for collecting and processing data and information for this purpose. An example of it can be data and spatial models that allow for

the collection, processing and analysis of these data as a function of time and space. This class of models is still not sufficiently used in the using and maintenance of technical means.

Therefore, the article draws attention to the current state of knowledge and perspectives in the use of spatial models and proposes an original solution of model that allows to calculate exploitation measures. It will provide a basis for further research, taking into account the different solutions to exploitation strategy and philosophy and no-exploitation ones and structures: organizational, informational and decision – making in the exploitation of selected classes of technical means.

In particular, the proposed model will be used in the exploitation of the technical means in the possession of the military and defence industry. These means are exposed to the occurrence of interactions that vary in time and space and affect the values of the assessment of the effectiveness, efficiency and reliability of their exploitation.

5 Acknowledgment

References

Bernhardsen, T. (1990) 'Geographic Information Systems', Arendal, Norway: Viak IT.

Cholewa, W., Kaźmierczak, J. (1992) 'Diagnostyka techniczna maszyn. Przetwarzanie cech sygnałów' ('Technical diagnostics of machines. Processing signals features'), Gliwice, Poland: Wydawnictwo Politechniki Śląskiej (in Polish).

Cieślak, M. (Ed.) (2005) 'Prognozowanie gospodarcze. Metody i zastosowania' ('Economic forecasting. Methods and applications'), Warszawa: Wydawnictwo Naukowe PWN (in Polish).

Karolewski J. (2006): 'Wdrażanie GIS w Katowicach' ('Implementation of GIS in Katowice'), *Wodociągi – Kanalizacja*, No. 11(33), komunalny.pl (in Polish).

Kaźmierczak, J., Loska and A., Dąbrowski, M (2012) 'Use of geospatial information for supporting maintenance management in a technical network system', *21st International Congress on Maintenence and Asset Management. Euromaintenance 2012.*

Kwietniewski, M. (2008) 'GIS w wodociągach i kanalizacji' ('GIS for water and sewage supply network companies'), Warszawa: Wydawnictwo Naukowe PWN (in Polish).

Longley, P. A., Goodchild, M. F., Maguire, D. J. and Rhind D. W. (2008) 'GIS. Teoria i praktyka' ('GIS. Theory and practice'), Warszawa, Poland: Wydawnictwo Naukowe PWN (in Polish).

Loska A, Dąbrowski M., The way of computer aided handling maintenance events and processes in a network technical system, International Conference Maintenance 2011 (Udržba 2011), October 19 – 20, 2011, Liblice, Czech Republic, pp. 177-181.

Loska, A. (2013) 'Exploitation assessment of selected technical objects using taxonomic methods', *Eksploatacja i Niezawodność (Maintenance and Reliability),* No. 15 (1), pp. 1–8.

Michalak D., Rozmus M. and Winkler T. (2013) 'Shaping of Working Conditions Using ICT Technology'. In: Haight J. M. (Editor): Handbook of Loss Prevention Engineering. Vol. 1. Wiley – VCH Verlag GmbH & Co. KGaA, Weinheim, pp. 423 – 443.

Report of research project within European Operational Programme 'Innovative Economy', activities: 1.4 – 4.1 titled: Integrated, intelligent system of monitoring and management of exploitation of water network on the area of the activity of Water and Sewage Supply Ltd. in Rybnik. Data of realization: 01.10.2010 – 30.09.2012 (in Polish).

Savic, D., Walters, G., Ashcroft, P. G. and Arscott, A. (1997) 'Hydroinformatics technology and maintenance of UK water networks', *Journal of Quality in Maintenance Engineering*, Vol. 3, No. 4, pp. 289-301.

Suchecki, B. (Ed.) (2010) 'Ekonometria przestrzenna. Metody i modele analizy danych przestrzennych' ('Spatial econometrics. Methods and models of spatial data analysis'), Warszawa: Wydawnictwo C. H. Beck (in Polish).

Wieczorek, A. (2010) 'Możliwości wykorzystania systemów GIS w określaniu funkcji środków technicznych mobilnych dla potrzeb prowadzenia analizy RCM' ('Possibilities of using GIS systems in a definition of functions of mobile technical means for conducting RCM analysis'), *The International Conference: Systems Supporting Environmental Management*, September, 5-8, 2010, Skalne Mesto, Czech Republic (in Polish).

Wieczorek A. (2012a) 'Needs and opportunities to use the model of the selected features of system: man – technical mean – environment in using and maintenance management in enterprise'. *The Conference: Innovations in Management and Production Engineering,* February 26 – 29, 2012, Zakopane, Poland, pp. 479 – 492.

Wieczorek, A. (2012b) 'Methods and techniques of prediction of key performance indicators for implementation of changes in maintenance organization', *Management Systems in Production Engineering*, No. 1(5), 2012, pp. 5-9.

Winkler T., Tokarczyk J. and Michalak D. (2013) 'Virtual Working Environment'. In: Haight J. M. (Editor): Handbook of Loss Prevention Engineering. Vol. 1. Wiley – VCH Verlag GmbH & Co. KGaA, Weinheim, s. 393-421.

LUT
University of Technology

LUT
Lappeenranta
University of Technology