Chair of Economic- and Business Management

Master's Thesis

Sucker Rod Management - Technical and Economic Evaluation of Changes to Innovative Processes

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Scope of Thesis

To Mrs. **Marlies Juri** the topic

Sucker Rod Management – Technical and Economic Evaluation of Changes to Innovative Processes

is given for elaboration in a master thesis.

In the first part of this thesis, the theoretical foundation shall be built to approach the problem. Hence, it is necessary, to provide the reader the basics of sucker rod systems, especially materials and failure mechanisms. Further, current processes and procedures used for long piece management shall be investigated as well as associated quality assurance/quality control standards. In order to manage sucker rods in an economically viable way, the theoretical part shall cover parameters used for measuring the performance of rod handling.

The focus of the practical part of this thesis is the development of new concepts with different levels of quality assurance and quality control for sucker rod management that are aligned with the needs of the major stakeholders. Therefore, a current state and cost analysis of the processes at OMV has to be performed. Following, based on the theoretical foundation, the required processes for the new concepts, such as a non-destructive testing method, shall be defined. After the technical and economic evaluation of the different workflow patterns, discoveries concerning major cost drivers as well as operational and technical implementation challenges shall be discussed and future recommendations derived. The results are supposed to indicate a clear preference on future investments and hence support the decision - making process at OMV.

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o.Univ.Prof. Dr. Hubert Biedermann

Lehrstuhl für Wirtschafts- und Betriebswissenschaften

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Kurzfassung

Der Pumpgestängestrang ist ein wichtiger Bestandteil der Pferdekopfpumpe, eine künstliche Fördermethode für Erdöl. Er stellt die Verbindung zwischen Oberflächen- und Untergrundinstallation her. Brüche des Gestänges führen zu hohen Reparaturkosten und erheblichem technischen Aufwand. Die Sicherstellung eines reibungslosen, ungestörten Betriebs und die Erhöhung der sogenannten ,,mean time between failure“ (MTBF) sind wichtige Optimierungsziele für OMV.

In den vergangenen Jahren startete OMV Projekte, die sich insbesondere mit der Qualitätsbewertung von gebrauchten Pumpgestängen befassen, um die Minimierung von Ausfällen voranzutreiben. Obwohl es ein Klassifizierungssystem für gebrauchtes Pumpgestänge auf Grundlage von Lastwechseln gibt, findet es in der Praxis keine vollständige konsequente Anwendung. Der aktuelle Inspektionsprozess basiert vorwiegend auf visuellen und empirischen Kriterien. Der Übergang von aktuellen subjektiven zu objektiveren Inspektionsprozessen und die Klassifizierung zur Wiederverwendung sind Aufgabenstellungen, denen es an neuen Ansätzen bedarf. Methoden wie ein RFID-Tracking System und eine zerstörungsfreie Messmethode der Korrosion und Materialermüdungsschäden stellen vielversprechende Lösungen dar.

Die Herausforderung bei der Anwendung dieser Methoden ist die Änderung bestehender Prozesse um eine Integration in den alltäglichen Arbeitsablauf zu gewährleisten. Darüber hinaus sollten diese Abläufe die Grundvoraussetzungen für einen kontinuierlichen Verbesserungsprozess erfüllen. Zudem verursachen diese veränderten Prozesse zusätzlichen technischen und finanziellen Aufwand. Um diese Faktoren zu erfassen, wurde zunächst eine aktuelle Zustandsanalyse bei OMV Austria durchgeführt. Prozesse, die die Handhabung von Pumpgestänge berücksichtigen, wurden von der Deinstallation auf der Sonde, ihrem Transport und ihrer Inspektion im Rohrlager bis zu ihrer Reinstallation in der Sonde verfolgt. Insbesondere der Situation im Rohrlager in Prottes bedarf es an Aufmerksamkeit. Schwachstellen in der Aufbereitung der Gestänge wurden aufgedeckt und Verbesserungspotenziale identifiziert.

Basierend auf diesen Erkenntnissen wurden neue Prozessschritte vorgeschlagen und in Arbeitsabläufe integriert. Das Ergebnis sind vier verschiedene Konzepte mit unterschiedlichen Ebenen der Qualitätskontrolle. Durch die Definition relevanter Parameter wurde für jedes Konzept eine wirtschaftliche und technische Bewertung vorgenommen. Die Analyse zeigt die Hauptkostentreiber für jedes Konzept und die betrieblichen und technischen Herausforderungen für die Implementierung auf. Die Ergebnisse zeigen klare Präferenzen, die das OMV Management bei der Entscheidung über zukünftige Investitionen unterstützen kann. Darüber hinaus enthält diese Arbeit Empfehlungen für neu gestaltete Arbeitsabläufe um eine Implementierung zu unterstützen.

Abstract

The sucker rod string is one of the most vital parts of sucker rod pumps, an artificial lift system for oil production. It provides the link between surface and subsurface equipment. Nonetheless, sucker rods are subject to failure, which leads to high expenses for repair and technical efforts. Ensuring smooth, undisturbed operations and increasing the mean time between failure (MTBF) are major optimization goals for OMV.

In recent years OMV has started projects which especially address the quality evaluation of used sucker rods, in order to approach the minimization of sucker rod failures. Though a classification system of used rods based on load cycles exists, it does not find complete application in practice. In addition, the current inspection process is based only on visual and empirical criteria. The transition from current subjective to more objective inspection processes and to classify them for reuse, are subjects that need to be addressed. Methods such as an RFID system and a non-destructive testing method of corrosion and fatigue represent promising solutions.

The challenge for applying these methods is the change of existing processes to integrate them into everyday work. Furthermore, they should fulfill the base requirements for establishing a continuous improvement process. Moreover, the change to these processes results in additional technical efforts and financial expenses. In order to capture these factors, first, a current state analysis in OMV Austria was carried out. Processes considering sucker rods were followed from the de-installation from the well, their transport and inspection at pipe yard until reinstallation in the well. Especially the situation at the pipe yard in Prottes was subject to research. Weaknesses in the processing of the sucker rods were uncovered and potential for improvement was identified.

Based on these findings new process steps were recommended and integrated into workflow patterns. The result is presented in four different concepts with different levels of quality assurance and quality control (QA/QC). Through the definition of relevant parameters, an economic and technical evaluation was applied and each concept ranked accordingly. This analysis showed major cost drivers for each concept and operational and technical challenges for implementation. Results show a clear preference which shall support OMV management to decide on future investments. In addition, the thesis gives recommendations for redesigned workflow patterns to support implementation.

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Abbreviations

add. … additional

avg. ... average

AISI …American Iron and Steel Institute

API … American Petroleum Institute

ASNT … American Society of Nondestructive Testing

boe … barrel of oil equivalent

e.g. … exempli gratia/ for example

ft … feet

GAE … Gänserndorf

GDB … general database (OMV)

in … inch

lb … pounds

N/mm^2 … Newton per square millimeter (SI unit, N/m^2)

NDT…non-destructive testing

m … meter

MFL … magnetic flux leakage

MTBF… mean time between failure

Pa … Pascal (SI unit)

psi … pounds per square inch (Imperial unit, US customary unit)

PT … production technology

PY … pipe yard

QA … quality assurance

QC … quality control

RFID … radio frequency identification

SF … safety or service factor

SR … sucker rod

TIR … total indicated run-out gauge

WI … well intervention

WO … work over

WLAN … wireless local area network

1 Introduction

In recent years OMV started special efforts to increase its efficiency in the production of oil. Therefore methods, processes, workflows, maintenance and operating criteria for their artificial lift installations are investigated. One of these goals is to increase the mean time between failures (MTBF) of sucker rod pumps. Sucker rod pumps consist of various parts that are prone to failure that can cause downtime of the well production. Statistics demonstrate that failures and resulting repair in sucker rod operated wells as well as the installation, handling and renewal of equipment are an important cost factor in the overall economics for producing oil.

1.1 Problem Description

Currently OMV is re-using sucker rods based on empirical operations criteria paired with visual inspection. Several projects and studies are ongoing, which investigate and determine objective criteria for classification. The latest effort is the implementation of radio frequency identification (RFID) tags where sucker rods are marked individually and therefore allow exact tracking of each individual rod respectively to its running and operation parameters. In addition, a new non-destructive testing method for sucker rods is developed and supposed to be tested for application at the pipe yard in Prottes. The migration of the sucker rod classification system from empirical based to more objective quality assurance and quality control (QA/QC) based criteria requires changes in the current processes and procedures of handling, evaluation, storage and management of the sucker rods.

1.2 Project Objectives

The thesis studies the necessary modifications to the actual processes as well as introduces new processes and evaluates the economic impact of the change. The outcome of the study provides recommendations for process changes described in concepts with different levels of QA/QC. These concepts are evaluated for their economic and technical effort. Criteria to compare these concepts are defined and listed in a ranking matrix. The thesis shall give the OMV management a sound idea about required effort, operational changes, cost and benefit of the objective classification method(s) and helps taking decisions on future investments.

2 Theoretical Part

The purpose of this part is to give an overview of artificial lift systems, especially sucker rod pumping systems and sucker rods as important components of this pump. Furthermore, it provides information about quality control and assurance methods and parameters as well as handling recommendations for sucker rods described in literature.

2.1 Artificial Lift Principles

The natural flow of a well is ensured by the balance of two pressure requirements at the bottom of the well. First, the pressure must be high enough to lift the fluids to the surface and second, it must be low enough to create an inflow from the reservoir. Due to natural depletion, the reservoir pressure declines over time and reaches a point where it is not able to meet the required pressure balance anymore.[1] Therefore artificial lift systems are installed. They lower the bottom hole flowing pressure to enable the inflow from the reservoir and provide enough energy to overcome the flow restrictions (e.g. hydrostatic pressure and fluid flow friction) along the well path. The outcome is production at all from the well or an increase in the production rate and an extended life of the well.[2] The selection of the most suitable lift system depends on various parameters such as reservoir type, fluid properties, desired production rate, pressure regime, surface facilities, infrastructure and economic evaluation.[3]

2.1.1 Sucker Rod Pump System

The most common artificial lift systems are downhole pumps. With a share of over 80% of artificial installations, sucker rod pumps are the most widely used type of downhole pumps in the industry. The long history of sucker rod pumps plays a big role in the popularity of this pump.[4] At the beginning of the oil and gas industry in the 19th century, sucker rod pumps were the first or only choice for artificial lift applications in shallow reservoirs. First, the rods were made of wood such as ash or hickory and at the end of the century, iron sucker rods were used. With the beginning of the 20th century carbon-steel box-and-pin rods were introduced.[5] Nowadays, sucker rod pumps are still common devices for lifting low to moderate liquid volumes from approximately 10 to 150 m^3/day and operating in shallow and medium-well depths up to 3500 m.[6] The increasing popularity throughout the years and numerous proven operations make it a favorable option. System components are easily available around the world and the technical

[1] Cf. Lyons, W. C. (1996) pp.570-571
[2] Cf. Takács, G. (2015) pp.1-2
[3] Cf. Hofstätter, H. (2019a) p.1
[4] Cf. Takács, G. (2015), pp. 7–8
[5] Cf. Beckwith, R. (2014) p.102
[6] Cf. Stewart, M. (2019), pp. 441–455

installation, operation and analysis of the pump performance are well known. Since it operates with very small lifting volumes and low intake pressures, it can be used until the very end of the well. Changes to the pumping capacity are easily accomplished too. One of the disadvantages of sucker rod pumps is, that they handle free gas very poorly. Gas causes a reduction of liquid production and mechanical problems for the pumps. The rod string is the connection of the surface motor to the downhole pump and transmits the drive energy to the pump. The reciprocating movement and continuous load cycles make it a very sensitive part of the pumping system. Corrosion is the main cause to start fatigue failures. Therefore, they must be protected with corrosion inhibitors. Further in deviated wells it is also exposed to high friction loads often leading to mechanical failures of the string and/or production tubing.[7] Sand and many other factors reduce the lifetime of the pump as well.[8]

The next section provides a short introduction to the working principle and the most important components of a sucker rod pump. The pumping system is divided into two parts regarding the equipment placement: the surface and downhole system (Fig. 1).[9]

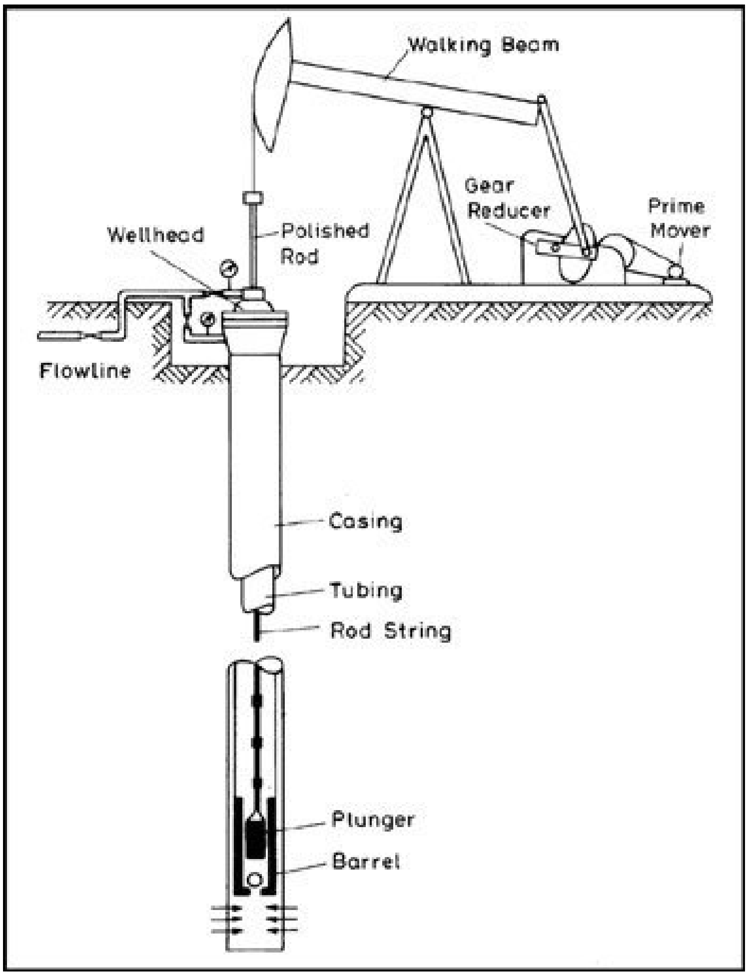

Figure 1: Sucker rod pump components[10]

[7] Cf. Takács, G. (2015), pp. 7–12
[8] Cf. Obersriebnig, J. (2016), p. 22
[9] Cf. Takács, G. (2015), p. 59
[10] Adapted from Takács, G. (2003), p. 13

The surface components consist roughly of a prime mover, a gear reducer and a pumping unit. The prime mover such as an electric motor, diesel or gas engine is used to power the pump. The gear reducer adjusts the high rotational speed from the prime mover to the pumping speed and the pumping unit transforms the rotary motion to the reciprocating vertical motion to operate the sucker rod string and furthermore the downhole installations. The pumping unit consists of the walking beam which commutes over the saddle bearing and the horsehead which is via steel wire ropes and the carrier bar connected to the polished rod. The polished rod therefore connects the surface pumping unit to the sucker rod string. A stuffing box seals off the polished rod and the tee to ensure that fluids are traveling into the flow line. The downhole components include the sucker rod string and the downhole pump. The sucker rod string runs through the tubing into the well. It creates the connection between the surface equipment and the downhole pump. Directly connected to the rod string is the plunger, which is the moving part of the downhole pump. It contains the traveling valve which opens during the downstroke and closes while moving the plunger upwards. The stationary part is composed of the pump barrel and the standing valve. This valve opens during the upstroke movement of the plunger to suck the fluid into the barrel (Fig. 2).[11]

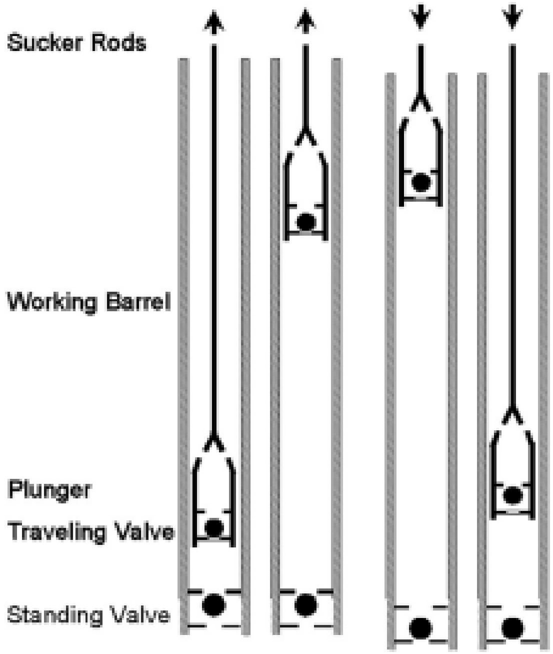

Figure 2: Upstroke and downstroke principle of a sucker rod pump[12]

The operation principle of a sucker rod pump is relatively simple (Fig. 2). When the upstroke starts, the traveling valve in the plunger closes, allowing the fluid column to be lifted to the surface. At the same time, the pressure drop in the barrel allows the standing valve to open. Due to the underpressure in the barrel and the well pressure, the fluid enters the barrel. The barrel is filled up until the end of the upstroke. When the downstroke starts, the standing valve closes and the traveling valve opens up. Fluids

[11] Cf. Takács, G. (2003), pp. 11–12
[12] Adapted from Takács, G. (2015), p. 62

now travel from the barrel through the plunger into the tubing string. When the plunger meets its lowermost position, the next cycle begins.[13]

2.1.2 Sucker Rods

The sucker rod string is considered the most critical part of the sucker rod pumping system. Providing the link between the surface installations and the subsurface pump, it plays a vital role in the efficiency of the system. A proper design is essential for reassuring safe operations. There are different types of rods available though the most common ones are solid steel rods. Since this thesis focuses on sucker rods made of steel, they will be described in more detail in the following sections.[14]

Solid steel rods

The solid steel rod is the most common used rod type in the industry. The American Petroleum Institute (API) developed various standards for the design as well as the care and handling of rods. According to API Specification for Sucker Rods 11B, the recommended length of a rod is 25 or 30 feet with a diameter of 5/8 in., 3/4 in., 7/8 in., 1 in. or 1 1/8 in.[15] The alignment of the single sucker rods, connected through threads with each other, creates the sucker rod string. The rod can be either a one-piece or a three-piece rod. The difference lies in the design of the connection. Usually, a one-piece rod is manufactured with two upset ends with threads. In case of lower strength designs and for the application in shallow wells, three-piece rods are used which have separate connectors screwed on each end. [16] [17] To meet the required string length eventually pony rods are used which are shorter than conventional sucker rods.[18]

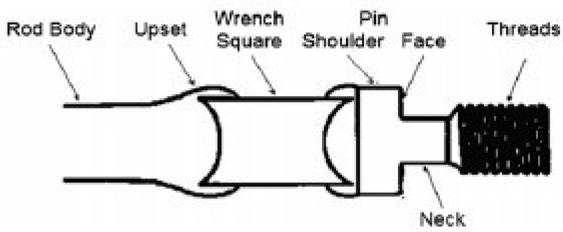

Figure 3: Sketch of a sucker rod pin end[19]

In detail, one-piece rods consist of two pin ends with male threads and a female thread coupling attached to one end. A so-called wrench flat or wrench square is used as an assistance for easier make-up (Fig. 3). [20]

Generally, full-size couplings allow the connection of the individual sucker rods. In case of limited spacing in the tubing, slim-hole couplings are also available. The outside

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[13] Cf. Takács, G. (2003) pp.13-14
[14] Cf. Takács, G. (2015) p.126
[15] Cf. API (2010) p.17
[16] Cf. Takács, G. (2015) pp.126 -128
[17] Cf. Mitra, N. K. (2012) pp.71-72
[18] Cf. Schlumberger, https://www.glossary.oilfield.slb.com/en/Terms/p/pony_rod.aspx (Retrieved: 12.08.2019)
[19] Adapted from Takács, G. (2015), p. 127
[20] Cf. Takács, G. (2015) pp.126-127

diameter of this type is smaller than of full-size couplings, but they are considered as weak links since they are not able to carry the same amount of loads. Sub couplings are used to connect two different thread sizes (Fig. 4). The joints of sucker rods play an important role considering the stability and integrity of the sucker rod string and of course the pumping system as a whole.[21]

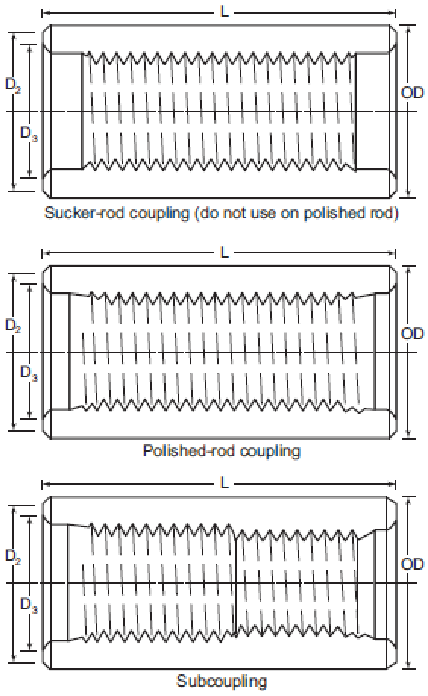

Figure 4: Different types of couplings for sucker rods[22]

Steel sucker rods have various advantages since they are easily available and are quite inexpensive compared to other rod material types. Manufacturers offer a wide selection of materials for steel rods and their mechanical properties and material grades are standardized by the API. This makes it easier for the user to choose the right rod and compare manufacturers. Individual defective rods or rod sections can be removed and exchanged with completely new or used rods without exchanging or discarding the whole string. Furthermore, steel sucker rods support tensile and compressive loads. Regarding the design, rods strings can be designed as a taper, so upper sections which have to endure more weight load are stronger than rods that are placed in a lower section where they have to endure less weight load. To prevent wear, rod guides can be placed on the rod body.[23]

Steel sucker rods also have their disadvantages since they are quite heavy which increases the load for the pumping unit. In addition, they are very prone to corrosion and have to be effectively inhibited for downhole conditions. Considering their storage and transport large spaces are required. Running and retrieving sucker rods takes up a lot of time since they have to be threaded together.[24]

[21] Cf. Takács, G. (2015) p.128
[22] Adapted from API (2010), p. 6
[23] Cf. Takács, G. (2015), pp. 126–136
[24] Cf. Takács, G. (2015), p.126, pp. 137–142

Polished rod

The polished rod is the uppermost part of the rod string and connects the rod string to the surface pumping unit. The purpose of the polished rod is to transfer the loads from the string to the surface pumping unit and to carry the full load of the string. In addition, it creates a hydraulic seal with the stuffing box around the rod string.[25] Therefore it must have a smooth surface and has to be sprayed occasionally with a coating to guarantee the integrity of the system. Compared to regular sucker rods, they only have male pins without an upset. Therefore, special polished rod couplings have to be used to ensure a tight connection. [26]

Special equipment

The next section describes auxiliary equipment for sucker rods. The described tools are used to ensure proper performance of the string and to decrease the occurrence of failures, e.g. due to extensive wear.

<u>Rod guides</u>

Rod guides are used to protect the sucker rods and tubing from wear. The rod guides center the rod along their path through the tubing and minimize their lateral movement.[27] Especially in deviated wells the rod and tubing have to endure high frictions. Rod guides avoid the direct contact between the metals reducing material wear especially at the contact of the couplings with the tubing wall.[28] Rod guides are made of thermoplastics. Common basic materials are Polyamide 66 (PA66) or often referred simply as Nylon, Polyphenylene Sulfide (PPS) and Polyphtalamide (PPA).[29] Depending on the operations temperature regime and the application environment, manufacturers list specific service limitations for their rod guides. Manufacturers also like to add glass fibers, aramid fibers or mineral fillers to alter the material properties.[30] [31] Glass fibers or aramid fibers increase the tensile strength and add toughness to the material. Mineral fillers (e.g. calcium carbonate, talc or silica) can improve the moldability (reduction in shrinkage while cooling) and stability of thermoplastics and are often used to reduce material costs. [32]

Rod guides are generally molded on the rod body. Alternatively, clamp-on guides exist which can be applied in the field. Molded guides are advantageous but have to be applied by a manufacturer and need a special machine to be installed. Guides are placed on the rod using injection molding. But before the process of injection molding starts, the section where the rod guide is placed is coated and a layer of sand is applied on the rod to improve bonding. Generally, molded guides have the advantage of high bonding strength, reducing the probability of displacement. The string is then placed in a machine where a mold device is installed around the rod body. The thermoplastics are melted and injected into the cavity of the mold. When the material cooled down and is solidified, the

[25] Cf. Hofstätter, H. (2019b) p.18
[26] Cf. Takács, G. (2015) pp.185-187
[27] Cf. Takács, G. (2015) p.188
[28] Cf. National Oilwell Varco (2019), p. 2
[29] Cf. Weatherford (2016), p. 5
[30] Cf. Weatherford (2016), p. 5
[31] Cf. Tenaris (2018), pp. 43–44
[32] Cf. Mraz, S. (2015)

mold is removed. A weld line is then visible at the rod guide. This is the section where the mold tool was parted to be removed from the rod. It is also usually the point where the two flow fronts of the melted thermoplastics met when they traveled around the rod body. Weld lines are considered as weak points of the rod guides. It is an area of lower strength of the material and guides are likely to break at this point. Sections of insufficient coating and the transition section from the coating to the rod body are further weak points for the rods when exposed to corrosive environments. Also, if the guide breaks, the whole rod must be removed. [33] [34]

Rod guides that are field installed have the advantage that they can be easily applied and removed from the rod, e.g. to inspect the rod body. They are hammered on, twisted on or two pieces are slid together on the rod. They are usually cheaper than molded guides and easier available. Field-installed rod guides have lower bonding strength to the rod body than molded guides and are therefore prone to displacement. Then the rod guides are not able to sufficiently protect the rod and tubing from wear anymore. [35]

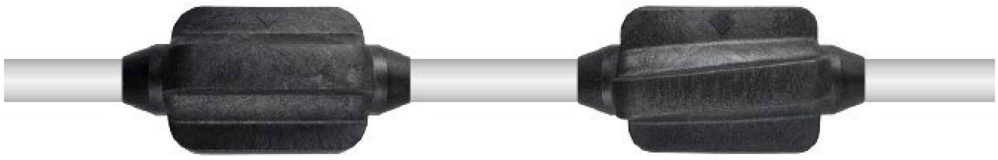

Figure 5: Straight and slanted vane rod guide[36]

To select the right rod shape the erodible wear volume (EWV) has to be considered. The erodible wear volume is the amount of rod guide material outside of the coupling diameter that can be eroded due to the abrasive motion against the tubing wall during the pumping cycle. The higher the EWV, the higher the expected guide life.[37] Rod guides come in various sizes and shapes, e.g. guides with straight vanes or slanted vanes (Fig. 5). Slanted rod guides reduce flow turbulence and can act as scrapers to remove paraffin build-up. Paraffin accumulation can block the flow path and reduce production rates. For heavy paraffin accumulations, reciprocating slides can be installed between two molded guides for easier removal.[38] Field-installed guides are often installed as reciprocating sliders.[39]

<u>Rod rotators</u>

A rod rotator is placed on top of the polished rod between the carrier bar and the polished rod clamp. It applies torque to rotate the sucker rod string. It is connected to a stationary part via a cable to activate an actuator lever which turns the cover cap above the polished

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[33] Cf. Varotsis, A. B. (2019)
[34] Cf. Blair, K. (2000), p. 14
[35] Cf. National Oilwell Varco (2019), pp. 21–26
[36] Adapted from Weatherford (2016), p. 10
[37] Cf. National Oilwell Varco (2019), p. 10
[38] Cf. Weatherford (2016), pp. 10–11
[39] Cf. National Oilwell Varco (2019), pp. 19–20

rod.[40] Its aim is the distribution of wear evenly around the rod string and the removal of paraffin from the tubing inside. [41]

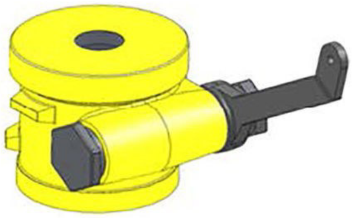

Figure 6: Sketch of a rod rotator[42]

<u>Sinker bars</u>

Sinker bars are used to apply more weight on the string during the downstroke.[43] They keep it in tension and straight which reduces sidewall forces as well as rod and tubing wear. Since they have a bigger diameter than sucker rods and are run just above the pump, sinker bars help to avoid the occurrence of buckling of the string. [44] Buckling occurs when the compressive stresses in the rod string are above a critical level. Consequently, the rod string cannot endure these stresses anymore and forms a helical shape in the tubing leading to failure of the pump system.[45] They are usually placed at the end of the rod string and right above the pump. Their weight should overcome the compressive forces at the bottom of the string. [46]

Materials

Sucker rods are usually made of steel with an iron content of more than 90%. To achieve the desired material properties like high strength and hardness, different alloys are used.[47] In addition, the steel structure is altered and optimized by treatment processes like tempering, normalizing, quenching and case hardening.[48]

The API Standard SPEC 11B recommends the classification of three rod grades: K, C and D. [49] The material specification is given by the American Iron and Steel Institute (AISI). It consists of a four-digit number. The first two numbers give information about which type of material is selected for this steel and the last two numbers about the carbon

[40] Cf. Takács, G. (2015) pp.190-192
[41] Cf. National Oilwell Varco, https://www.nov.com/Segments/Completion_and_Production_Solutions/Process_and_Flow_Technologies/Artificial_Lift/Rod_Pump_Systems/Rod_Rotators.aspx (Retrieved: 08.08.2019)
[42] Adapted from The Weir Group, https://www.global.weir/products/product-catalogue/rod-rotators/ (Retrieved: 16.12.2019)
[43] Cf. Weatherford (2006) p.60
[44] Cf. Takács, G. (2015) p.192
[45] Cf. Takács, G. (2015), pp. 107–108
[46] Cf. Takács, G. (2015) p.192
[47] Cf. Takács, G. (2015), p. 135
[48] Cf. Mitra, N. K. (2012), p. 73
[49] Cf. API (2010), p. 2

content present in the steel. [50] According to API SPEC 11B, the following materials should be used for the API grade specification:

Table 1: Overview API Grades and recommended chemical composition given by AISI [51]

API Grade	Chemical Composition (AISI)	Details
K	AISI 46XX Series Steel	Molybdenum steel with nickel. Ni 0.85-1.82%, Mo 0.20-0.25%
C	AISI 10XX Series Steel	Plain carbon steel, Mn 1.00% max
D Carbon	AISI 10XX Series Steel AISI 15XX Series Steel	Plain carbon steel, Mn 1.00% max Plain carbon steel, Mn 1.00-1.65%
D Alloy	AISI 41XX Series Steel	Molybdenum steel with chromium, Cr 0.50-0.95%, Mo 0.12-0.30%
D Special	Special alloy composition	Combination of Ni, Cr and Mo with min. total of 1.15% alloying content

Since Grade C is the plain carbon steel rod, it is the least costly rod type but should be applied only in non-corrosive environments and for average pumping loads. Grade K is used in mildly corrosive environments. Grade D rods endure higher stresses but should be used in non-corrosive or effectively inhibited wells.[52]

The following table shows the tensile strength limitations of API grades:

Table 2: Mechanical strength properties of steel rod API SPEC 11B [53]

API Grade	Minimum Yield 0.2% Offset psi (Mpa)	Minimum Tensile psi (Mpa)	Maximum Tensile psi (Mpa)
K	60,000 (414)	90,000 (620)	115,000 (793)
C	60,000 (414)	90,000 (620)	115,000 (793)
D	85,000 (586)	115,000 (793)	140,000 (965)

[50] Cf. Total Materia, https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=kts&LN=EN&NM=333 (Retrieved: 13.08.2019)

[51] Adapted from Total Materia, https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=kts&LN=EN&NM=333 (Retrieved: 13.08.2019)

[52] Cf. Mitra, N. K. (2012), p. 73

[53] Adapted from API (2010), p. 3

Rod design

The design for the rod string is the first essential factor to optimize the lifetime of a rod and prevent failures due to undersizing and overloading. To design the ideal sucker rod string, all loads acting on the string must be defined. A proper design method that calculates these loads, provides the information to choose the correct rod size, length and material for the desired application. When determining the loads, the essential property of the sucker rod string is its elastic behavior. Due to forces acting at the surface and downhole at the subsurface pump. Elastic force waves that travel at the speed of sound through the rod are produced. The waves are of different magnitudes and phases. They interfere and reflect, influencing the actual loads occurring in the string. Since the elastic behavior of sucker rod strings is a very complex matter, it is often difficult to calculate the parameters by hand and with simple calculators. They are more easily solved with the help of special computer programs that can solve the damp wave equation.[54]

The main forces and loads that are acting on the string are tension, compression and friction forces as well as fluid and dynamic loads. Tension force occurs due to the weight of rods distributed along the string. Each rod has to carry the weight of all rods below and therefore tension a constant static force throughout the whole cycle. In downstroke, the force acts in the direction of the displacement and is called a positive force. Compression force is a buoyant force and opposes the rod weight. It describes the lift of the rod string caused by the fluid. The density difference between the material and the fluid effects this force. During downstroke, the rod moves downwards into the fluid and the buoyancy force of the fluid acts upwards. It acts in the opposite direction of the rod movement. The force is called negative. Friction forces are caused by viscous forces acting because of the contact between rod string and the produced fluid. If the rods move upwards, the fluid moves with the rods and the friction force acts against the rods. During the downstroke, the rods move downwards and the viscous forces act against them. Therefore, the mechanical friction opposes the movement. Due to the fluid load which is equal to force of the hydrostatic net pressure of the fluid in the plunger. It is a concentrated force acting at the bottom of the string only during the upstroke, the fluid in the plunger moves with the rod string upwards and is positive. Dynamic loads are results of changes in acceleration during the pumping cycle of the moving rods and fluid column. Magnitude and direction are constantly changing but are usually positive for the upstroke and negative for the downstroke.[55]

During the complete pumping cycle, the sucker rod string has to endure cyclic loading. This cycle of alternating high and low stress leads to fatigue of the material. Therefore, the endurance limit of the material has to be considered in the design. During the upstroke, tension increases due to the load of the fluid lifted, the dynamic loads and the friction forces. During the downstroke, only the buoyant weight load is positive, dynamic loads and friction forces are subtracted. [56] [57]

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[54] Cf. Takács, G. (2015), pp. 141–142
[55] Cf. Takács, G. (2015), p. 143
[56] Cf. Takács, G. (2015), p. 144
[57] Cf. Mitra, N. K. (2012) p. 74

A common design method for sucker rod strings is described by the API with API TR 11L Design Calculations For Sucker Rod Pumping Systems in addition to API BULL 11L3 Sucker Rod Pumping System Design Book.[58] [59] The basis of these calculations is the Goodman diagram.[60] It is used for displaying the endurance limit of materials. The mean stress σ_m [Pa or psi] on the x-axis of the graph is plotted against the alternating stress σ_a [Pa or psi] on the y-axis. The mean stress σ_m [Pa or psi] is the arithmetic mean of the maximum and minimum stress. The alternating stress σ_a is the difference between the peak stresses and the mean stress. The point σ_{fat} [Pa or psi] stands for the fatigue strength in terms of stress amplitude where σ_m is 0. This means that the material is subject to alternating tensile and compressive stress of the same value. It is under fully reversed loading. σ_{ts} [Pa or psi] displays the ultimate tensile strength of the material (Fig. 7). The Goodman relation (Eq. 1) therefore says that the fatigue life of a material is decreased with increasing mean stress in correlation with given alternating stress. If the coordinate lies under the line given by the Goodman relation, then it should not fail under the given stresses. Is the coordinate above the line, then the part is in the unsafe region and is very likely to fail. [61]

Equation 1

$$\sigma_a = \sigma_{fat}\left(1 - \frac{\sigma_m}{\sigma_{ts}}\right)$$

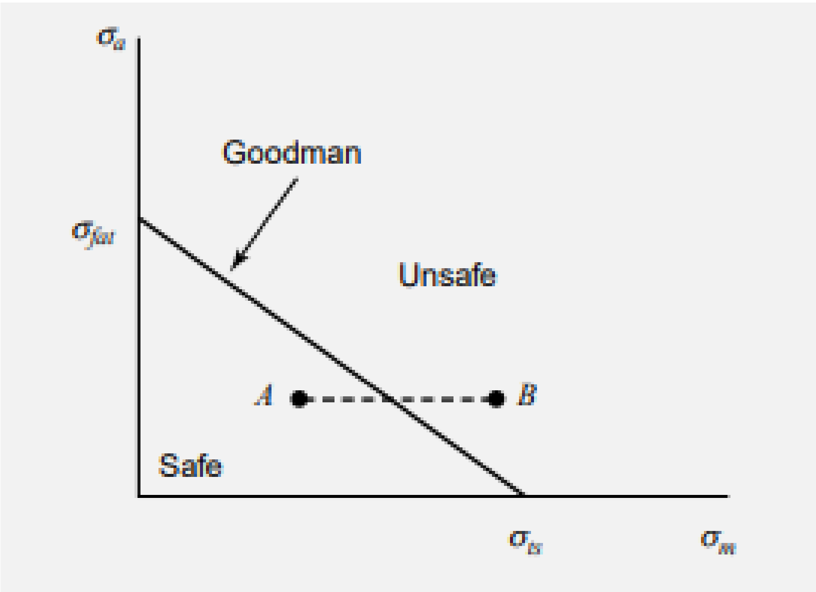

Figure 7: Goodman diagram[62]

[58] Cf. Hofstätter, H. (2019b), p. 17
[59] Cf. API (2019), pp. 21–22
[60] Cf. Mitra, N. K. (2012), p. 74
[61] Cf. Hertzberg, R. W. et al. (2013), pp. 506–508
[62] Adapted from Hertzberg, R. W. et al. (2013), p. 507

However, the original Goodman diagram is not accurate enough to calculate the loads of the sucker rod string. In order to apply it to sucker rods, the following modifications have been made: [63]

- The maximum tensile stress must be less than the yield strength.
- Compression is not allowed, it causes buckling. The minimum stress value is set at zero. The diagram portion left of the zero ordinate is eliminated.
- The y-intercept should have a safety factor of two, reducing the intercept to the tensile strength T_a [N/mm² or psi] divided by four.
- A safety factor on the tensile strength apex is recommended with 1.75.
- A safety factor or service factor (SF) is added considering that exposure to corrosive environments can cause severe damage.

See Eq. 2 and Fig. 8 for the modified equation and diagram to calculate the maximum allowable stress S_a [N/mm² or psi]in the rod material with the minimum tensile strength S_{min} [N/mm² or psi] of the material.

Equation 2

$$S_a = SF\left(\frac{T_a}{4} + 0.5625\ S_{min}\right)$$

The outcome, the modified Goodman diagram (Fig. 8) was introduced by the API and is still in use nowadays. [64]

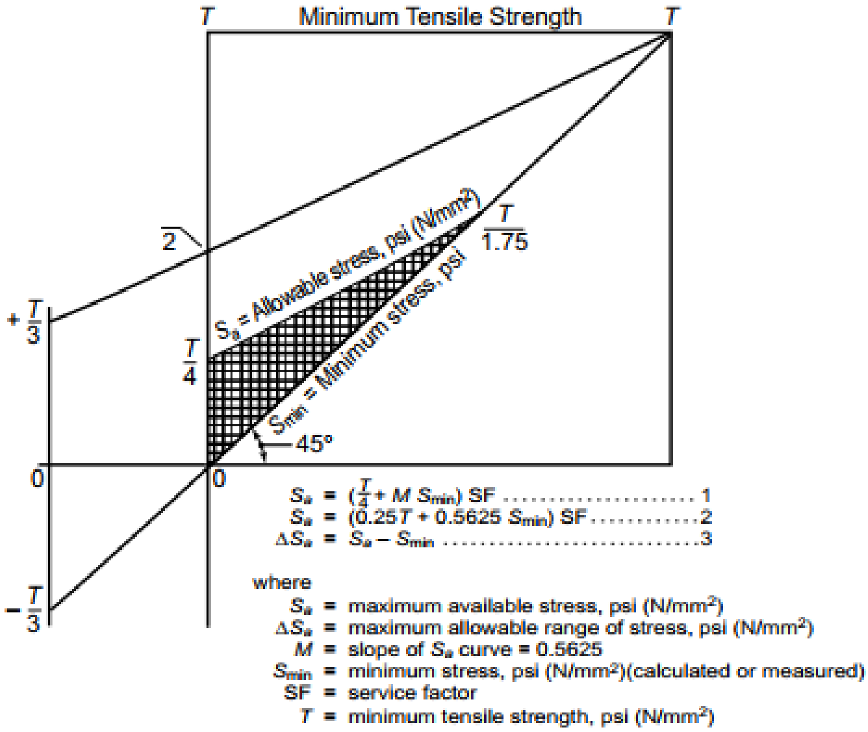

Figure 8: Modified Goodman Diagram - Stress Diagram for Allowable Stress and Range of Stress for Sucker Rods in Non-corrosive Service by API [65]

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[63] Cf. Parameswaran Nampoothiri, M. P. (2001), p. 17
[64] Cf. API (2008b), p. 3
[65] Adapted from API (2008b), p. 3

The described calculation guideline is applicable to API standardized sucker rods. Manufacturers with products that differ from these standards, generally specify calculation modifications for their rod materials.[66]

According to this standard, the following steps are required to achieve a design:

- A preliminary selection of components for the installation and operating conditions. This includes the plunger diameter, pumping speed, stroke length and sucker rod string design. Corresponding values should be taken from API 11L3 and 11L4.
- The operating characteristics of the preliminary selection are calculated using API 11L. Including all relevant parameters, such as desired production, load, stresses, horsepower, torque when using a rod rotator etc..
- The calculated pump displacement and load are compared with the values of the preliminary selection. Modifications and changes to the component`s selection are then made to meet the selection criteria and safety factors according to company regulations.[67] [68]

The minimum required information and the calculated output parameters are presented in Table 3.

Table 3: Input and output parameters for sucker rod design given by API 11L [69]

Input parameters	Output parameters
Fluid level (H) in ft	Plunger stroke (Sp) in inch
Pump depth (L)in ft	Pump displacement (PD) in barrels /day
Pumping speed (N) in strokes per minute (SPM)	Peak polished rod load (PPRL) in pounds (lb)
Length of surface stroke (S) in inch	Minimum polished rod load (MPRL) in lb
Pump, plunger diameter (D) in inch	Peak crank torque (PT) in lb-in
Specific gravity of the fluid (G)	Polished rod horsepower (PRHP)
Tubing diameter in inch	Counterweight required (CBE) in lb
Sucker rod composition	

Additionally to the API 11B recommended calculation guideline, computer programs are in use to give more accurate design solutions and prediction of the performance of the string.[70] These programs, for example RodStar are able to predict rod loads that are calculated by solving the damped wave equation, so the solutions do not have to rely on approximations like they are described in the API design procedure. [71]

[66] Cf. Takács, G. (2015), p. 155
[67] Cf. API (2008a), pp. 6–7
[68] Cf. Hofstätter, H. (2019b), p. 19
[69] Cf. API (2008a), p. 7
[70] Cf. Bradley, H. B. (1987), pp. 9–3
[71] Cf. Takács, G. (2015), p. 174

Failure mechanisms

To guarantee a proper working pumping system and cost control, the management and minimization of sucker rod failures are main priorities. Classification and root cause analysis are the first steps to improve operations and the mean time between failure (MTBF). Systems to document and report failure occurrences are established to take preventive and corrective actions. This section describes the most important mechanisms and root causes of sucker rod failures.[72]

Operating failures

Abrasive wear of the rod string through contact with the tubing can become a massive problem for the whole artificial lift system. Rod material is removed by the abrasive motion induced by the pumping cycle. The cross-section of the string or the coupling is reduced or protective coatings are removed. The cause for extensive wear is often a not properly centered or guided sucker rod string. Also, a combination of compressive rod loads due to fluid pound or gas interference that forces the string to bend, deviated wellbores or the displacement of the tubing string are reasons that lead to a decentered sucker rod string.[73]

Rod guides help to keep the string centered and prevent the contact between the sucker rod string and the tubing wall. However, with the installation of this equipment, another failure mechanism can occur. The wash area at the lower end of the rod guide is critical to corrosion. If the guides are not entirely bonding to the rod body, fluid can settle in small openings and initiate crevice corrosion. The contact points of the rod surface, the coating, and the molded rod guides are starting points for this type of corrosion.[74]

Fatigue

One of the most critical failure mechanisms for sucker rods is fatigue. It is the tendency of a metal to fracture under cyclic stressing. Failures occur at stress levels below the yield point and after the repetitive influence of cyclic loading.[75] They start with small ruptures at the rod surface that act as stress raisers. The cause of this rupture is either mechanical damage, corrosion or deformation of the rod. Wear or rubbing on the tubing in deviated wells also creates severe damage to the material. Small cracks propagate further. The metal cross-section is reduced, and the stress is locally concentrated inducing an overload in the material. The load cycles continue and at some point, the material is not able to carry the load anymore. The sucker rod breaks. The examination of the break face is essential to identify this failure cause. Fatigue breaks show two different areas, a smooth and a coarse area (Fig. 9). The smooth area is formed by the two break faces rubbing together while enduring the load cycles. The coarse area is formed by the tensile stretch that occurs before the rod finally breaks.[76]

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[72] Cf. Bradley, H. B. (1987), pp. 9–8
[73] Cf. Norris (2007), pp. 6–8
[74] Cf. Norris (2007), p. 8
[75] Cf. Oberndorfer, M. (2018), pp. 30–31
[76] Cf. Takács, G. (2015), pp. 180-181

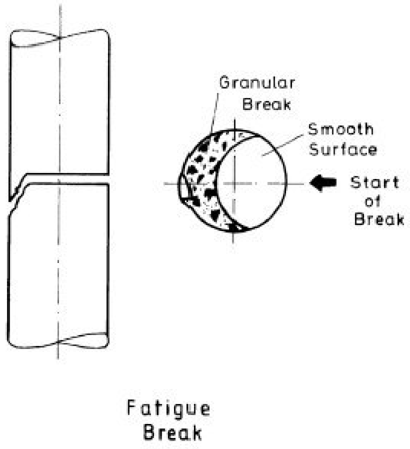

Figure 9: Sketch of a fatigue break face [77]

Tension breaks

Pure tensile breaks are relatively rare. The material is stretched due to overload to a point where the tensile strength of the material is exceeded, resulting in a break. This can be avoided by limiting the pull to 90% of the yield strength. The break face of a tensile break is coarse and shows a granular surface (Fig. 10). If the rod is stretched, little cracks can form which act as stress raisers and initiate the process of fatigue failure. [78]

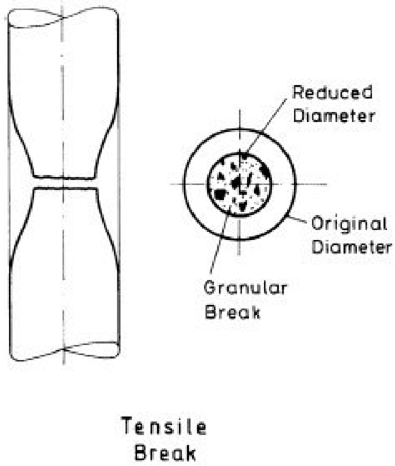

Figure 10: Sketch of a tensile break face [79]

Deformation, surface damage and connection failure

Damages to the rods can be caused by improper handling of the rods, careless make-up and break-out procedures and bending. Sucker rods experience an increase in local stress at the point of the bend during applied load. During the load cycles, the rod is bent and straightened. Repeatedly, the ultimate material strength is exceeded. This leads to the creation of a stress fatigue crack. Points of surface damage act as stress raisers as well. The type of damage and orientation influence the magnitude of stress. Transverse

[77] Adapted from Takács, G. (2015), p. 179
[78] Cf. Takács, G. (2015), pp. 179–180
[79] Adapted from Takács, G. (2015), p. 179

damages and deep, sharp nicks contribute to higher stresses than longitudinal or shallow damages. [80] Failures in connections occur due to improper make- up of sucker rods and therefore loss of tightness. If the preload on the connections is insufficient, the pin shoulder and the coupling face will not stay in contact. The pin threads are held partly by the coupling, but the undercut section is bent under cyclic loading which leads to little cracks at the bend section or the root of the threads. The process of fatigue failure is initiated. Tensile failures can occur due to overloading the joint by applying too much make-up torque. Failures due to cross-threading are often caused when threads are damaged and have not been adequately inspected. Failures of couplings are similar to pin failures. Often a loss of tightness, the development of a crack and further fatigue failure are causes of the break. The cracks which act as stress raisers can be formed inside the coupling or outside.[81]

Corrosion failures

Corrosion occurs when the material is chemically or electrochemically reacting with the environment leading to a deterioration of the material and its properties. The rod is exposed to the fluids in the well. These fluids can contain different corrosive components like CO_2, H_2S or bacteria which initiate corrosion pitting and therefore cracks. This leads to the combined action of corrosion and fatigue since the crack acts as a stress raiser and the high cyclic loads encourage fatigue. Corrosion can also lead to the reduction of material area causing a tensile break. Corrosion failures can be avoided by a proper material selection and by an effective inhibition program with chemicals for sucker rods.[82]

Common types of corrosion that furthermore initiate the failure mechanism of corrosion-fatigue are:

Sour corrosion: H_2S is present in the well and creates corrosion pits. The pits are often small and sharp. The indications for H_2S corrosion are a black iron sulfide scale on the rod and the smell of rotten eggs. The iron sulfide scale covers the sucker rod and the pit. The scale is highly insoluble and cathodic to steel and enhances the rate of corrosion. [83] Besides, hydrogen can penetrate the surface of the rod and causes damage to the material. It can travel into small voids and combine into molecules that cannot diffuse from the void, accelerating the pressure and causing blistering, it can also react with the steel components to form hydrogen compounds that cause embrittlement.[84]

Sweet corrosion: When CO_2 combined with water is present in the well, carbonic acid is formed. Together with the iron in the metal, it forms iron carbonate which will deposit in the pits. Compared to H_2S, pits are usually larger and the metal loss is bigger. [85] The corrosion severity increases with CO_2 partial pressure and temperature. [86]

[80] Cf. Norris (2007), p. 10
[81] Cf. Takács, G. (2015), pp. 182–183
[82] Cf. Norris (2007), p. 16
[83] Cf. Norris (2007), p. 17
[84] Cf. Oberndorfer, M. (2018), pp. 91–92
[85] Cf. Bradley, H. B. (1987), p. 9
[86] Cf. Norris (2007), p. 17

Figure 11: CO_2 corrosion on sucker rods [87]

Oxygen: If oxygen is present with water in the well, the corrosion process is very fast. The pits are usually shallow and broad-based. It is important to prevent the entry of oxygen into the system as good as possible. Weak points are often surface facilities or a not properly sealed off flow line. [88]

Bacteria: Deterioration of a metal can also occur through the activity of living organisms in the well. The most important ones are sulfate reducing microorganisms. They reduce sulfate to sulfide and furthermore H_2S is formed in the well. [89]

Crevice corrosion: This type of corrosion takes place inside a crevice when metals or metals and non-metals overlap. A corrosive fluid that acts as an electrolyte is trapped in a crevice created through insufficient bonding of the materials. Anodic and cathodic processes occur at the surface of the metal. Oxidation takes place in the crevice. Oxygen molecules in the stagnant fluid are depleted forming hydroxide. The metal surface becomes anodic. The excess of positive charged ions in the crevice needs to be compensated. Chloride ions or other types of anions from the solution outside of the crevice migrate into it. A local electrochemical corrosion cell is formed. The metal is further attacked, and corrosion pits are created. These pits act as stress raisers and again the process of fatigue failure is initiated. [90] As mentioned before, this type of corrosion is often experienced near the rod guides.

2.2 Current Processes and Procedures of Long Piece Management

The management of goods including their tracking, handling, storage and transport is an important factor for ensuring smooth operations. The following sections describe solutions for the identification of goods as well as storage and transport solutions especially for long steel bars like sucker rods. An RFID system is currently tested for application in OMV Austria by tagging sucker rods.

2.2.1 RFID System

Radio frequency identification (RFID) is an object identification, tracking and data collection technology. The working principle is based on radio waves that allow wireless data transmission. The technology is used by various industries for improving their

[87] Adapted from Norris (2007), p. 20
[88] Cf. Bradley, H. B. (1987), p. 9
[89] Cf. Oberndorfer, M. (2018) pp. 93-95
[90] Cf. Mouritz, A. P. (2012), pp. 493–520

inventory management, data management and quality control by tracing products during different processes and life-cycle stages. [91]

An RFID system consists of three main components which include (Fig.12):

- A transponder or RFID tag which is directly attached to the product. The microcircuit of the transponder contains a unique identification code.
- A reader which is needed to receive the signals emitted by the tag.
- An antenna, usually attached to the reader that emits radio waves to amplify the signal from the reader to activate a tag and to return the signal from the tag to the reader. [92]

The reader is connected via a server to a database and an information management software. The information of the individual tags is then visualized through a stationary computer or a handheld device.[93]

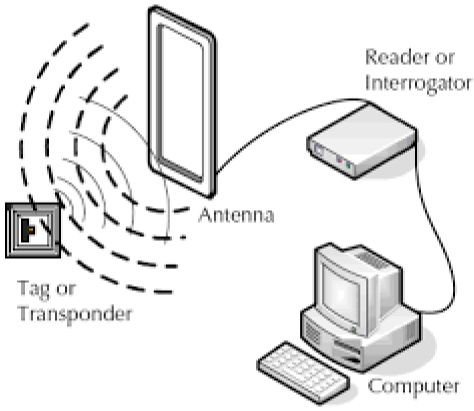

Figure 12: Main components of an RFID system [94]

Tags

The major types of RFID tags are active and passive tags. Active RFID tags have an internal power source and memory that allows them to store data directly. The advantage of an active tag is the wide read range, but they are bigger in size and more expensive than passive tags. Passive tags need power generated from the reader to emit a signal. This signal is then received by the reader and the information is interpreted. Passive tags are more cost-effective but have a lower reading range. A third option are semi-passive tags which combine some characteristics of active and passive tags. This type of tag contains an internal battery to power the microcircuit but needs a reader to be activated. [95]

Frequencies

An RFID system can operate in a low, high or ultra-high frequency field. Low frequency (120-140 kHz) tags have a reading range from 0-0.5 meters whereas high (13.56 MHz)

[91] Cf. Li, N.; Becerik-Gerber, B. (2011), p. 1089
[92] Cf. Liukkonen, M. et al. (2014), p. 9
[93] Cf. Liukkonen, M. et al. (2014), p. 9
[94] Adapted from Abou El Majd, B. (2014), p. 1
[95] Cf. Li, N.; Becerik-Gerber, B. (2011), p. 1090

and ultra-high frequency (868-928 MHz) tags can be read in a distance up to 100 meters.[96] [97]

Applications

RFID has numerous application fields. Majorly it is used as a tracking system for individual components and hence can be applied for sucker rods as well. Some examples of application fields are outlined below.

Tracking and supply system

RFID technology has a big application field in tracking products or components. The real-time information distribution enables the company to track the product through various processes and update the status of the product to establish a life cycle monitoring system. Companies can use this technology in storage areas to identify individual products and to update their stock levels. The information gained through the traceability of the product is furthermore assessed and used to optimize inventory and supply management. [98]

Construction management

In construction projects, RFID tags are used to track and secure assets by sending information to the site manager if assets have been taken. These assets are often structural steel components. [99] When the components are received at yards, they need to be documented. Gates with installed readers can capture the RFID information while the truck passes through them. The information is then automatically sent to the database. Otherwise, the tags have to be manually read with handheld readers. During the assembly process, RFID technology is used to reference the assembly history in the database. Every time the status of an individual component changes, the data is updated. By tracking the individual components, the manager is able to monitor the status and progress of projects. This can be used to control cost and time efficiency and to recognize possible delays and take early actions. [100] [101]

Quality assurance/control

Inspection and certification processes are data intensive. The data gained from such methods are inspection reports, results from testing facilities, certifications and specifications. These data sets need to be connected to the individual inspected components. Through the unique identification code, the results from various QA/QC methods can be linked to the desired component. The status of the inspected object is then changed whether it passed the inspection or not. The information can be accessed

[96] Cf. Liukkonen, M. et al. (2014), p. 33
[97] Cf. Li, N.; Becerik-Gerber, B. (2011), p. 1090
[98] Cf. Li, N.; Becerik-Gerber, B. (2011), pp. 1091–1092
[99] Cf. Motamedi, A.; Hammad, A. (2009), pp. 243-244
[100] Cf. Li, N.; Becerik-Gerber, B. (2011), p. 1092
[101] Cf. Motamedi, A.; Hammad, A. (2009), p. 244

through the database or if active tags with storage activity are used, saved directly on the tag. [102]

Data structure

Information for every component should be updated with RFID based systems throughout the full lifetime of the product. Life cycle information of the tagged component is stored in the database or if tags with storage capability are used, a subset directly on the tag. For easier data management and life cycle analysis, it is recommended to define a specific data structure. Furthermore, special software should be assigned for read and write competences.[103]

Benefits of an RFID System

Considering life cycle management, products can be traced, and information related to different life stages can be captured and stored in a database. This information can be used to apply an accurate life cycle analysis. Processes are more visible, and the information exchange is improved. In warehouse and storage management, entrance and exit processes can be carried out faster with multiple tag reading. Access to storage location information and tracking of individual components is possible through a data management system. In addition, inspection or repair history can be connected to the individual tag ID in the database or directly on the tag. This would provide more accurate quality control and assurance management. [104]

Challenges and limitations

Noises that interfere with the RFID signal and shortened readability range, radio waves when reading multiple tags are topics of concern. Also, there is no international standard for RFID systems currently available. Therefore, interference with tags and readers from different manufacturers might be possible.

- Costs for active tags and infrastructure for all stakeholders to achieve seamless communication must be considered.
- Design and implementation strategies, process changes, investment for infrastructure must be defined and evaluated.
- Data security and protection are issues that need to be taken care of. [105]

RFID in the oil and gas industry

In the oil and gas industry, the RFID system is used as a helpful tool for improving computational and physical infrastructure. RFID tags have the advantage that they are applicable in harsh environments. The major goals for the application of an RFID system in the oil and gas industry are an improvement of quality control and information supply for decision making, optimization of production schedules, increase of production, reduction of human errors and tracking of real-time inventory status and therefore decrease overall operating costs. RFID can be used in all parts of the supply chain from

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[102] Cf. Li, N.; Becerik-Gerber, B. (2011), pp. 1092–1093
[103] Cf. Motamedi, A.; Hammad, A. (2009), p. 247
[104] Cf. Motamedi, A.; Hammad, A. (2009), p. 252
[105] Cf. Motamedi, A.; Hammad, A. (2009), pp. 253–254

exploration to delivery of end products. In asset management RFID is used for linking history data of usage to every individual pipe or flange via a tag. This information includes operating information like temperature, flow rate velocities and mud composition. In yards, the tags are used for identification and selection for reuse. Through maintenance services, the information is updated until products reach the final stage and must be disposed of. Handheld readers or readers at gates are used to read the information. [106]

Latest developments allow to track RFID's in real time when production pipe and sucker rods are run into the well. A solution for using the RFID system with sucker rods is described in chapter 3.3.1.

2.2.2 Transport and Storage Management Systems

The following chapter summarizes the research on transport management systems for long goods. It lists different storage and transport solutions for handling of long goods such as pipes and steel bars. These systems are currently not used at the pipe yard in OMV Austria but are part of the investigation for improvement regarding transport and storage systems.

Service companies in the oil and gas industry provide systems for the transport, handling and inspection of tubular goods. These management systems often include ID tracking like RFID, special inspection treatments according to API standards and storage or transport solutions to avoid damages to the rods.[107] [108] [109]

Solutions for transport of tubular goods can be stack systems. Designed for long term usage and durability, these systems could lead to more safety and need specific handling.MSI Pipe Protection Technologies provides such a handling system with Rhino® Tubular Handling Systems (Fig. 13). It is manufactured under ISO standards and is designed for drill pipes, casings or tubings. Their advantage and features are that they are simple to stack, eliminate metal to metal contact and allow high density stacking and therefore less storage volume. They also have special lifting tools for proper handling and easy transport of the packages. [110]

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[106] Cf. Felemban, E. A. et al. (2013), pp. 80–83
[107] Cf. Omni-ID, https://www.omni-id.com/oil-gas-industry/ (Retrieved: 14.02.2020)
[108] Cf. National Oilwell Varco, https://www.nov.com/products/sucker-rod-inspection-services (Retrieved: 14.02.2020)
[109] Cf. Cobalt, https://www.cobaltextreme.com/Sucker-Rod-Inspection.html (Retrieved: 28.06.2019)
[110] Cf. MSI Pipe Protection Technologies, https://essentrapipeprotection.com/rhino-tubular-handling-systems/ (Retrieved: 14.12.2019)

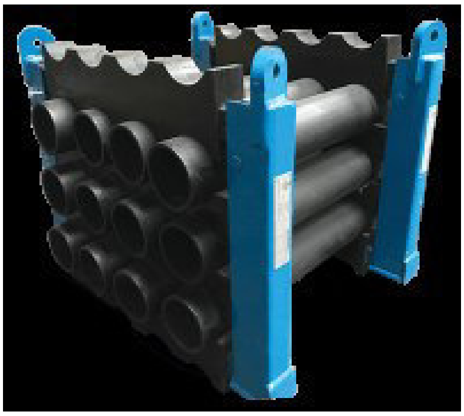

Figure 13: Rhino® Tubular Handling System [111]

At OMV in Austria, transport systems for new sucker rods from manufacturers are often constructed with plastic and wood elements to avoid damage to the rods. Rods are placed layer by layer in a frame system with plastic layers separating the sucker rods. Sometimes individual layers are held together by a steel frame (Fig. 14) that must be screwed together at the top.

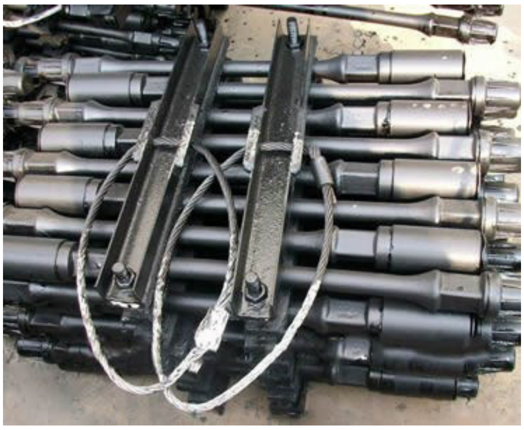

Figure 14: Steel frame with plastic separators and bolts screwed together at the top[112]

Another option is to use a wooden frame that must be fixed with a metal band. This solution is displayed on the left in figure 15. It shows new sucker rods in a transporting and storage system from the manufacturer Tenaris. Boxes out of wood are used as well but are often unstable and not fit for long term storage (Fig.15). Lifting eyes are provided for loading and handling with T- shaped hooks or slings.

[111] Adapted from MSI Pipe Protection Technologies, https://essentrapipeprotection.com/rhino-tubular-handling-systems/ (Retrieved: 14.12.2019)
[112] Adapted from Baotou Liande Oil and Mechanical, http://suckerrodchina.com/suckerrod/sucker-rod.html (Retrieved: 17.12.2019)

Figure 15: Transport and storage solutions for sucker rods at OMV pipe yard in Prottes

2.3 QA/QC of Sucker Rods Proposed by Industry

Proper quality management is essential to ensure a consistent fulfillment of the requirement for materials or services and is an important success factor for companies. Standards and regulations help to implement quality management systems in companies to achieve their goals and create competitive advantages. The purpose of quality assurance is to prevent mistakes and defects of goods by implementing testing and inspection methods. Quality control focuses on the process or procedures that are carried out to check the quality of a product. The goal of these methods is to guarantee operational safety and overall reduce operating costs. [113] In this case, increasing the mean time between failure (MTBF) of sucker rod installations. Throughout the industry manufacturers and service companies are offering special programs and packages for material testing and inspection of sucker rods as well as systems for inventory management. In general, the industry differs between two testing groups: destructive testing and nondestructive testing.

2.3.1 Destructive Testing Methods

Destructive testing is often used when materials are procured from new manufactures or when it is necessary to perform periodically quality control and assurance tests.

Tensile test

The test object (Fig.16), a metal, is pulled apart at a constant rate. The tensile load applied divided by the cross-sectional area of the test object, equals the stress. The

[113] Cf. Manghani, K. (2011), pp. 34–35

change in gage length divided by the original gauge length gives the strain. The tensile testing results should give a stress-strain curve. This curve provides information about the tensile properties like yield strength, ultimate tensile strength and breaking strength of the material.[114]

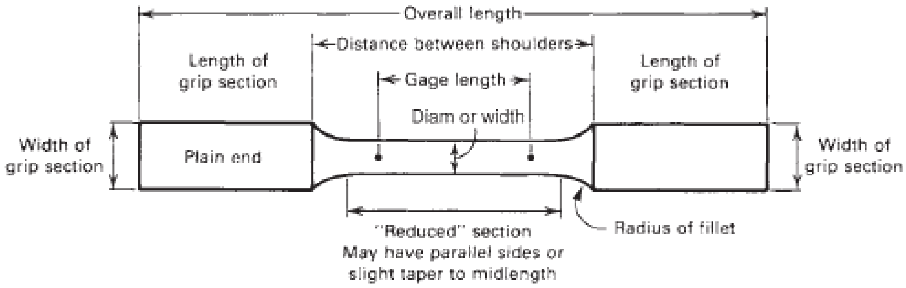

Figure 16: Test specimen for tensile testing method [115]

Hardness test

Hardness tests are used to determine the ultimate tensile strength of the material and to approximate the yield strength. Two typical testing methods are the Brinell and the Rockwell hardness test. For the Brinell test, a hard steel ball usually from steel or tungsten carbide with a diameter of 10 mm is pressed onto the surface of a metal object. The typical load that is applied is 3000 kg (Fig. 17). The diameter of the indentation is measured and the Brinell hardness number is calculated in addition to the applied load.[116]

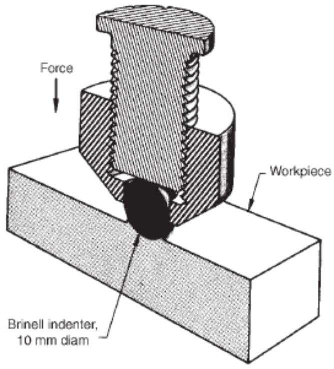

Figure 17: Schematic of the Brinell test method, the steel ball is pushed into the material [117]

For the Rockwell tests spherical and cone shape indenters are available. The most common one is a diamond cone with an angle of 120° with a spherical apex having a 0.2 mm radius. During the Rockwell test, two different loads are applied to the material. The first load is a minor load with 10 kg. The major load can be up to 150 kg. [118] The minor load applied is held constant for a period and the depth of the indentation is measured. Then the second load is applied and again held for a specific time. The major force is

[114] Cf. Oberndorfer, M. (2018), pp. 22–23
[115] Adapted from Oberndorfer, M. (2018), p. 22
[116] Cf. Campbell, F. C. (2013), pp. 85–91
[117] Adapted from Campbell, F. C. (2013), p. 86
[118] Cf. Campbell, F. C. (2013), p. 91

then released and returns to the minor force and is held again. Again, the depth of indentation is measured, and the two depths are compared. The difference in height is then used to calculate the Rockwell hardness. [119]

Notch toughness

Notch toughness tests help to identify the amount of energy that can be absorbed during fracture of the material and the ductile to brittle temperature. Since fracture behavior is strongly dependent on the temperature, the test is carried out at different set test temperatures. At high temperatures, fractures are likely to deform in a ductile manner and at low temperatures in a brittle manner. The test is carried out with a pendulum with a specific weight and length that is dropped from a specific height to hit the specimen of material. The specimen has a notch on one side to allow easy fracture. The different angles of the hammer from the drop to the impact, from the specimen and after the impact are used to calculate the absorbed energy. The results are used for material selection[120] [121]

Corrosion testing

Corrosion testing is used to investigate the alteration of material under environmental influences. The conditions by which the material will be surrounded in the field are simulated in special temperature- pressure vessels, so-called autoclaves. The material in the form of coupons is exposed to not only temperature and pressure conditions but also various chemicals, liquids and gasses like water, H_2S and CO_2. The coupon in the autoclave is either static or stirred. The simulation takes place at least five days. After the test, the weight loss of the material is observed and the corrosion rate (mm/year) is estimated. [122] [123]

Chemical analysis

Chemical analysis is used to provide information about the composition of the material. It controls if the alloys meet the required values. There are various test methods available to perform this analysis.

Optical emission spectrometry (O.E.S.): electrical energy is applied via an electrode to the sample. Through this process the surface of the metal sample heats up and vaporizes, enabling the atoms to excite. This leads to the emission of characteristic emission lights for each element.[124]

X-ray fluorescence spectrometry (XRF): AN X-ray beam impinges on an element, electrons are ejected, and their energy is released sending out secondary x-rays. The energy emitted depends on the electron's distribution. From the intensity of this energy, the quantity of the element can be determined in the material.[125]

[119] Cf. Wiederhorn, S. et al. (2006), pp. 314–315
[120] Cf. Oberndorfer, M. (2018), pp. 27–28
[121] Cf. Wiederhorn, S. et al. (2006), pp. 343–344
[122] Cf. Oberndorfer, M. (2018), p. 158
[123] Cf. MagnaSafe, https://magnasafe.com/products/corrosion-testing-autoclaves.php (Retrieved: 05.09.2019)
[124] Cf. Shimadzu, https://www.shimadzu.com/an/elemental/oes/oes.html (Retrieved: 14.02.2020)
[125] Cf. Cheremisinoff, N. P. (1996), pp. 73–75

Inductive coupled plasma atomic emission spectrometry (ICP-AES): A metal sample is vaporized, and the element atomizes in a hot argon plasma. The atoms collide and emit characteristic spectra which are detected which a special vacuum tube or so-called photomultiplier tube that are sensitives detectors of light. [126]

2.3.2 Non-Destructive Testing

NDT inspection is used by manufacturers or by the buyer to control and assure the quality of the produced goods. NDT testing is also applied to inspect used products to decide if they are still suitable for installation in the field or are outranged and must be deposed. The following section describes common inspection methods that are used in the oil and gas industry to inspect sucker rods. The most common methods are visual and electromagnetic inspection.

Visual inspection

It is probably the first method used for inspecting objects and to reject faulty pieces. The inspector looks at the surface of the object to check its characteristics. Discontinuities in finish and color are noticed and bigger cracks, scratches and corrosion are detected. Visual inspection is executed by direct viewing with the naked eye or with the help of devices like magnifying glasses, mirrors, microscopes or computers assisted viewing systems. The disadvantage of this method is the subjective valuation of the examiner of the potential flaws and it is only applicable to surfaces or openings.[127]

Electromagnetic inspection

This section describes especially eddy current and magnetic flux leakage inspection methods.

Eddy current method

The eddy current method is an electromagnetic test applied to electrically conductive materials. The change in electrical conductivity caused by cracks, corrosion, heat affected area and coating irregularities is detected. Equipment needed for this test are a generator, a test coil and recording equipment. The working principle is based on the interaction of the magnetic field and the test material. Because it is an electromagnetic induction technique it does not require direct contact with the test object, however, the distance from the object needs to be as close as possible. The further the object is away from the coil the higher the noise, which reduces the accuracy and reliability of the measurement. [128]

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[126] Cf. Cheremisinoff, N. P. (1996), pp. 45–46

[127] Cf. ASNT, https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT (Retrieved: 05.09.2019)

[128] Cf. Campbell, F. C. (2013), pp. 215–216

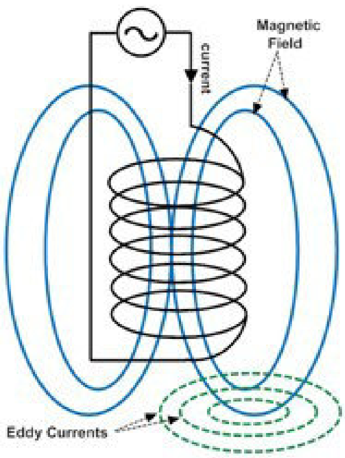

Figure 18: Two different magnetic fields are displayed, the field around the coil in blue is the primary electric field induced by a current, the field in green represents the flow of the eddy currents. [129]

The object is placed inside a coil or the coil is placed near the object. The generator then produces an alternating current which is sent through the test coil and generates a magnetic field all around the coil. If an object, for example, a tube, passes through or by the coils the effective current increases. This happens because the magnetic field induces currents (eddy currents) in the tube circumferential to the coil (Fig. 18). In addition to the primary magnetic field, the eddy currents induce a secondary magnetic field (Fig. 19). The two fields counteract. If the coil passes over a crack, the eddy current flow is impeded and flows in a different direction. This causes changes to both electromagnetic fields. These changes are monitored and observed by alterations of the electrical impedance and the induced voltage of the coil. The signals coming from the measurement of these parameters are then sent to the amplifier and are filtered for noise and demodulated by a computer. The final output is then displayed on an oscilloscope or a chart reader and must be interpreted by the user.[130]

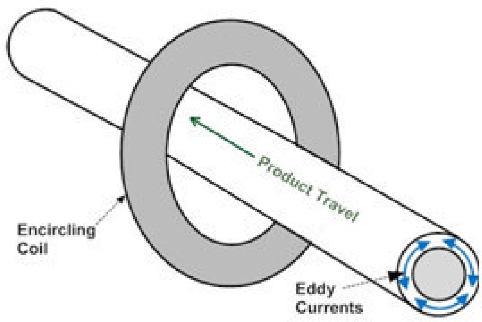

Figure 19: A sample of tube is shown passing through the encircling coil, the flow of the eddy currents in blue is parallel to the coil arrangement and flow circumferential. [131]

[129] Adapted from ASNT, https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT (Retrieved: 05.09.2019)
[130] Cf. Campbell, F. C. (2013), pp. 216–218
[131] Adapted from ASNT, https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT (Retrieved: 05.09.2019)

For the inspection of steel bars, such as sucker rods, usually encircling coils are used. Encircling coils though have the disadvantage that the detection flaws orientated parallel to the eddy currents is difficult. A solution is to rotate the encircling coil or test piece at high speed and apply spiral scanning. Coils are the most common used test probes for eddy current inspection.[132]

The advantages of this method are the high sensitivity to detect surface defects like cracks and corrosion pits with little preparation and cleaning of the test object. Even through surface coating and multi-layer structures measuring the layer thickness of the coating is possible. In addition, no direct contact of the material with the sensors is needed but of course, the further the object is separated from the sensors, the lower is the resolution and accuracy. Furthermore, it can be automated, given the potential for a rather fast inspection and the test equipment can be made portable. It can be used to detect wall thickness and localized discontinuities. However, the method is limited to conductive materials that support the flow of an electric current. Defects that are parallel to the surface are hardly detectable with encircling coil probes if they do not deviate and cross with the eddy currents. Therefore, rotating coils can be used and multiple coils or special coil probe configurations with array probes must be used to detect flaws in all orientations. Reference samples must be used to set the tester sensitivity. [133] [134]

Magnetic flux leakage

Magnetic flux leakage is a method to detect defects via a change in magnetic flux through a testing object. To execute the inspection, the test object is magnetized with a permanent magnet, current flow or magnetizing coils. The object is magnetized almost to saturation to induce a strong magnetic field. This makes the method more sensitive. If the magnetic flux in the object crosses a defect the magnetic flux lines leak out around the position of the defect (Fig.20). This is due to the reduction of the effective permeability and the cross-sectional area at the defect. The fluxes leak in three different directions. These directions are described as the axial, radial and tangential components. With the help of sensors, these flux directions can be measured, and the shape and size of the defect can be investigated. The sensors, usually an array of Hall effect sensors, are placed between the poles of the magnet bridge. They give a voltage signal proportional to the flux density of the magnetic field in the testing object. Noises can be eliminated by passing the signal through high-pass and low-pass filters with suitable cut-off frequencies. Large noises are usually eddy current signals which occur through the movement of the magnet over the surface. Much sharper noises with high frequency are induced through surface roughness and permeability variations in the testing object. [135] [136]

[132] Cf. Campbell, F. C. (2013), p. 333
[133] Cf. TWI, https://www.twi-global.com/technical-knowledge/faqs/faq-what-are-the-advantages-and-disadvantages-of-eddy-current-testing (Retrieved: 18.09.2019)
[134] Cf. Campbell, F. C. (2013), p. 231
[135] Cf. Bhagi, P. C. (2012) pp. 7-12
[136] Cf. Drury, J. C. (2018), pp. 2–3

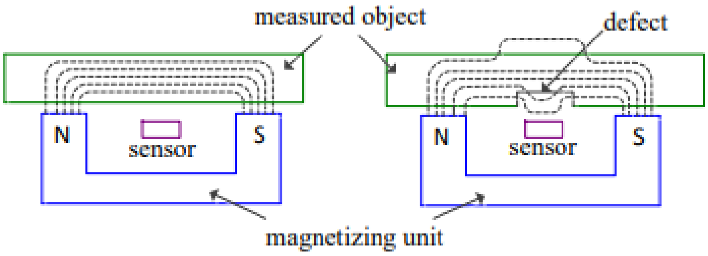

Figure 20: The dashed line indicates the magnetic flux lines, flowing from north to south. [137]

One of the advantages for this method is that it is very fast if automated. Furthermore, it has high surface sensitivity and can be used combined with other electromagnetic inspection methods for better indications. The method is although limited to ferromagnetic materials and signals might need interpretation because the method is very sensitive to velocity changes.[138]

2.3.3 API 11BR – Care and Handling of Sucker Rods

The API standard 11 BR contains various recommendations and descriptions of procedures to ensure proper handling and quality assurance for sucker rods. The following paragraph represents a summary of the recommendations for inspection of used sucker rods and couplings, as well for the transportation, handling, storage, running and pulling of sucker rods. OMV Austria states their handling, storage and transport specification in an internal guideline based mostly on recommendations from the API standard. Further information about procedures in OMV is outlined in chapter 3.1.1 to 3.1.4.

Inspection of sucker rods and couplings

The standard 11 BR recommends a combination of various inspection methods that have been described in the sections before. This includes especially visual and electromagnetic inspection methods. According to this standard, visual inspections should focus on the detection of damage, corrosion or wear. The area near the guides should draw special attention since often discontinuities in the coatings at or under the rod guide are weak points. Severely bent and kinked rods should be rejected immediately as well as rods with clear signs of mechanical damage and rod wear. To complete the inspection, the rejected rod shall be clearly separated from the acceptable rods and tagged or marked within 18 inches of either shoulder with red paint. The acceptable rods should then be lubricated at the threads before applying pin protectors. A corrosion inhibitor should be applied to the rods.[139]

[137] Adapted from Han, W. et al. (2014), p. 10362
[138] Cf. Bhagi, P. C. (2012), pp. 7, 13–14
[139] Cf. API (2008b), pp. 9–14

Handling, transportation, storage, running and pulling

In regards to handling rods, they should be inspected on delivery to avoid that damaged rods are placed in the storage. Every sucker rod should have thread protectors on both ends. Packaged rods should be stored as a packed unit until the run in the well. For handling the sucker rods only material and tools that are non abrasive to the rods should be used. If they are unloaded at the wellsite, they should be placed on service racks. The racks should be placed away from vehicles and traffic. Racks shall have at least three supports. Sucker rods in packages should be lifted and laid down using a forklift or crane without damaging the rods. Unpacked sucker rods have to be handled individually and single sucker rods must be carried at two points. Directly walking on rods should be avoided by using wooden planks as support when walking on the packages.[140]

Sucker rods should be transported in packages inside protected cases or placed on special racks on the vehicle shelves in a horizontal position. Blockages for transportation should be placed directly under the crosswise supports of the package. The blockage should not touch the sucker rods. Sucker rod packages should be stacked so the bottom supports rest squarely on the top of the lower package. Tie-down chains, straps or cables should pass over the crosswise supports without contacting the rods. They should prevent movement of the packages during transportation. Sucker rods in packages should be lifted and laid down using a forklift or crane without damaging the rods. [141]

Unpackaged rods should have cross supports near the rod ends and at least two other equally spaced intermediate positions. Spacers between the layers of sucker rods should be long enough to reach beyond the length of the stack at both sides. If the spacers are not notched to prevent the rods from falling off, they need to be chocked with blocks on the ends. It is recommended to sort sucker rods according to size and grade. They should be stored at locations with minimum exposure to corrosive environments. They be stacked on racks or sills covered with a material that should protect the sucker rods from abrasion. Packages should be stored on racks under each support of the package and stacks should be in vertical alignment. Stored rods should be inspected regularly, cleaned with a brush and sprayed with a preventative that does not become fluid under 52 °C. Used rods should be lubricated and covered with clean thread protectors.[142]

At the wellsite, after the protectors are removed from the threads, the rods should be inspected for damage and be if necessary, cleaned before running into the well. When the single rods are tailed into the mast, the sucker rods should not touch the ground. To avoid cross-threading, it should be made sure that the rods are placed directly above the wellbore. To ensure proper make-up, threads should be clean and undamaged. They should also be lubricated and should be made up using the circumferential displacement method. The coupling faces should make proper contact with the shoulder face. Care should be taken during breaking of joints to not damage the threads and rods. Joints should not be hammered with hand wrenches. Instead, cheater bars should be used. Hammered or over-torqued couplings should be discarded since they give a high

[140] Cf. API (2008b), p. 15
[141] Cf. API (2008b), p. 15
[142] Cf. API (2008b), pp. 15–16

probability to failure. If rod hangers are not available for the operation than the single rods should be pulled and then carefully placed on the racks in singles. [143]

2.4 Parameters for Reuse of Sucker Rods

The following chapter describes a selection of parameters that are used for describing and measuring the lifetime of sucker rod pumps and especially sucker rods. Some of these parameters like MTBF for sucker rod pumps and load cycles for sucker rod strings are used by OMV Austria as performance and lifetime parameters.

2.4.1 MTBF

The mean time between failure (MTBF) is one of the most common used performance indicators for artificial lift systems. It is a measure to quantify the reliability of a repairable product. MTBF can be used to analyze the performance of a whole unit or just a specific component. To achieve a value for the MTBF, various tests and statistical analysis of the individual components have to be performed to predict the rate of failure. The meaning of the MTBF is not as simple to just be described in a number. For a complete understanding of the value, it must be defined what exactly is counted as a failure. If this question is answered in combination with the information of repair times, the determination and interpretation of MTBF is validated. [144]

Simply, the MTBF is calculated as an arithmetic mean by dividing the total operating time for a defined period with the number of failures that occurred in this time period (Eq.3). [145]

Equation 3

$$MTBF = \frac{total\ operating\ hours}{number\ of\ failures}$$

As an indicator of the reliability of a product or component, the MTBF is also used to evaluate quality. However, it must be noted that the MTBF as decision-making criteria has its limitations. The pump and pump system components in the field operate at different conditions. They differ in their performance parameters like strokes per minute (SPM) or stroke length. The days of operation are therefore not giving an indication about the loads and conditions they had to endure. Additionally, the definition of the time between failures varies throughout literature. Eventually, the time measure includes the repair time after the failure occurred as well instead of starting the time calculation at the point where the component operates again after repair time. In field the MTBF is generally applied considering the pump as a whole and not individual components of the ALS system. In OMV in Austria, the MTBF is calculated for every individual artificial lift system and all systems together (Eq.4). Therefore the number of operating wells is multiplied by the reporting period (days). The reporting period can be monthly or based

[143] Cf. API (2008b) pp. 14-16
[144] Cf. Torell, W.; Avelar, V. (2004), pp. 2–3
[145] Cf. Forsthoffer, M. S. (2017), pp. 547-548

on a year-to-date and 12 months rolling calculation. The product is then divided by the number of well failures that occurred in this period.[146]

Equation 4

$$MTBF = \frac{number\ of\ operating\ wells * reporting\ period\ (days)}{number\ of\ well\ failures}$$

The current values in OMV considering sucker rod pumps for MTBF (year to date) are 1751 days (January 2019 – September 2019) and for MTBF (12 months rolling) 1915 days (September 2019).[147]

2.4.2 Load Cycles

Hein and Hermansson (1993) state that the lifetime of a sucker rod system is dictated by cyclic loading and the magnitude of the loads. The changes of loads due to net lift effects, the well deviation and unaccounted friction loads influence the lifetime of the rod. This means that the loads are not always the same during each pumping cycle and the rod experiences different loads depending on the position in the well. A first approach to determine the fatigue strength related to load cycles was adapted with the generation of the Goodman diagram. As described earlier the Goodman diagram shows the expected stress range for a given cycle and therefore is used to determine the maximum allowable rod stress. The basic diagram was developed by using very simple and short metal test objects. The objects had to run tests with very high cycle rates with about 1750 cycles per minute. The output of the tests was a fatigue life expectation of 10 million load cycles in non-corrosive environments. Since real sucker rods differ strongly to the objects used for tests and the generation of the diagram, modifications must be made. To make the diagram suitable for the application on real sucker rods, safety factors are applied. The API defined modifications on the Goodman diagram which resulted in the generation of the modified Goodman diagram. The expected fatigue life expectations were not adjusted, remaining at 10 million load cycles. Throughout the years, numerous improvements have been made in the manufacturing of sucker rods. The MTBF was increased and the expectations for the improvement of fatigue life were very high. Hein and Hermanson assumed a rise from the minimum cycles to failure from 10 to 50 million. But compared to other literature the expectation of 50 million cycles could not be verified. [148]

The value of 10 million cycles should be taken with care in practice, since this theoretical number may not be achieved in field operations due to numerous unpredictable factors influencing the rods. It is still nowadays very difficult to track the load cycle of every sucker rod to recognize when it reached the set limit for disposal. Therefore, it is challenging to decide when the sucker rods can be reused which is currently an issue encountered at OMV in Austria. The approach of OMV to use load cycles as classification criteria for used sucker rods is described in chapter 3.1.3.

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[146] Cf. Marschall, Ch. (2018), p. 4
[147] OMV Austria E&P GmbH (2019c)
[148] Cf. Hein, N. W. J.; Hermanson, D. E. (1993), pp. 1–6

2.4.3 Load

Load cycles alone might not be expressive enough to give exact information about the sucker rod life. Every sucker rod string endures different loads, dependent on the well trajectory and their installation depth. Sucker rods that are placed further to the top and rods that are placed in deviated sections endure higher stresses than others. Mahoney (2006) describes a net load value that can be used combined with the number of load cycles to draw a better picture of the magnitude of loads that the sucker rod string has to endure. The net load *Fo* is calculated by taking the gross calculated fluid load that is lifted by the pump and subtracting the pump intake pressure. Multiplying the *Fo* load with the number of cycles and dividing it by one million gives the *CFo* load. This number should give a more accurate measure to consider both the magnitude and the cycles. In addition to the MTBF, the load cycles and the *Fo* load, give a data set that helps the operator to see which wells are or will be in need of intervention soon. It also gives the operator an idea to predict the life of the equipment for that well. [149]

2.4.4 API Parameters

API 11 BR recommends a degradation of used rods to classify them in three classes. The standard describes a couple of parameters that should be considered and evaluated before reusing the rod. After the evaluation of these parameters, the rods can be separated into three different classes: Class I, II and III.[150]

This classification system is not applied at OMV Austria but could be partly used in the future for improving the current classification system to change sucker rod inspection from subjective to more objective criteria.

Elongation

Alternating loads during operations can cause the sucker rod to elongate. The elongation is limited to 2 inches per rod for all three classes. If they exceed this value, they must be rejected.[151]

Maximum allowable bend

For the measurement, either a straight edge or ruler or a total indicated run-out gauge (TIR) can be used. The straight edge measures the height difference between a horizontal plain and the rod. If it exceeds 0.065 in, the rod is rejected for all three classes. Another option is to perform the measurement with a TIR-gauge. The run-out refers to any deviation from the perfect roundness, the concentricity and therefore occurrence of a bend. TIR-gauge is applied to a rotating cylindrical object where the difference between the maximum and minimum measured value gives the TIR value. The TIR gauge can be a dial indicator or a laser. Rods that are inspected by the TIR gauge and are considered for a downgrade to Class II and III can be cold straightened. [152]

[149] Cf. Mahoney, M. W. (2006), pp. 1–2
[150] Cf. API (2008b), p. 10
[151] Cf. API (2008b), p. 10
[152] Cf. API (2008b), p. 10

Table 4: API 11BR limits for max. allowable bend

	Class I	Class II	Class III
12 in straight edge	0- 0.065 in		
TIR	0- 0.130 in	0.150 – 0.300 in	0.300 in

Mechanical damage and wear

Severe mechanical damage like cracks and sharp indentations is cause for rejection in all classes. If the mechanical wear and the size of corrosion pits stay in defined limits, the rods can be downgraded according to the table below. The eddy current inspection should be used to indicate a reduction in diameters. The electromagnetic flux leakage inspection is a method that is able to indicate changes in the diameter and to indicate the size of cracks. [153]

Table 5: API 11 BR limits for mechanical damage and wear

	Class I	Class II	Class III
Reduction of cross-sectional area due to wear	0 %	0-20%	20-30%
Corrosion pit size	0-0.020 in	0.020-0.040 in	0.040-0.060 in

Threads, pin ends, upset areas

The sections of sucker rod pin end, upset area and rod body that are not inspected by electromagnetic methods should be inspected or using a longitudinal electromagnetic field. Threads should be inspected using an API standardized ring gauges to check if the threads are properly manufactured. Threads that are damaged on the first three threads are rejected except class III rods. The threads must be repaired with a thread chaser. How “minor damage” is defined is up to the user. [154]

Table 6: API 11BR limits for damage, corrosion depth, and wear

	Class I	Class II	Class III
Damage on threads	-	-	Minor beyond first three threads
Corrosion depth at threads	0-0.005 in	>0.005 in	>0.005
Wear on pin shoulder	0-0.020 in	>0.020 in	> 0.020 in
Damage or wear at upsets	-	-	>0 in

[153] Cf. API (2008b), p. 10
[154] Cf. API (2008b), p. 10

Taking this classification system into account, used sucker rods can be evaluated by applying new stress curves. The allowable stress limit for the grades is decreased associated with the material loss on the rod. This gives the new stress limits depicted as curves. (Fig. 21) If the allowable stress, defined as the peak polished rod load (PPRL) in psi and the ratio of the minimum polished rod load (MPRL) to the PPRL gives a value that is below the lines for the according class and grade, the used sucker rod can be reinstalled.[155]

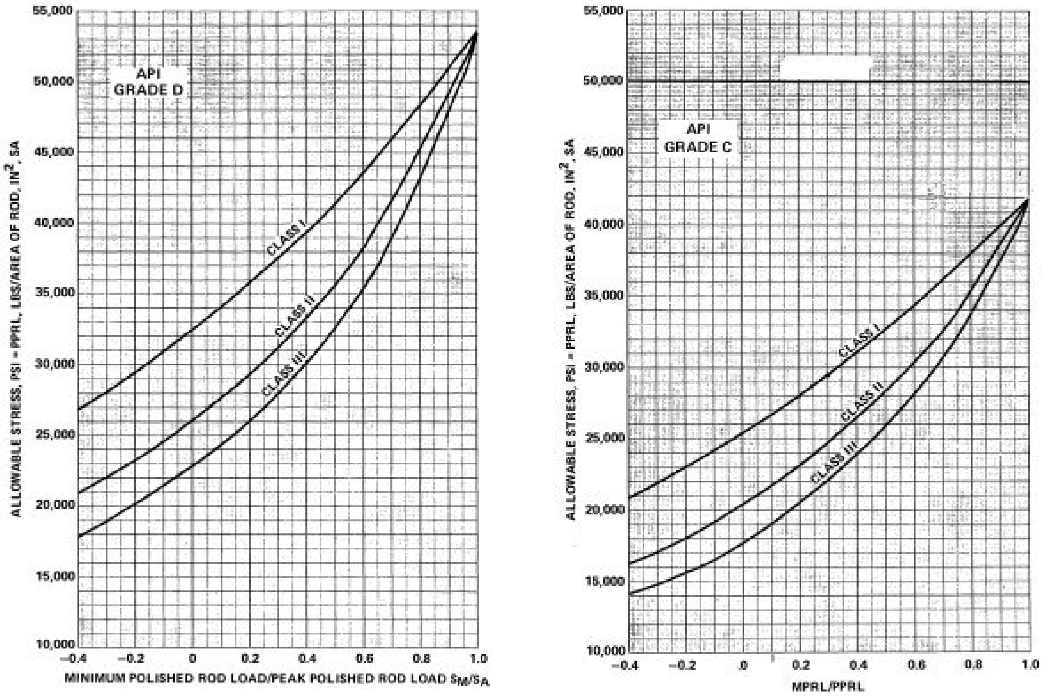

Figure 21: Modified allowable stress curves for the three classes of used API grade C and D [156]

If the allowable stress, defined as the peak polished rod load (PPRL) in psi and the ratio of the minimum polished rod load (MPRL) to the PPRL gives a value that is below the lines for the according class and grade, the used sucker rod can be reinstalled.[157]

[155] Cf. Hein, N. W. J.; Hermanson, D. E. (1993), pp. 3–12

[156] Adapted from Hein, N. W. J.; Hermanson, D. E. (1993) pp. 449-450

[157] Cf. Hein, N. W. J.; Hermanson, D. E. (1993), pp. 3–12

3 Practical Part

In order to establish a sucker rod management system with higher levels of quality control and more objective classification criteria, an analysis of the current state at OMV Austria was carried out. After the identification of weak points, solutions for improvement were investigated. Current processes that are in need of rearrangement or new processes were defined. Concepts for the implementation of new technologies and modifications of workflows were developed and technically and economically evaluated.

3.1 Current State Analysis at OMV

OMV AG is an internationally operating company in the oil and gas industry with its headquarter located in Vienna, Austria. The company's businesses reach into the upstream and downstream sectors.

Production in Austria reached over 26,000 boe in 2018, covering about 10% of the domestic market demand. The most important production location in Austria is the Weinviertel region. OMV Exploration & Production GmbH located in Gänserndorf supervises over 1000 wells for oil and gas production, water injection and storage purposes. [158]

Approximately 470 wells are equipped with sucker rod pumps, of which around 400 were operating in 2019. Storage capacities for equipment are located in Gänserndorf and at the pipe yard in Prottes. The pipe yard in Prottes is operated by a service and technology company for the oil and gas industry. The pipe yard personnel in Prottes consists of 20 people. The yard serves as a storage area for various goods, mainly tubings, casings, drill pipes, sucker rods and other tubular goods, auxiliary equipment and materials. Furthermore, the pipe yard is also responsible for the inspection of tubular goods. Transport by truck between the wellsite and the pipe yard is carried out by a local transport company.

3.1.1 Sucker Rod Specifications

OMV Austria states the design criteria for sucker rods in an internal specification document. The specification mentions API Spec. 11B as the basis for their requirements. OMV Austria uses sucker rods and pony rods with the API grade D and a minimum length of 2 feet. Couplings are spray metal-coated without wrench flats. The current manufacturer for sucker rods is Tenaris in Campina, Romania. Rod guides are produced and installed by Ebenhoeh International SRL, also located in Campina, Romania.[159]

Manufacturers have to pass a strict QA/QC inspection process before being accepted as a supplier to OMV. The inspection is carried out by a third-party inspector who is

[158] Cf. OMV Austria E&P GmbH (2019a) p. 1
[159] Cf. Hönig, S. (2012) pp. 2-4

assigned by the asset management. A regular technical audit is carried out every three years directly at the manufacturer to ensure the quality of the products. Since the audits for QA/QC at Tenaris have proven themselves, material testing for sucker rods is only carried out occasionally at the laboratory in Gänserndorf. These tests include tensile tests, chemical analysis, hardness tests with Brinell or Rockwell and a notch impact test. They are obligatorily performed for suppliers who are delivering for the first time to OMV or if nonconformities have occurred in previous orders. [160]

Visual inspection for new sucker rods is carried out at the delivery point at the pipe yard. This visual inspection concentrates on the control of the continuity of the coating of the rods (they are bathed in a bitumen type coating at the manufacturer) any cracks or surface discontinuities. Rod guides are rejected if they show any sign of damage and thread protectors must be intact. Sucker rods are delivered in transport systems that are displayed in figure 15.

3.1.2 Classification of Used Sucker Rods Based on Parameters Influencing Rod Failure

This chapter gives a short background about sucker rod failures in OMV Austria and provides support for a better understanding of special terms.

In 2019, T. Lindemann investigated parameters that influence the failures of sucker rods. Data about sucker rod failures that occurred between January 2016 to December 2018 was collected. 52 sucker rod failures which occurred during this period in OMV Austria were studied for their failure root cause and circumstances. [161]

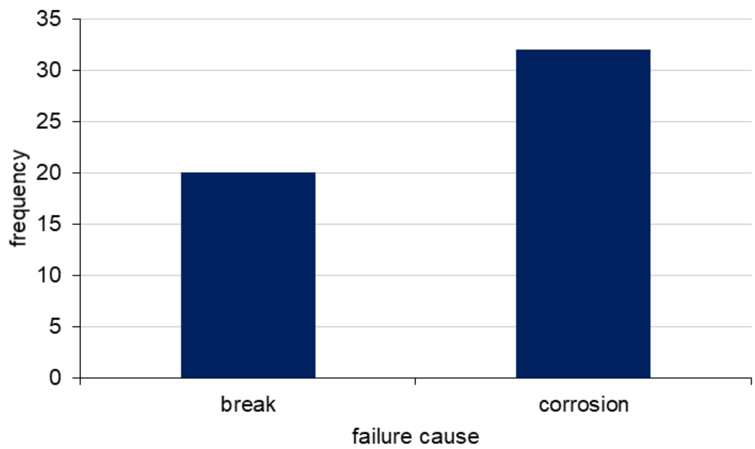

Figure 22: Histogram of failure cause [162]

The results show that the cause for 32 of these sucker rod failures was corrosion, the other 20 failed due to bending, overstressing, abrasion or other mechanical failures (Fig.22). 31 of these failed rods were rods that were used before in another well or have been pulled and were reinstalled in the same well. 21 rods were newly installed. The frequency of the failure position shows that the majority of failures accumulate at the

[160] Cf. Zehethofer, G. (2016) pp. 9-11
[161] Cf. Lindemann, T. (2019), p. 28
[162] Adapted from Lindemann, T. (2019) p. 28

protector or around the protector region (Fig. 23). A possible reason for this phenomenon can be imagined being caused by crevice corrosion or one of the associated failure mechanisms that have been described in the chapters before. [163]

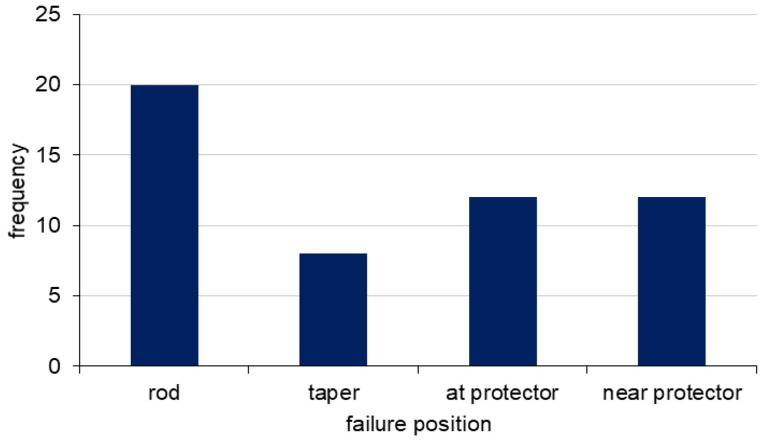

Figure 23: Histogram of failure position [164]

Sucker rods that are broken, are sent to the laboratory in Gänserndorf for precise failure analysis. The laboratory reports are currently the most important source for root cause analysis and investigation of rod break influencing parameters. Implementing tracking systems for individual identification of sucker rods could improve the data gathering and root cause analysis for sucker rods for developing new classification systems based on different parameters.

In OMV Austria around 125 well interventions for sucker rod pumps are carried out per year. Reasons for sucker rod pump failures are e.g. failures of the pump itself, polished rod breaks or sucker rod breaks. In 2018 around 18 failures were due to sucker rod breaks. Costs for well interventions and the production loss due to unplanned deferments are issues that OMV wants to minimize. Below a summary of key parameters of well interventions and associated production losses from the general database (GDB) of OMV is displayed. The values are used for cost estimations in the following chapters of this thesis:

- Avg. costs well intervention for a sucker rod pump: 74.968 EUR
- Avg. time for well intervention for sucker rods: 38 hours
- Avg. deferment time due to sucker rod break: 36 days (data from 66 wells from December 2014 – July 2019)
- Avg. loss of production due to sucker rod break: 585 BOE (data from 66 wells from December 2014 – July 2019)
- Avg. loss of revenues due to sucker rod break: 31.357 EUR (calculating with an oil price of 60 $/54,40 EUR); (data from 66 wells from December 2014 – July 2019)[165]

[163] Cf. Lindemann, T. (2019) pp. 28-29
[164] Adapted from Lindemann, T. (2019), p. 29
[165] OMV Austria E&P GmbH (2019b)

3.1.3 Classification of Used Sucker Rods in OMV

OMV Austria together with OMV Petrom, a Romanian oil company part of the OMV AG, has defined an internal classification system for used sucker rods that is based on the numbers of endured load cycles. Rods that exceed the lifetime of 16 million load cycles shall be disposed. Since rods are not individually tracked, the number of load cycles accounts for the rod string. Although there exists inconsistency in the classification guideline itself between a limit of 16 or 20 million load cycles, the limit of 16 million is applied prevalently in practice. The classification distinguishes between four complement recommendations for rods:

- Rods in rod strings that endured less than 8 million load cycles are considered as “new” rods. If they have to be exchanged in the rod string, they shall be complemented with new rods or the whole rod string must be exchanged with new rods. Rods with up to 8 million load cycles that show wear on the protectors should be transported to the pipe yard and be inspected.
- Rods in rod strings that endured more than 8 million load cycles are considered “used” rods. They shall be complemented with used rods from the pipe yard or the whole rod string should be exchanged with used or new rods. Again, if they show wear at the rod guide, they should be inspected at the pipe yard.
- Rods in rod strings that endured over 16 million load cycles and that caused no problems should be completely exchanged with new or used rods at the next well intervention. Rods should be transported to the pipe yard and be put to scrap.
- Rods in rod strings that endured over 16 million load cycles that showed a frequency of damages shall be replaced completely with new rods and the old rods should be put to scrap at the pipe yard.[166]

The load cycle numbers of the individual wells are displayed in the general database (GDB). If the sucker rod string is completely exchanged from the well and another rod string is installed, the load cycle count is set to zero. If the sucker rod is just complemented with new or used rods, the load cycle count remains.

The classification system for used sucker rods in theory and for the engineer to design a rod string differs from the classification system that is applied in practice in pipe yard. Sucker rods in the pipe yard are not sorted in load cycle categories. The pipe yard in Prottes distinguishes its storage areas solely between new and used rods. In contrast to the theoretical classification system, the term “new” only applies to sucker rods that have never been installed in a well. Rods that have been installed but endured less than 8 million load cycles are also classified as “used” rods.

The pipe yard distinguishes between the following batches for sucker rods:

- A-New: New rods that are still packed in their original frames or sucker rods that were never installed but delivered back from the wellsite
- B-75%: Used rods that passed the inspection process and are ready to be reused
- D-25%: Used rods that are waiting for inspection
- E-Scrap: Rods that were delivered to the pipe yard to be put to scrap and rods that did not pass inspection

[166] Cf. Kavoussi, F. (2014), p. 41

It must be noted that the percentage number in the name of the batch does not exactly represent the monetary value of the rods. It should give the indication that the technical limits of the rods are deranged. The following table 7 shows the average monetary values of rods in batches that are used for internal cost allocation.

Table 7: Valuation of stock for sucker rods in SAP

Price	EUR
avg. A-NEW	93,99
avg. B-75%	31,10
avg. D-25%	7,27

Used rods have separate storage places according to their material number. The material number of the sucker rods accounts for their diameter and rod guide design and is simultaneously order number for the SAP software system that is used for stock management. The stock at the pipe yard consists of approximately 26,500 sucker rods including scrap. Around 40% of stock belongs to batch A-New, 30-40% of stock belongs to the D-25% batch and around 10 % to B-75%. The rest is categorized as E-Scrap. Currently, the pipe yard distinguishes between 12 main material categories for used rods. The material number of the sucker rods describes their diameter, the number of rod guides, the diameter of rod guides and the length of the rod. The following table 8 displays the individual material numbers for sucker rods.

Table 8: Material numbers for sucker rods at OMV Austria

Blank sucker rods	
Material Number	*Type*
700740	Sucker rods 1” x 25 ft
700741	Sucker rods 7/8” x 25 ft
700742	Sucker rods 3/4” x 25 ft
Sucker rods with rod guides	
Material Number	*Type*
1062435	Sucker rods 1” x 25ft – 2 guides 3 1/2”
1062436	Sucker rods 1” x 25ft – 4 guides 3 1/2”
1062452	Sucker rods 7/8” x 25ft – 4 guides 3 1/2”
1062453	Sucker rods 7/8” x 25ft – 2 guides 3 1/2”
1062454	Sucker rods 7/8” x 25ft – 4 guides 2 7/8”
1062455	Sucker rods 7/8” x 25ft – 2 guides 2 7/8”
1062456	Sucker rods ¾” x 25ft – 4 guides 2 7/8”
1062457	Sucker rods ¾” x 25ft – 2 guides 2 7/8”
1079354	Sucker rods 1” x 25ft – 4 guides 2 7/8”

3.1.4 Current Processes and Procedures for Used Sucker Rods

This section describes the current processes and procedures for sucker rod management at OMV Austria. Currently, two different options for workflows considering handling of sucker rods exist, covering processes at the office of production technology at Gänserndorf, deinstallation and installation at the wellsite as well as processes at the pipe yard. After pulling the string from the well the sucker rods can be transported to the pipe yard where they are put to scrap or inspected. A new rod string consisting of new or used rods is installed in the well (sucker rod change). Another option is to control the sucker rod string after pulling directly at the wellsite, replacing rods if necessary and reinstall the string in the same well (sucker rod control).

Pumping system failure

If the sucker rod pump experiences a failure, the well is in need of a well intervention. The plan to carry out an intervention and which equipment should be installed in the well is determined by engineers of the production technology department in Gänserndorf. The design includes the intervention plan and furthermore the composition of the sucker rod string. The engineers use the software RodStar for their calculations. In addition, the engineer uses the general database of OMV (GDB) for well information and previous designs and SAP for information about the current stock levels in the pipe yard. The design plan is sent to various interested parties, including the workover department and the pipe yard. The engineer checks the GDB and decides, if the current sucker rod string should be inspected or put to scrap. Regarding the economic evaluation of well interventions, a cost estimate based on a predefined Excel template has to be made.

Pulling at the well

The sucker rods are pulled by the workover personnel that usually consists of five men. One man controls the crane that lifts the sucker rods at the sucker rod hanger. Two men are positioned directly at the wellhead where one installs the rod hanger and the other uses the hydraulic torque machine. Two workover men are pulling the sucker rods on three rack posts in about 1.5 m to each other and a length of approximately 2-3 m. They are sorted according to their disassembly order and number. Layers of sucker rods are separated with wooden bars, If the sucker rod string is pulled due to a well intervention procedure, the individual rods are first roughly inspected by the workover personnel at the wellsite. As mentioned before two different options exist to proceed: sucker rod change or sucker rod control.

Sucker Rod Change

If the engineer gives the instruction for a total sucker rod string change, the rods are transported to the pipe yard in Prottes. There, they are inspected by the pipe yard personnel and sorted according to the classification system used in the pipe yard.

Transport to pipe yard

Sucker rods are picked up from the racks by a truck using a bar with loops. The sucker rods are picked up in bundles and are loosely transported on the truck.

Arrival at pipe yard

At delivery, the rods are checked whether they ordered for inspection or have to be put to scrap. The rods are not checked for their load cycle number. Used rods that are due for inspection are put together in bundles and marked with a note about the name of the well, delivery date, number of rods and type. They are classified as D-25% before inspection and are placed by the truck on racks. If the sucker rods were installed in a well that carried a lot of paraffin, they have to be cleaned and are placed near the paraffin oven. The sucker rods are placed with the forklift on a carriage that is pulled into the oven. Paraffin is removed by heating up to a temperature from 80 °C up to 140°C. After the treatment, they are placed at a small storage area near the inspection racks (Fig. 24).

Figure 24: Pipe yard in Prottes

Inspection of rods

The inspection and storage of inspected sucker rods is orientated on the recommendations described in API 11BR. The inspection of rods is not a regularly applied process. Stock levels for used rods on their lower limits trigger the demand for sucker rod inspection requests. Sucker rods that are clean or just slightly dirty are transported to the inspection racks and are cleaned with hot water or steam if necessary. Then the rod bodies are visually inspected for cracks, corrosion pittings, wear, erosion spots, threads, rod body, rod guides and the sections near the rod guides. Followed by rod guides measurement. With a ruler, the abrasion is determined and checked if they are in the predefined limits for reuse. Couplings and threads are tested by using a caliper and a sleeve similar to the description in the API standard 11BR (Fig. 25).

Figure 25: Caliper and sleeve for checking threads

If they do not pass the visual inspection and the thread testing, they are marked with red paint and scrapped If qualified for reuse, threads are lubricated, and thread protectors are applied with a turning motion and a hammer impact. Rods that pass the inspection receive a white mark, meaning they are inspected and used. The corrosion inhibitor is then sprayed on the rods (Fig. 26) and has to sit approximately an hour before movement.

Figure 26: Application of corrosion inhibitor

The rods are then stored according to their material number, size and number of rod guides. Storage areas consist of three concrete racks and multiple steel bars. The sucker rods lay on wooden bars to avoid metal to metal contact and are classified as B-75% sucker rods. Currently, 13 storage areas (two for material nr. 1079354) exist for used rods.

Order for reuse

If used rods shall be installed in a well, the transport truck drives to the storage area of used rods in the pipe yard and picks rods from the needed category up in bundles with loops.

Reinstallment in well

Sucker rods are unloaded from the truck at the wellsite and placed on the operating racks. In case different SR sizes are used they are sorted by the workover personnel according to size. Protectors at the threads are removed. Threads are roughly visually checked and lubricated. Rods are then piece by piece pulled to the wellbore. The rod hanger is installed underneath the coupling and the crane hook lifts the rods via the rod hanger. The rods are made up by hand and finally by the hydraulic torque machine. If all rods are installed, the workover personnel checks if the sucker rod string length and installs pony rods for space out before the polished rod is made up.

Excessive rods

Rods that have not been used for the string are transported back to the pipe yard. After visual inspection, checking and lubricating the threads of the rods are protected with corrosion inhibitor and put back to the appropriate storage area. The following figure displays the current workflow for a sucker rod change (Fig. 27).

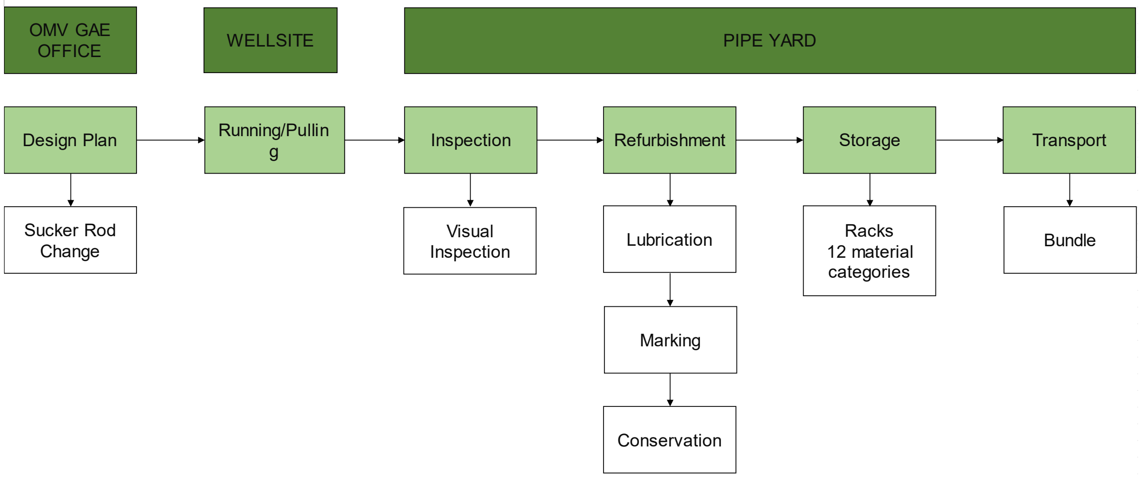

Figure 27: Simplified workflow of a sucker rod change

Sucker Rod Control

If the well intervention plan foresees a sucker rod control (Fig. 28), the sucker rods are inspected visually by the personnel at the wellsite. Another description for used sucker rods appears on this occasion in the well intervention reports: “old” rods. These types of sucker rods are not damaged and after thorough visual inspection by the personnel at the wellsite are immediately reused. Defect rods are exchanged with either new or used rods. Once all rods are pulled and visually inspected, the wellsite personnel order the necessary amount for complementing the string from the pipe yard. Defective rods that shall be scraped are laid to the side and later transported to the pipe yard. There they are marked as scrap and put to disposal.

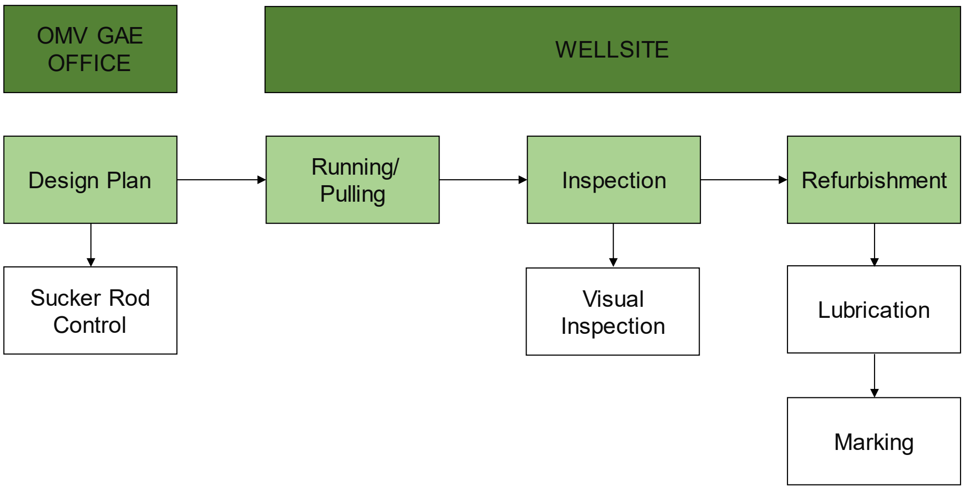

Figure 28: Simplified workflow of a sucker rod control

Sucker Rod data management

OMV uses two applications for saving information about sucker rods. SAP software is used for stock management and internal accounting and the general database (GDB) is used for monitoring the production system and storing data about well components and well interventions.

SAP

The pipe yard uses the software SAP for stock management. The sucker rods are recorded according to the material number and batch. Used sucker rods that need to be inspected are recorded to the material number that describes the sucker rods without rod guides and batch description D-25%. Used sucker rods that passed inspection are recorded according to their material number and are valued batch B-75%. Sucker rods that need to be put to scrap or did not pass inspection are recorded according to the material number to their batch description E-Scrap.

General database (GDB)

The general database provides information about the production system and all wells in Austria. Information about the rod string design is linked to the individual well in the database and visible in the well design plans. Since a tracking system of individual sucker rods is currently not given, the string composition is generic.

3.1.5 Weak Point Analysis

To identify weaknesses in the application of the current sucker rod management system, an analysis of processes and procedures involving sucker rods was carried out. The following sections describe the found weak points.

Classification system

The classification system can only be correctly applied to a rod string where the exchanged string was composed completely of new rods. After a sucker rod change, the load cycle track is set to zero whether the newly installed rod string consists of completely new rods or used rods from the pipe yard. If the sucker rods were controlled at the wellsite and reinstalled, the load cycle count is not changed. After the rods are inspected at the pipe yard, they are just sorted according to their size and amount of rod guides. Although the pipe yard receives the design plan for the intervention which contains information about the load cycle number, there is no tracking or sorting in the pipe yard according to the number of load cycles. The used rods with different load cycles are mixed up and are not sorted into rods below 8 million load cycles and above 8 million load cycles as requested by OMV regulations. Inspection reports which are part of the invoices only give information about the number of rods that were inspected, and which passed and not. Sometimes the inspected rods are not attributable to their last installed well. Since the pipe yard uses paper or metal plates as notes for the bundles, they are not readable anymore after a long storage time.

Handling of sucker rods

Sucker rods that are moved from the wellsite to pipe yard are picked up in bundles and placed on the truck in loose states. During this handling of sucker rods, the steel bars experience bending and metal to metal contact. Furthermore, they are exposed to movement on the load bed of the truck which might cause damage to the rods.

Visual inspection

Visual inspection is a subjective testing method. Only defects that are seen with natural eyesight can be detected. Little cracks and scratches might not be seen. The decision which sucker rods are damaged or outranged and therefore should be deposed is based on guidelines from the management and mostly experience of the inspector. A particular concern for visual inspection is the area underneath the protector which can only be inspected if the rod guides are removed from the sucker rods. The inspection at the well only consists of a visual inspection of the rod body and threads and is not as precise as inspection with gauges and rulers at the pipe yard. Additionally, potential damages might be overseen due to the time pressure for work at the wellsite.

Inspection area

The inspection area is placed in proximity to the paraffin oven and the gamma-ray inspection method for tubing under open sky. Therefore, the inspection process is not only dependent on the demand for used sucker rods but also on weather conditions. Rain, wind and snow influence the inspection process negatively. The corrosion inhibitor for example cannot be applied to the sucker rods if it rains or heavy winds occur. If the inspection of tubing is carried out simultaneously to a sucker rod inspection, the corrosion inhibitor must be applied cautiously. The inhibitor might be carried by the wind to the tubing inspection area and disturb the inspection personnel.

Storage at pipe yard

In the pipe yard used sucker rods are directly placed at the buffer storage section (D-25% batch) and waiting for inspection. The sucker rods are picked up from the truck and are bundled together with thin wires so they can be transported as packages (approx. 116 sucker rods in one package to not exceed the lifting maximum of the forklift.). Some of these sucker rod bundles have a storage time of several years. The reason for this long storage time of the sucker rods is the lack of a regular and continuously applied inspection process. Sucker rods of the D-25% batch are inspected on demand if the stock values of the refurbished sucker rods reached their lower limits. The sucker rods experience bending due to the unequal load distribution and are in metal to metal contact. They do not have protectors on threads and are not preserved with a corrosion inhibitor. Besides, the storage area is not sheltered, exposing the material to severe weather conditions throughout the years (Fig. 29).

Figure 29: Buffer storage area for all sucker rods of batch D-25%

3.2 Cost Estimation and Analysis of Current Processes and Procedures

The following chapter explains and shows the result of a calculation to quantify current expenses that are created for processes and procedures that involve handling sucker rods at the wellsite and handling and inspection procedures at the pipe yard. Many operating expenses are covered with a general maintenance rate and bear the difficulty to comprehend all costs that are directly linked to sucker rods. Therefore, the calculations are partly based on assumptions and estimations. The development of a base case should provide a quick overview of the most important cost factors and workflows regarding sucker rod management in OMV Austria.

Data for calculation was gathered through an Excel cost estimate template that OMV uses for planning well interventions, well intervention design plans, invoices and charge rate lists from service companies, data exports from the general database, SAP database and estimations of the department of material management.

General considerations

Costs are displayed and calculated with net values. Current processes describe the workflow options, sucker rod change and control. 125 well interventions where sucker rods have to be pulled occur per year. This value was taken considering data from well interventions from the year 2015 to 2018 (Fig.41). In 40% of cases the sucker rod string is changed, in the other 60% the sucker rod string is controlled at the wellsite and integrated with used or new sucker rods. This assumption was taken after examination of well intervention design plans of sucker rod pumps from 2015 to 2018.

This base case refers to a sucker rod string consisting of 130 sucker rods, considering an average well depth of 1000 m. The assumption was taken since the majority of wells with sucker rod pumps are around 1000 m deep and the sucker rods at the pipe yard have a length of 25 ft (Fig. 40).

Wellsite

Costs at the wellsite include the facilities and facility staff for running and pulling the sucker rod string. They are charged on an hourly base. Facility staff consists of 5 people. Values for these factors were taken from the cost estimate template that is used by production engineers for planning a well intervention. Time needed at the wellsite for pulling and running sucker rods is estimated with 5 hours.

Truck transport includes transporting sucker rods back and forth to the wellsite and pipe yard. Costs are as well charged on an hourly base. Transport costs for a sucker rod control workflow and partial change of sucker rods are less than for a complete change of the sucker rod string since the amount to load and transport is less. All values were taken from OMV cost template for well interventions.

Pipe yard

Costs for the paraffin oven include handling of sucker rods and power consumption expenses for operating the oven. Costs are charged per procedure. 130 sucker rods can be cleaned with one procedure of 10 hours. Values are taken from cost estimates from the department of material management. For example, costs for office management at pipe yard are charged on an hourly basis and are estimated using 2019 charge rates from Tuboscope Vetco for OMV.

60% of changed sucker rod strings experience a visual inspection at pipe yard, 40% of changed sucker rod strings are outranged and are put to scrap. Again, assumptions were taken from well intervention design plans. The costs for inspection were estimated by examination of bills from Tuboscope Vetco and 2019 charge rates. This service is charged with an hourly rate per inspector. This rate includes the handling and transport of the sucker rod according to the inspection process, cleaning with hot water, visual inspection, rod guide inspection, thread inspection and lubrication, corrosion inhibition, marking and material costs. It does not include the costs for paraffin removal. From inspection reports, it is estimated that it takes 8 hours to inspect 100 pieces of sucker rods. The inspection is always carried out by two people. 20% of sucker rod strings are covered with paraffin and must be cleaned in the oven. This is considered when calculating average costs for the processes in the pipe yard. Sucker rod strings that are outranged must also be cleaned before putting to scrap. Inspection of excessive rods that are delivered back to the pipe yard is included as well and estimated with 25 pieces.

Table 9 shows the estimated costs for a sucker rod change process and a sucker rod control process as well as the estimated costs for handling and inspection of sucker rods per year. Calculations per year consider the various workflows for cleaning sucker rods strings with paraffin scale as well as rod strings that are put to scrap.

Table 9: Cost estimation of current processes and procedures

Cost estimation current processes and procedures base case		
Description	Sucker rod change	Sucker rod control
Well site	€ 5 072,29	€ 4 612,29
Pipe yard	€ 6 461,53	€ 203,48
Total process costs	**€ 11 533,82**	**€ 4 815,77**
Cost estimation per year		
Total costs per year	**€ 662 505,65**	

3.2.1 Definition and Description of Required Processes and Procedures for SR Management for Reuse

In OMV, two projects that concentrate on improvements for a sucker rod management are ongoing. One of these projects tests the application of RFID tags to create a tracking and information system for individual sucker rods. The second project focuses on the objective evaluation of used sucker rods. Therefore, the application of a non-destructive testing method that is based on the magnetic flux leakage method is tested. To integrate a tracking system and a non-destructive method, new processes must be introduced, and current processes must be redesigned.

This chapter gives an idea of new or redesigned processes that are necessary to integrate the RFID system and the objective inspection method in a sucker rod management system at OMV. In addition, solutions for storage and handling of sucker rods are introduced to prevent sucker rod damage because of mishandling.

3.2.2 Tracking Process

To apply the classification system of OMV/Petrom correctly the endured load cycles have to be known. This can be achieved by applying a tracking system using e.g. RFID tags. These tags are installed under one protector of the sucker rod. The RFID tags are passive tags. Data for the individual sucker rods is stored in the general database. For accessing this information, a connection to the database is necessary.

At the wellsite sucker rods run through a housing with the reading antenna. This reader is installed directly to the wellhead. The antenna is connected via a cable to a switch box where the reader, a minicomputer and diverse circuits are placed. The signals from the tags are transmitted via the antenna to the reader. The data is then processed with a minicomputer and transmitted via WLAN and an interface to the general database. There the data is stored and structured. Data such as the well number, installation and de-installation date and information about installation depth, dog leg severity and load cycles can be linked to the individual sucker rods. Sucker rods that pass any set limits of these parameters are then automatically marked in the database. This gives the opportunity to analyze sucker rod history data and develop new classification systems based on rod failure analysis and better rod string design. Therefore, sucker rod breaks can be reduced and a reduction in well interventions, costs and production losses can be achieved.

For better organization at the pipe yard, handheld readers can be used to verify information about the individual sucker rods. The handheld reader is placed in near distance to the tag. Through the wireless data exchange with the database the staff can see the individual information about the sucker rod on the device. This could be used in future to sort Sucker rods according to their load cycle range 0-8 million load cycles and 8-16 million load cycles or other classification parameters. The pipe yard would need for this application a connection to the general database so that personnel has real-time access to the information. Table 10 shows the data set of sucker rods where RFID tagging is tested in a pilot field application. However, data sets are flexible and can be enlarged and sorted according to the required information, e.g. tag number, well, SR status, SR lifetime etc..

Table 10: Data structure in general database for sucker rod tagging

TAG ID	Installation date	Removal date	Depth (m)	Dog leg severity (°/30m)	Load cycles cumulative	Load cycles at installation	Diameter (inch)	Number of rod guides

3.2.3 Non-Destructive Testing

Visual inspection reaches its limits when it comes to objectively measurable data and in particular when the surface is covered by coatings, isolation or e.g. molded rod guides. Removing these rod guides is associated with technical effort and additional costs. Therefore, OMV teamed up with Tuboscope Vetco to develop an NDT inspection process that enables objective control of corrosion and fatigue of sucker rods without removal of the molded rod guides.

The proposed solution consists of a non-destructive testing device that operates on the principles of magnetic flux leakage and eddy current testing. The sucker rod which shall be tested is railed through a magnetizing double coil system (Fig. 30) where magnetic flux leakage is measured by a set of hall sensors with 64 pairs of signal paths. Additionally, magnetic flux change is measured with two continuous coils evaluating the cross-sectional area detecting material loss. Finally, the device measures the hardness of the material along the entire sucker rod to detect eventual changes in material parameters due to load cycling. The individual signals are processed creating a sum signal, which with the help of proprietary measurement software. The inspection results are presented as a graph on the computer. Through a defined threshold, failure positions are indicated on the graph. The calibration of the error threshold is pre-performed by sample rods. [167]

[167] Janßen, M.; Maier, R. (2019), pp. 2–8

Since test results must be assigned to a defined and clearly identified object each sucker rod has to be trackable individually. Within OMV this required individual tracking system was started beginning 2019 and uses RFID tagging. Data of the test results are saved into the general database and assigned to the individual rod. Future data processing shall provide an automatic status update of the rod. Furthermore, the gained data can form the base for the development of a sucker rod life prediction software. Based on the inspection and the definition of the sucker rod status the sucker rod is categorized and respectively stored. The information of the storage space allocation will be included in the database.

At the time the thesis is written OMV planned to install the inspection system stationary in the OMV pipe yard in Prottes. Regardless, the option for a mobilization of the device is given but has to be investigated further for practical application and associated cost.

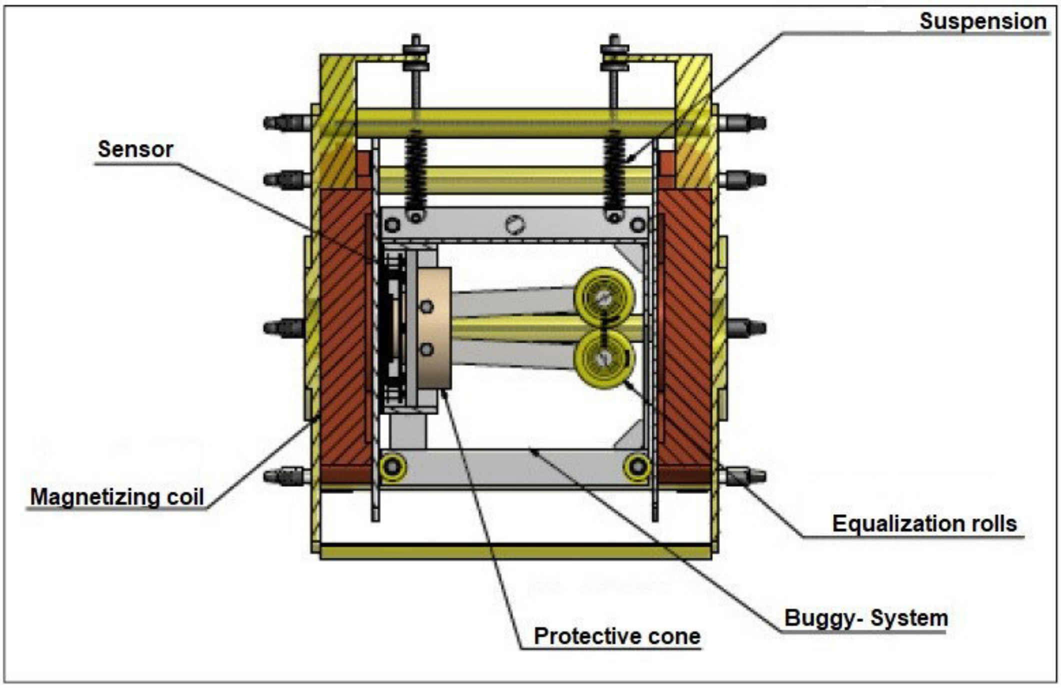

Figure 30: Magnetizing double coil system for non-destructive sucker rod inspection[168]

3.2.4 QA/QC Process and Required Change

As mentioned before in the OMV Austria asset, used sucker rods are only inspected visually at the moment. To change from the subjective inspection process to an objective process a review in a holistic approach covering transport, inspection and inspection workspace, classification, storage and storage space, planning and re-use for sucker rods is necessary. A continuous improvement approach for the process will help to reduce the time OMV requires to execute one or parts of one or several of the tentative concepts described and economically evaluated in section 3.4.

[168] Modified from Janßen, M.; Maier, R. (2019), p. 5

3.2.5 Continuous Improvement Process

The application of an RFID tagging system and a non-destructive inspection method will provide additional data for the classification of sucker rods. This data interconnected to general well data, operational data and failure analysis data can lead to support better planning and prolonged use of sucker rods. Each new data set will help to evaluate and learn from historic data triggering adjustments and improvements continuously, closing the cycle by setting new operating goals and applications. The final goal of the effort shall lead to prevent failures, increase well performance and MTBF of the AL system. This provides the base requirement and significant optimization potential for a high-level sucker rod management system. The potential process for continuous improvement is described in the schematic below based on the PDCA- cycle.[169]

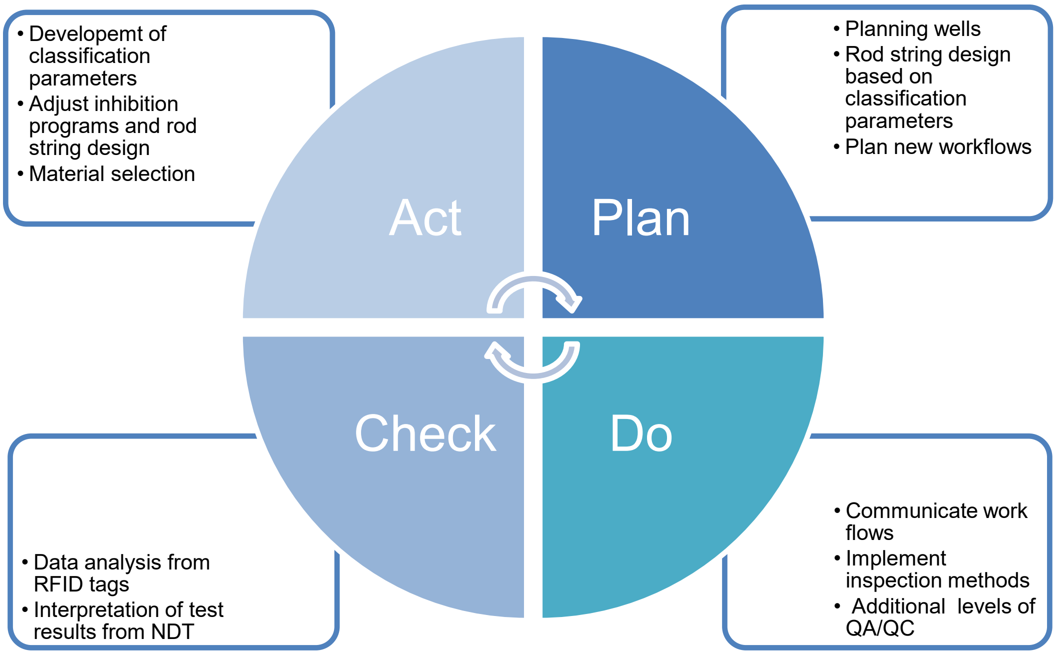

Figure 31: PDCA-cycle for sucker rod management[170]

3.3 Development of Concepts for Classification

This chapter describes concepts for work or process flows to improve the sucker rod evaluation and handling as part of a management process of used rods in OMV Austria. These concepts shall give an idea how workflows must be redesigned to integrate new innovative systems and inspection methods and how transport and storage can be modified to fit the purpose. Systems and methods include the RFID tracking system, the objective inspection method and a hypothetic outline for a transport and storage solution for sucker rods. For concept 1, 2 and 3 the option for a sucker rod control at wellsite is

[169] Cf. Moen, R.; Norman, C. (2009), pp. 6–7
[170] Modified from Moen, R.; Norman, C. (2011), p. 7

eliminated. This means if a sucker rod string is pulled from the well, it has to be transported to the pipe yard for inspection. The additional option for a sucker rod control at the wellsite with inspection of the pipe yard personnel is considered in concept 4.

3.3.1 Concept 1

Concept 1 describes a sucker rod management system using RFID technology with a sucker rod change and visual inspection at pipe yard (Fig. 32).

Production Technology- Office Gänserndorf

Production engineers design the well intervention. Information about the sucker rods due to tagging can be analyzed via the general database. Based on this evaluation, engineers decide, if the sucker rod string should be put directly to scrap or if the sucker rod string should be inspected by the pipe yard personnel.

Wellsite – disassembly of rods

The RFID housing with the antenna is installed at the wellhead and additional electronic devices are connected to the database. The sucker rod string is pulled at the wellsite. Information about the disassembly date is captured in the database. The sucker rods are placed at the racks and sorted according to the disassembly order. The truck picks up the sucker rods in bundles from the racks with loops and places them on the load bed. The sucker rods are then transported to the pipe yard with the note if they should be put to scrap or should be inspected.

Pipe yard – delivery of used rods

At the arrival of the truck with sucker rods the pipe yard personnel check the delivery note. The truck unloads the sucker rod bundles and places them either at buffer stock racks or directly at the control/inspection racks. The buffer stock should only be considered as a short-term storage solution for incoming goods. The pipe yard personnel might bundle the sucker rods at buffer stock and mark them with a note about their arrival date, well information and specific parameters. This note should give a quick overview and distinction of the sucker rod strings. The buffer stock should provide support in periods of heavy workload. Since the sucker rod control at the wellsite is not considered for this concept, this will surely be the case for the pipe yard.

Inspection at the pipe yard

At the inspection racks the inspectors use the handheld readers to check the tag. It might be necessary to turn and move the sucker rods to gain a signal from the tag.

The inspectors can now see the various parameters for the sucker rods and sort them according to the classification system and to their size. Sucker rods that do not fulfill criteria for reuse are put to the side and marked with red paint.

Sucker rods that fulfill the criteria for reuse, are scanned and experience a status update, with information that they are waiting for inspection. The status is changed using the handheld reader.

Sucker rods that passed the first sorting are then visually inspected. Sucker rods that pass the inspection process are scanned and achieve the status “visual inspection passed”. They are marked with white paint. The threads of these sucker rods are lubricated and equipped with protectors. Finally, they receive a corrosion inhibition.

If they do not pass visual inspection, sucker rods are scanned and achieve the status “visual inspection not passed” or “scrap” in the database with additional information about the rejection cause. They are also marked with red paint at the pipe yard and put aside.

In the next step the sucker rods are transported to their respective storage area. E.g. taking the load cycles as classification criteria for storage areas, sucker rods are stored in the appropriate storage areas according to seize, material and load cycle range.

Order for reuse

According to the classification system, the engineer selects the sucker rods for installation in the well and checks the availability of stock. If used rods are proposed to be installed, the engineer mentions the desired category for used sucker rods (0-8 million load cycles or 8-16 million load cycles) in the design plan. The design plan is then sent to the pipe yard and workover department. The order for transport with a material list is forwarded by the workover department to the transport company.

Transport to wellsite

The transport truck drives to the pipe yard and picks up the ordered sucker rods from their storage yards with loops and places them on the load bed. The truck then delivers the sucker rods to the well.

Wellsite - assembly of rods

The workover personnel install the antenna housing for RFID identification on the wellhead. The sucker rods are installed in the well running through the RFID antenna housing. Information about the assembly date is processed and send to the database.

Pipe yard - back delivery

Excessive rods from the wellsite are transported back to the pipe yard, visually checked and identified with RFID readers. They are then transported back to their storage area.

Figure 34 represents a simplified version of a potential workflow using the RFID system.

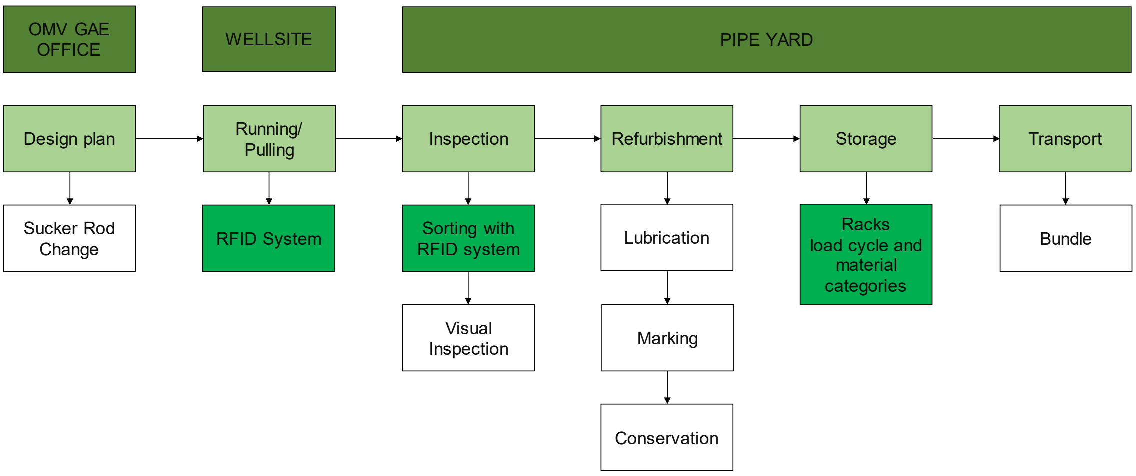

Figure 32: Simplified workflow for concept 1

3.3.2 Concept 2

Concept 2 describes a sucker rod management system using RFID technology with a sucker rod change and a visual inspection and non-destructive testing at the pipe yard (Fig. 33). It follows the same workflow as concept 1 until the point of refurbishment during visual inspection. The process flow for concept 2 proceeds here as following.

Objective inspection

Sucker rods that passed the visual inspection process are scanned with the RFID reader and receive a status update in the data base to "visual inspection passed". These sucker rods are now ready for the non-destructive inspection method. Sucker rods are inspected piece after piece. Two pipe yard employees are putting the sucker rod in the conveyor rail. The sucker rod passes through an RFID reader which sends the information for identification to the computer system. The sucker rod travels through the inspection device. The operator sees the ID of the tested sucker rod, evaluates processes the test results. The sucker rod is thereafter placed on the racks for refurbishment. The status of the sucker rod and the category assignment is updated automatically and send to the general database.

When the sucker rod passed the inspection, a sign is given to the inspection personnel at the end of the inspection device. The sucker rod is then placed on the appropriate racks, according to category assignment, for refurbishment. If the sucker rod does not pass the inspection process, a sign is given to personnel to put them aside and mark them as scrap with red paint. Sucker rods on the refurbishment rack receive thread lubrication and application of thread protectors. The corrosion inhibitor is then sprayed on the sucker rods and the sucker rod moved to the specified storage location.

The workflow following order for reuse, transport to wellsite, wellsite-assembly of rods and pipe yard-back delivery are the same as described for concept 1.

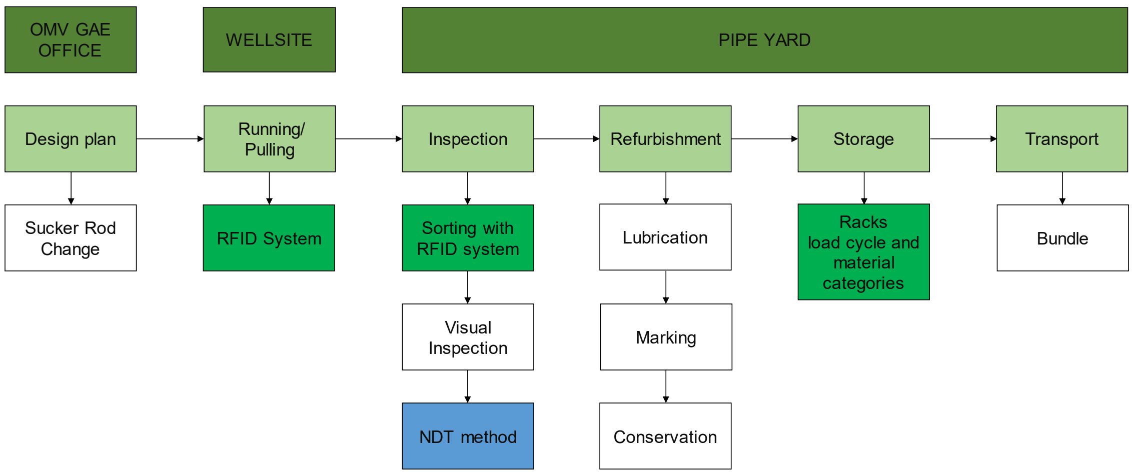

Figure 33: Simplified workflow for concept 2

3.3.3 Concept 3

Concept 3 describes a sucker rod management system using RFID technology with a sucker rod change, a visual inspection and non-destructive testing at the pipe yard and a special storage/transport system for sucker rods (Fig. 34).

Wellsite – disassembly of rods

Personnel at the wellsite prepares the transport system for the sucker rods. This transport system in ideal case is stable and protects the sucker rods from any metal to metal contact. A possible solution consists of a stable metal frame with plastic or wooden bars as separators between the layers. Once the frame is filled the holding system is fixed with screws providing stability to the transport frame.

Pipe yard – delivery of used rods

The truck unloads the sucker rods in their transport system and places them either at a buffer stock near the inspection racks or directly on the racks.

After refurbishment, they are put into transport frames. With support of a forklift and the frames are transported to the appropriate storage areas.

Order for reuse

According to the classification system, the PT engineer selects the sucker rods for installation in the well and checks the availability of stock. If used rods are proposed to be installed, the engineer mentions the desired category for used sucker rods (0-8 million load cycles or 8-16 million load cycles) in the design plan. The design plan is then sent to the pipe yard and workover department. The order for transport with a material list is forwarded by the workover department to the transport company.

Transport to wellsite

The transport truck drives to the pipe yard and picks up the ordered sucker rods from their storage yards in their storage/transport frame with loops and places them on the load bed. Sucker rods are transported from the pipe yard to wellsite in the transport frames.

Wellsite – assembly of rods

Rods are unpacked by the workover personnel from the transport box and directly used for installation.

Pipe yard – back delivery

Sucker rods that were not installed in the well remain in the transport frames and are returned to the pipe yard. The pipe yard unpacks the redelivered sucker rods from the transport system, carries out a visual inspection and processes the rods for re-storage.

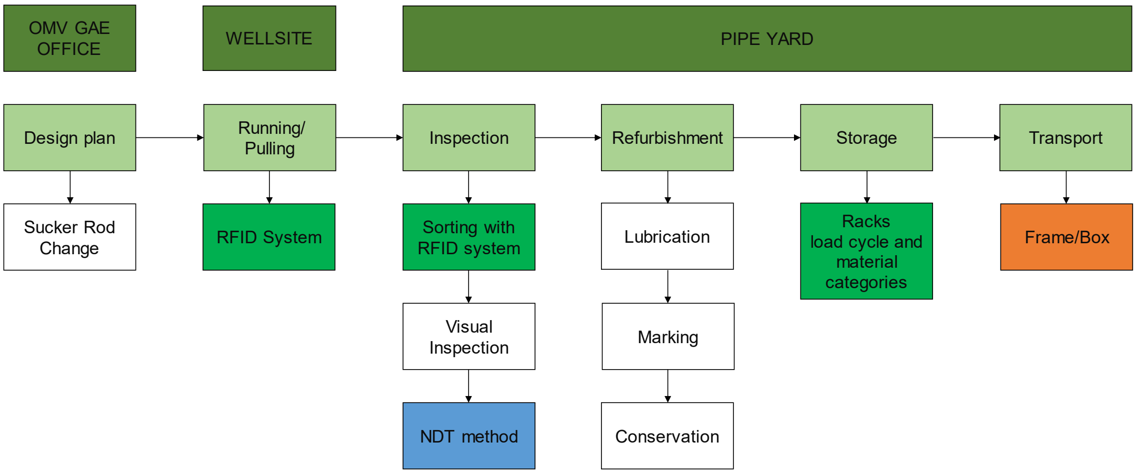

Figure 34: Simplified workflow for concept 3

3.3.4 Concept 4

Concept 4 describes a sucker rod management system using RFID technology with a sucker rod change and control, a visual inspection and non-destructive testing at pipe yard or directly at wellsite (Fig. 35).

Considering that some sucker rod strings must be completely replaced due to their load cycles and must be cleaned due to paraffin deposition at the pipe yard and that on several wellsites the space is limited, concept 4 describes a hybrid system. This means that there are two different workflow options for the management of used sucker rods. A sucker rod change, which is identical to the workflow pattern described in concept 2 and a sucker rod control, where the rod string is after pulling, directly inspected at the wellsite and is reinstalled in the same well. The processes and procedures of a sucker rod control at the wellsite are described as following.

Sucker Rod Control

The engineer orders a sucker rod control at a wellsite which is also spacious enough and provides all necessary connections to set up the inspection device. The pipe yard personnel must therefore mobilize the device and truck transport picks up new or used rods for complementing the rod string.

Wellsite

The sucker rod string is pulled running through the RFID antenna housing and is immediately sorted to relevant racks according to defined process criteria (re-installation QA/QC inspection, scrap). The ones which are destined for re-installation are marked with a number according to their disassembly order as support and to ease the correct installation sequence. Inspectors carry out a visual inspection for surface damage, rod guides and threads. Rods that did not pass the inspection process experience a status change to scrap and are marked with red paint. Once the rod passed the visual inspection, it is inspected with the non-destructive testing method. Results are saved and transferred to the database. Rods that did not pass get an automatic status change for scrap and are marked with red paint. Rods that passed get a status change for the inspection pass. These rods are placed on the racks and are lubricated at the threads. Sucker rods that did not pass the inspection are either replaced with new rods or with used rods according to the classification system. After inspection, the NDT inspection device is demobilized and together with the outranged rods transported back to the pipe yard. The sucker rods transported to the wellsite for complementation and which were not used are visual inspected and if required refurbished for storage at the appropriate pipe yard storage areas.

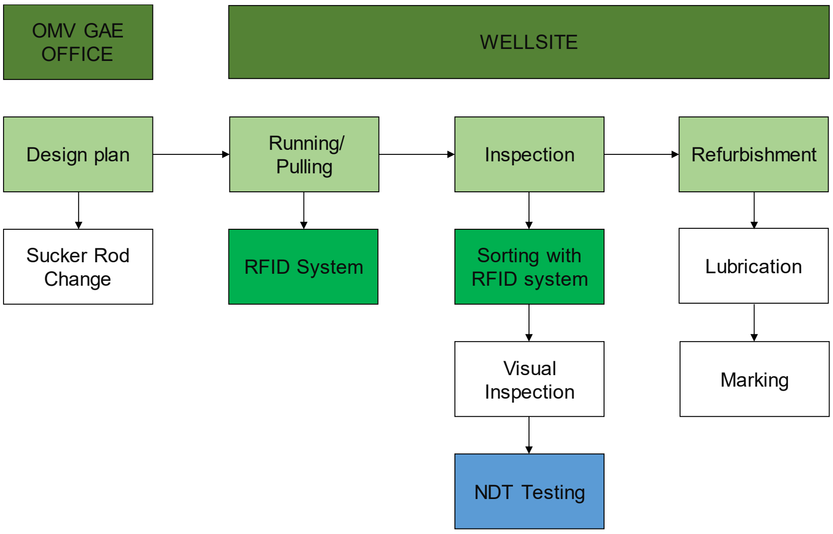

Figure 35: Simplified workflow for concept 4

3.4 Economic and Technical Analysis of Concepts

Internal processes are often very complex and difficult to mirror in complete detail. Since the described processes are interdependent and influenced by many parameters, they do not always follow exactly the same pattern. However, taking into consideration base calculations from current processes and procedures, a business case was developed using a simplified approach that concentrates on a few but essential parts in the workflows. The unknown or not fully developed and practically experienced processes are considered in the calculated values according to known costs but also partly based on estimations and assumptions. The output of this analysis aims to provide a rather qualitative than an absolute quantitative idea about cost ranges. In addition, a collection of capital expenditures for long-term or single purchase are displayed. Though a detailed investment analysis for the individual concepts is not part of this thesis, these capital expenditures are later used for comparison between the individual concepts in the ranking matrix. Data for the RFID system was gathered through the pricings of manufacturers and estimations. Time and additional required manpower for the non-destructive testing method are based on assumptions except the inspection charge rate of the service company. Values for the transport and/or storage systems are estimated. To compare the economic analyses of the four concepts, the base parameters for the assumed work task are specified below.

3.4.1 Assumptions for Cost and Time Estimation of Processes and Procedures

The economic analysis of the four concepts is based on the assumptions outlined below and evaluates the additional operating costs due to process changes and operating costs for equipment. Finally, savings by reduction of sucker rod breaks needed to cover the calculated additional operating costs are indicated. The goal is to give an estimation of additional costs and time effort per year for each concept.

General considerations

125 well interventions occur per year where a sucker rod string must be pulled from the well. For concept 1-3, 105 of these rod strings need to be inspected at the pipe yard. 20 of these sucker rod strings can be put directly to scrap because the engineer sees that the whole string is over the limits and decides to put them to scrap. For concept 4 which consists of a sucker rod change/control system, 75 rod strings are inspected at the wellsite, 50 in the pipe yard and 20 are put directly to scrap.

Inspection process

A sucker rod string consists of 130 sucker rods with RFID tags. 90% of 130 sucker rods pass the first inspection due to classification parameters. 117 pieces are visual inspected. 100 pieces pass visual inspection. It takes two hours to inspect 100 sucker rods using non-destructive inspection.

Additional operating costs per year

Calculation per year considers operating costs due to process changes and equipment for the RFID technology, the inspection method and the transport system itself. Due to the fact that concept 1-3 do not consider a management system with sucker rod control at the well, additional costs for transport from and to pipe yard are included in the calculation. Furthermore, it considers also process deviations due to sucker rod strings directly put to scrap.

Savings

Savings consider the average costs for a well intervention for a sucker rod break. The current average of costs for a well intervention is 74.968 EUR (Fig.49). Savings also include the average production deferment due to a sucker rod break failure. Deferment rate does not only consider the downtime of the well but the production difference until it reaches its average rate again. Therefore, data from 66 deferments of wells from December 2014 to July 2019 were taken. The average value is 31.870 EUR. The deferred production is valued with an oil price of 60$ (54,46 EUR; conversion factor US $/ EUR = 1,10167). Savings also include the excessive costs of processes.

Miscellaneous

Due to the complexity of processes and various influencing parameters and uncertainties, it is not possible to capture all cost factors exactly. To cover and consider these expenses as well, process changes, operating costs and investment costs received a 10% plus for miscellaneous expenses.

Capital expenditures

Since the objective of this economic analysis is focused on additional operating costs for a sucker rod inspection system as part of the current sucker rod management process, investment costs for required capital expenses to implement a fully functional sucker rod management system were not included in the calculations, however, estimations are displayed for comparison. A detailed investment analysis is not part of the objectives of this thesis and in particular the costs for structural changes of the pipe yard area are not evaluated and included.

3.4.2 Concept 1

At first, this chapter describes the additional costs for implementing a sucker rod management system based on the workflow and additional technologies for concept 1 outlined in chapter 3.3.1. Second, a technical evaluation was carried out for this concept to display advantages and disadvantages especially considering the application of an RFID system.

Cost estimation

Additional operating costs due to process changes refer to changes in handling and inspection per fully carried out sucker rod change. Taking the general considerations into account, additional operating process costs per year include deviations from this process flow. Since not all sucker rod strings are inspected at the pipe yard and some are put directly to scrap, some steps are not necessary.

Additional operating costs due to process changes

At the wellsite, the installation of the housing with the antenna and the electronic devices takes a few minutes in effort. Since the housing elongated the wellhead, it is sometimes necessary for the personnel to build up a mounted platform for access to the wellhead. Additional time effort to prepare for pulling sucker rods from the well is estimated with a total of 15 minutes including installation set up and installation and de-installation on the wellhead. The same time effort accounts for the process set up for pulling at the well, including de-installation of equipment and adding 30 minutes at the wellsite for each well intervention. Costs were estimated using the same hourly rate for facilities and staff as in the base case.

Since the option of a sucker rod control at the wellsite is eliminated, the sucker rods must be brought to the pipe yard. Sorting the racks with the help of the handheld reader takes additional time effort for the pipe yard personnel. The sucker rods must be placed on the racks and turned to find the position of the tag to read the information. In addition, the sucker rod status has to be updated with the handheld reader. Costs were estimated using the current charge rate for inspection of sucker rods.

Additional operating costs for equipment (Table 11)

The tags themselves create additional costs when buying new sucker rods. In addition, the placement of the tag under the rod guide and rod guide molding is considered to create additional costs to the usual molding procedure. Also, antenna and antenna cables might experience damage and have to be replaced throughout the year.

Table 11: Additional operating costs for implementation of concept 1

Additional costs due to process changes per inspection		
Description	Sucker rod change	
Well site	€	415,23
Pipe yard	€	70,28
Add. process costs per inspection	**€**	**485,51**
Additional operating costs per year		
Additional operating costs due to process changes per year	€	105 341,64
Additional operating costs for equipment per year	€	36 448,51
Add. operating costs per year	**€**	**141 790,15**

Capital expenditures for equipment

OMV Austria uses four well intervention rigs, therefore housing, reader and minicomputer have to be bought four times, with additional two sets of equipment for replacement. Furthermore, server connections (database) and certifications have to be made. The RFID tag ID and well data have to be linked to each other in the database. In addition, the RFID installations have to be certificated by TÜV Austria to prove that they fulfill the requirements. Costs for the RFID system are partly taken from manufactures and from estimations.

Savings

Savings consider saved costs due to reduction of sucker rod breaks and therefore well intervention costs. Also, deferment of production per well intervention for a sucker rod break is considered. Process costs are also saved due to reduction of well interventions for sucker rod breaks.

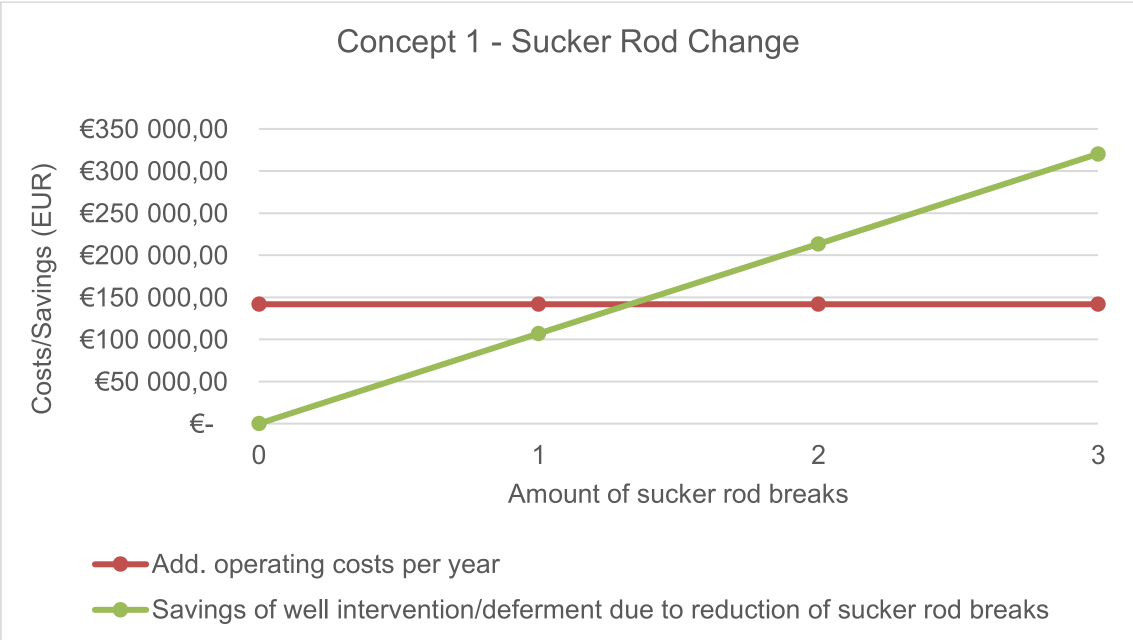

Figure 36: Required savings of well interventions/deferment to cover operating expenses per year for concept 1

Interpretation of result

The red line in figure 36 indicates the additional operating costs per year for concept 1 and the green line the amount of savings per saved sucker rod break and therefore well intervention and deferment. The x-axis depicts how many sucker rod breaks and must be saved to cover the additional operating costs. The lines cross above one so at least two sucker rod breaks must be saved per year.

Technical evaluation

Considering the implementation of an RFID system, the following benefits and limitations were identified.

Benefits (optimization potential)

A reduction of well interventions per year due to correct sorting according to the classification system and elimination of failure roots is possible. Data is automatically transferred to the database during running and pulling and sucker rods are individually trackable. Data about the well conditions, rod string position, dogleg severity etc. can be linked to the individual rods and the information gained through the tracking process can be used for establishing an advanced failure analysis system. This gives the opportunity for investigating parameters other than load cycles for classification and preventing rod failure. Furthermore, it would be possible to create an inventory management system by connecting the RFID system to SAP software. This would enable a precise warehouse entrance and exit control of individual pieces and innovative stock keeping. In addition, an optimization in rod string design can be achieved by developing a software-assisted planning process that evaluates the tagging data and calculates a design plan for the assembly position for each rod.

Limitations (risks and uncertainties)

The currently used RFID tag system is only considered for sucker rods with rod guides. A total functioning tracking system is achieved if the majority of wells with sucker rod pumps are equipped with tagged sucker rods. Rough time estimation for implementation can be made by considering the MTBF of sucker rod pumps. Additional effort for data analysis must be made and the rearrangement of storage area for additional categories in the pipe yard must be considered.

3.4.3 Concept 2

The following chapter describes the cost estimation and technical evaluation for concept 2. It includes the evaluation of all additional processes and procedures outlined in chapter 3.3.2.

Cost estimation

Cost calculations are influenced by the implementation of an RFID system in addition to a non-destructive testing device.

Additional operating costs due to process changes (Table 12)

At the wellsite, the same costs apply as described for concept 1. Whereas at the pipe yard, additional to the costs of the RFID system, the inspection of the sucker rods with the non-destructive testing device considered in the calculations. The inspection with this device is charged per piece and not on an hourly basis.

Additional operating costs for equipment (Table 12)

Same costs apply here for the RFID system as described in concept 1. Despite, costs for energy consumption of the non-destructive testing method are included. Needed connections are four standard safety outlets (230V/50 Hz, single-phase), a circuit breaker (16 A) and a residual circuit breaker (30mA). The maximum power consumption is approximately 690 W. Since the option of sucker rod control at the wellsite is eliminated, sucker rods must be inspected with the testing device at the pipe yard. This leads to an additional workload for the pipe yard personnel. Therefore, it is recommended to hire an additional person who will be responsible for the coordination of sucker rod management.

Table 12: Additional operating costs for implementation of concept 2

Additional costs due to process changes per inspection		
Description	Sucker rod change	
Well site	€	415,23
Pipe yard	€	865,69
Add. process costs per inspection	**€**	**1 280,92**
Additional operating costs per year		
Additional operating costs due to process changes per year	€	206 480,20
Additional operating costs for equipment per year	€	117 948,51
Add. operating costs per year	**€**	**324 428,71**

Capital expenditures for equipment

Again, the same costs apply here as described in concept 1. Since the NDT is currently in development, investment costs for NDT are estimated. Server connections for the NDT to save test results in the database have to be made. An additional RFID reader to identify the sucker rods for the testing device is therefore necessary. Costs for a container as operator housing to store the electronic equipment and workbenches to place and sort sucker rods before and after testing are included in the calculations as well.

Savings

The calculations include the same types of savings as described in concept 1.

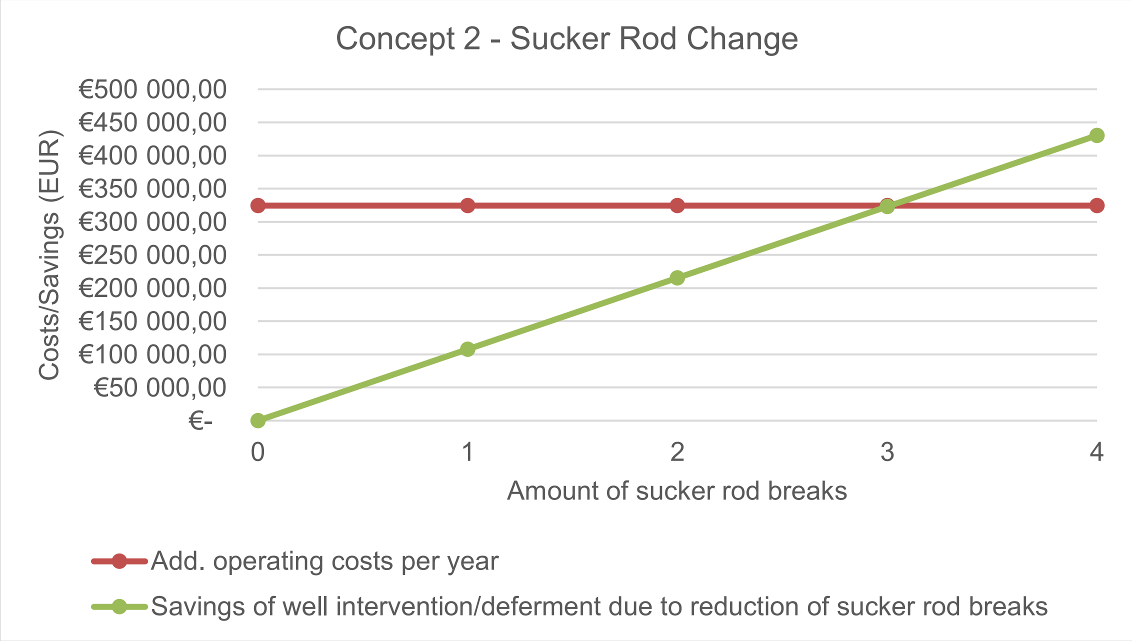

Figure 37: Required savings of well interventions/deferment to cover operating expenses per year concept 2

Interpretation of result

To cover the additional operating costs per year, at least four sucker rod breaks must be saved (Fig.37).

Technical evaluation

The evaluation concentrates on the application of a non-destructive testing device for an additional level of quality control to the RFID system.

Benefits (optimization potential)

The highly sensitive inspection method could significantly improve the detection of potential stress raises for sucker rod failure. Therefore, a more precise inspection of sucker rods for cracks, cuts and surface damages that cannot be seen with visual inspection only, could be detected. In addition, inspection for the area under the rod guide without removal is possible. The loss of cross-sectional-area can be determined, hence leading to a more accurate corrosion detection. Test results can be linked to the individual sucker rod ID. This gives the opportunity for advanced analysis of failures and well conditions that influence the materials' lifetime. Besides, the evaluation of test results can help to adjust inhibition programs.

Limitations (risks and uncertainties)

Additional time effort for inspecting sucker rods is needed at the pipe yard where also a rearrangement of the inspection area for optimized handling might be necessary. Also, the accuracy of measurement has not been verified yet. Furthermore, threads cannot be inspected with the non-destructive testing device. They have still to be inspected visually and with gages.

3.4.4 Concept 3

The concept is evaluated following the same pattern as for the concepts before. In addition, the handling of a potential transport and storage system is evaluated to get an idea how much impact it has on the overall cost situation.

Cost estimation

Besides the RFID system and a stationary placed non-destructive testing at the pipe yard, these calculations include additional costs due to process changes and equipment for a potential implemented transport/storage system for sucker rods.

Additional operating costs due to process changes (Table 13)

At the wellsite the same costs apply as described for concept 1. In addition, the staff must sort the sucker rods in and out of the transport system. This takes additional time and influences the costs of the facilities and staff.

Before sorting and inspection of sucker rods at the pipe yard, they must be taken out of the transport system and on the control racks which will elongate the process of inspection. Additional effort for office management was included as well and additional effort for handling sucker rods with a forklift for packaging.

Additional operating costs for equipment (Table 13)

The same costs apply here for the RFID system and the non-destructive testing method as described in concept 2. Besides, the transport equipment system might be exchanged with new parts on a regular basis.

Table 13: Additional operating costs for implementation of concept 3

Additional costs due to process changes per inspection		
Description	Sucker rod change	
Well site	€	1 660,92
Pipe yard	€	1 153,99
Add. process costs per inspection	**€**	**2 814,91**
Additional operating costs per year		
Additional operating costs due to process changes per year	€	395 651,50
Additional operating costs for equipment per year	€	122 948,51
Add. operating costs per year	**€**	**518 600,01**

Capital expenditures for equipment

Again, the same costs apply here as described in concept 2. In addition, costs for a special transport and storage system are estimated.

Savings

The calculations include the same types of savings as described in concept 1.

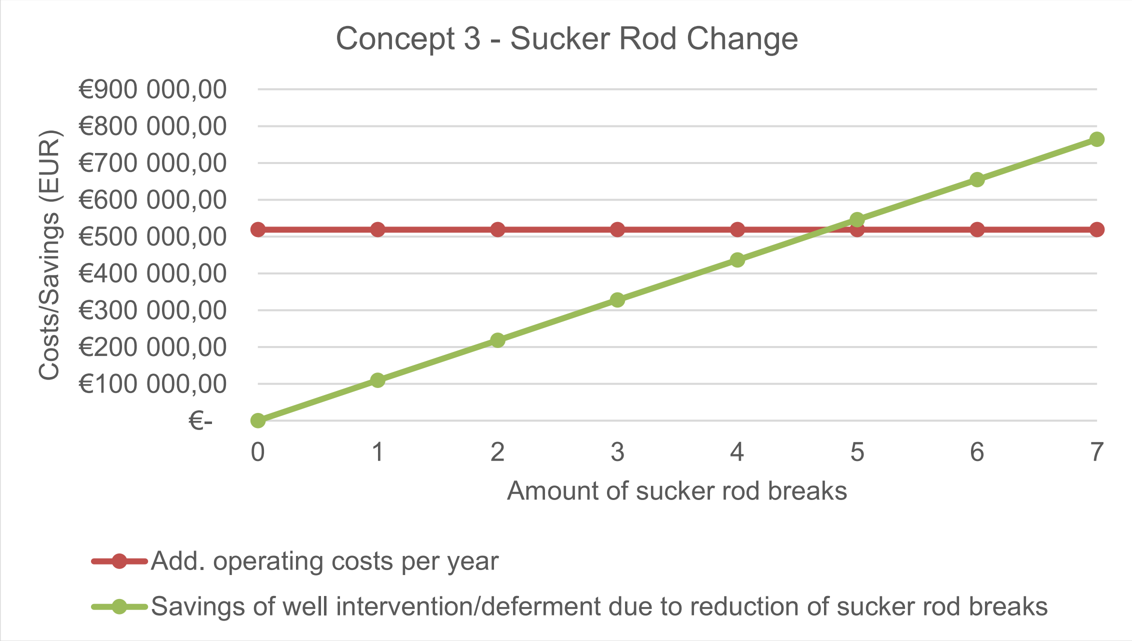

Figure 38: Required savings of well interventions/deferment to cover operating expenses per year concept 3

Interpretation of result

To cover the additional costs per year, at least five sucker rod breaks must be saved per year (Fig. 38).

Technical evaluation

The following points evaluate the application for a transport/storage system for sucker rods. In regard to the RFID and non-destructive testing, the same points apply here as well.

Benefits (optimization potential)

Advanced handling of sucker rods is provided with a transport/storage system. Sucker rods are separated from each other by layer and in stabilized position due to the frame to avoid metal to metal contact, bending and other possible damage during transport with truck and forklift. Besides, if they are put in packages and they can be stacked in the pipe yard which reduces storage area. This gives the opportunity to sort sucker rods into additional classification categories.

Limitations (risks and uncertainties)

A perfectly functional transport system for multiple reuses must be still developed. The concept depicts just the potential workflow if a transport and storage system is used. The design of the transport and storage system is rather unclear and therefore cost factors as well. As well as application issues at the pipe yard and wellsite might be encountered.

For packing the sucker rods into this transport arrangement, additional time effort for handling sucker rods must be considered Also, additional storage areas for transport system equipment and tools must be available. Sucker rods can just be handled and transported in packages and cannot be individually chosen from the storage area.

3.4.5 Concept 4

The chapter is structured in the same way as for the concepts before. A special focus lies on the evaluation of process changes due to a mobile non-destructive testing device.

Cost estimation

Besides the option of a sucker rod change with an RFID and non-destructive inspection process at the pipe yard, cost estimates also consider the option for an inspection process at the wellsite.

Additional operating costs due to process changes (Table 14)

The same costs apply as in concept 2 for a sucker rod change. Besides, if sucker rods are controlled at the well, the costs for facilities and staff rise since it is estimated that the inspection process at the wellsite will elongate the well intervention time. Costs for visual and objective inspection at the wellsite are calculated with the same time and hourly rate as inspecting the rods at pipe yard.

Considering costs for the pipe yard for a sucker rod change, the same costs are taken as for concept 2. If the non-destructive testing device is mobilized for inspection at the wellsite (sucker rod control), a rate for demobilization and mobilization is charged. Furthermore, costs for additional coordination and office work are estimated.

Additional operating costs for equipment (Table 14)

The same costs are considered as described in concept 2.

Table 14: Additional operating costs for implementation of concept 4

Additional costs due to process changes per inspection		
Description	Sucker rod change	Sucker rod control
Well site	€ 415,23	€ 2 491,37
Pipe yard	€ 865,69	€ 3 358,67
Add. process costs per inspection	€ 1 280,92	€ 5 850,05
Add. process costs per inspection (weighted)	€ 2 965,35	
Additional operating costs per year		
Additional operating costs due to process changes per year	€ 407 735,32	
Additional operating costs for equipment per year	€ 117 948,51	
Add. operating costs per year	**€ 525 683,83**	

Capital expenditures for equipment

Again, same costs apply here as described in concept 2.

Savings

The calculations include the same types of savings as described in concept 1.

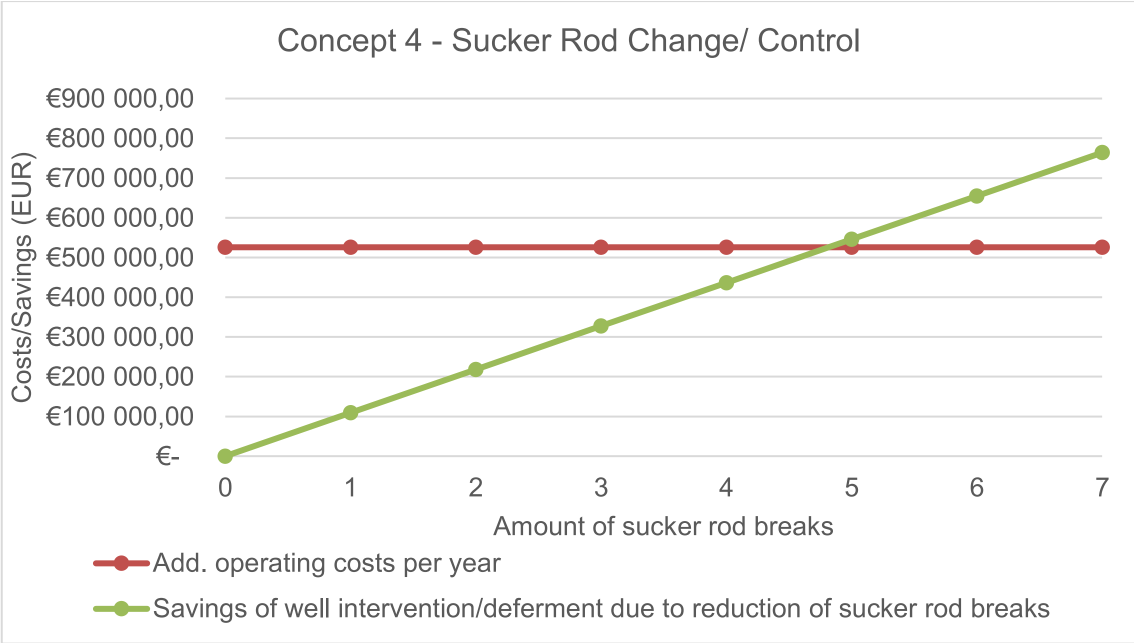

Figure 39: Required savings of well interventions/deferment to cover operating expenses per year concept 4

Interpretation of result

To cover the additional operating costs per year, at least five sucker rod breaks must be saved per year (Fig.39).

Technical evaluation

Generally, the same points as outlined in concept 2 account for this concept as well. The following arguments concentrate especially on the evaluation of processes for a sucker rod control at the wellsite.

Benefits (optimization potential)

As mentioned before, sucker rod inspection can be mobilized which enables direct inspection at the wells. Therefore, sucker rods are reinstalled in the same well which gives the opportunity for more accurate adjustments to corrosion inhibition programs.

Limitations (risks and uncertainties)

An additional time effort for inspecting sucker rods at the wellsite is needed if a sucker rod control is carried out. This could be problematic since elongation of working hours at the wellsite has a high impact on well intervention costs leading to severe time pressure. Furthermore, multiple mobilization procedures and uneven ground at the wellsite might influence the sensitivity of the measurement.

Limited space for inspection at the wellsite complicates the handling and set up of the inspection device. Due to these space issues inspection cannot be carried out at every wellsite. Additional effort for pipe yard personnel to coordinate and plan mobilization of the inspection device to not severely interfere with the inspection process at the pipe yard must also be considered.

3.5 Comparison of Concepts Using Ranking Matrix

To evaluate and compare the concepts, a ranking matrix was developed and specific evaluation criteria were defined selected for the best possible display of economic values and additional time efforts (Table 15). Criterion "Additional process costs per inspection" describes the additional costs due to process changes for a fully carried out sucker rod change process for concept 1, 2 and 3 and the average additional process costs for a fully carried out sucker rod control or change in concept 4. "Additional operating costs per year" includes the additional costs due to process changes and the additional equipment costs and personnel costs per year for the concepts. "Required saved sucker rod breaks" is defined as the amount of well interventions due to sucker rod breaks that need to be saved to cover the additional operating costs per year. "QA/QC" level indicates the various stages for a sucker rod quality system. Visual inspection is taken as a base requirement (level 1). The RFID system improves the quality control system by giving more precise information about the sucker rod classification parameter (level 2). Together with a non-destructive testing system, an additional control mechanism would be in place, therefore the QA/QC level would be even higher (level 3). For concept 3, an improved transport system would be applied to protect sucker rods during transport. Therefore, a fourth quality assurance mechanism would be in place (level 4). Capital expenditures are listed for comparison of one-time investments that have to be made to implement the various quality control systems. "Additional time (hour) at wellsite per year" describes the additional time effort needed at a well intervention using the RFID system, sorting sucker rods in and out of a transport system or installing the non-destructive testing method at the wellsite. "Additional time (hour) at pipe yard per year" estimates the additional time effort for the pipe yard personnel to sort sucker rods with an RFID system, unpacking sucker rods from a transport system or inspecting sucker rods with a non-destructive testing device. For the coordination of a properly working sucker rod management system with an RFID-system and a non-destructive testing device, an additional person for OMV is recommended to be employed. This applies to concepts 2 to 4.

Table 15: Criteria and values for comparison of concepts

Ranking Matrix - Criteria and Values				
	Concept 1	Concept 2	Concept 3	Concept 4
Criteria				
Add. process costs per inspection	€ 500	€ 1 300	€ 2 800	€ 3 000
Add. operating costs per year	€ 142 000	€ 324 000	€ 519 000	€ 526 000
Required saved sucker rod breaks per year	2	4	5	5
QA/QC level	2	3	4	3
Capital expenditures	€ 89 000	€ 110 000	€ 130 000	€ 110 000
Add. time (hour) for wellsite per year	60	60	240	290
Add. time (hour) for pipe yard per year	230	490	750	380
Additional staff (OMV)	0	1	1	1

The rating of the individual concepts is based on a grading system with points from 1 to 5, with 5 being the highest score and 1 the lowest (Table 16). The highest values are divided by the maximum points setting the grading limits (Table 29). Adding up the points for each criterion, the concepts are ranked from first place to fourth place.

Table 16: Ranking matrix of concepts

Ranking Matrix of Concepts				
	Concept 1	Concept 2	Concept 3	Concept 4
Criteria				
Add. process costs per inspection	5	3	1	1
Add. operating costs per year	4	2	1	1
Required saved sucker rod breaks per year	4	2	1	1
QA/QC level	3	4	5	4
Capital expenditures	2	1	1	1
Add. time (hour) for wellsite per year	4	4	1	1
Add. time (hour) for pipe yard per year	4	2	1	3
Additional staff (OMV)	5	1	1	1
SUM	**31**	**19**	**12**	**13**
RANKING	**1**	**2**	**4**	**3**

The results should give an idea which concept is not only favorable in economic terms. As explained before, the various concepts have their individual optimization potentials and risks and uncertainties. Therefore, the ranking matrix should indicate the economic and technical effort for each concept. Furthermore, it should provide support to the management for decision making.

4 Interpretation and Recommendation

Taking the first two criteria of "Additional process costs per inspection" and "Additional operating costs per year", significant differences between the first three concepts can be seen. The high costs of concept 3 and 4 are mainly explained by the extensive time elongation for work at the wellsite (see criterion "Additional time (hour) for wellsite per year). Additional working hours at the wellsite have severe cost impact compared to additional working hours at the pipe yard. This is caused by the high operating costs of the facilities that are needed at the wellsite for the well intervention and which remain there during the additional time required for the objective QA/QC inspection. These exaggerating costs can be avoided by transferring the inspection processes to the pipe yard. The pipe yard has more opportunities to manage the workload and is not exposed to severe time pressure.

Overall, concept 3 received the lowest rank, since the time effort for packing and unpacking sucker rods has a severe impact on the overall costs. Nonetheless, it is recommended to investigate the application of transport or packing systems further. In combination with fully or partly automated warehouse management systems e.g. with a crane instead of a forklift, handling times can be accelerated and the impact from the packing and transport process reduced and optimized.

Considering the additional quality levels ("QA/QC level") and the optimization potentials from the technical evaluation, it is assumed that each concept will reach the required reduction of sucker rod breaks. According to the result of the ranking matrix, concept 1 with the implementation of an RFID system shows the most favorable option in comparing costs to benefits. Through the data gathering of an RFID system, more accurate parameters that have a strong influence on the sucker rod life can be defined and evaluated through tools like supervised machine learning. This gives the opportunity for better adjustments of inhibition programs and preventive actions as well as the potential of higher reduction of failures than solely the reduction due to classification on the base of load cycles. Besides, the RFID system does not only show optimization potentials in quality management of goods but for inventory and warehouse management systems as well.

In combination with the non-destructive testing method it can lead to deeper knowledge and understanding of failure mechanisms. Since it is known that corrosion has an important influence on the sucker rod life, an inspection with NDT methods will be more precise than visual inspection only with the tremendous advantage that corrosion underneath molded rod guides can be detected. Furthermore, corrosion is not only affecting sucker rod material but all well components exposed to an aggressive environment. The results of data analysis provide therefore opportunities for improving the material selection of all pump system components and increasing the MTBF. In addition, the gained information supports the implementation of a software program to create an intelligent sucker rod design for each individual well.

Nonetheless, concept 2 clearly received lower points than concept 1. The reason behind this outcome is primarily explained due to higher operating costs for the testing device. This also influences the process order for inspection at the pipe yard. Therefore, the workflow pattern recommends a visual inspection before using the objective inspection. Refurbishment should remain at the end of the inspection process chain to avoid unnecessary application of lubrication, thread protectors and corrosion inhibitors. A possible solution to counteract high operating cost fluctuations would be to define a flat rate per month or year for processing a certain amount of sucker rods. This could also keep the continuous work process going in order to reduce waiting times before inspection. However, the results show that the mobilization of the device is a rather costly option and it is recommended to place it stationary at the pipe yard.

The application of a transport system as additional protection via transport, might reduce the occurrence of fine notches as well. An additional reduction in sucker rod breaks could therefore be achieved for concept 3 since a handling solution in form of a frame or transport box reduces or eliminates damages to the rods. Potential bends or cuts are minimized and will result in a longer lifetime.

Considering the criterion for “Additional time (hour) at the pipe yard per year” it is necessary to address the topic of additional workload. In exception of concept 4, the elimination of a sucker rod control is advocated. This leads to a severe rise in workload for sucker rods at the pipe yard. The additional organizational effort for concept 2, 3 and 4 can be covered by an additional person who is solely responsible for the coordination of the inspectors for processes and procedures regarding sucker rods at the pipe yard and a correctly applied management system. Besides the pipe yard will be under increased time pressure for inspection. Adjusting to weather conditions will be a limiting factor. Therefore, it is strongly recommended to roof at least the inspection area for an undisturbed working environment. In addition, the installation of an automated conservation system for sucker rods should be considered.

Capital expenditures of the concepts do not differ as much as other criteria in the valuation, though concept 1 shows the lowest expenses.

Finally it has to be mentioned that inspection and refurbishment of used rods are generally more favorable than buying new rods. This assumption is based on the comparison of additional operating costs of concepts with costs of new rods. Taking the average value for new sucker rods from table 7 and choosing to not control and inspect rods at all and instead of buying new, the add. expenses of over 1 million EUR have to be made per year. Even if the option of sucker rod control at the wellsite remains and just eliminating the inspection at pipe yard, which would lead to add. expenses of about 350.000 EUR for new rods per year, still a clear preference for concept 1 and 2 is indicated.

5 Conclusion

Since there is not always one simple solution, this thesis offers a selection of ideas for implementing innovative and efficient systems for sucker rod management. The analysis of the current situation shows major weak points and optimization potentials. This includes especially inconsistent understanding of classification systems, processes and procedures. Though specifications and guidelines do exist in theory, they do not find a correct or consequently followed application in practice. Lacks in information and communication are important points that need to be addressed and discussed. Based on current information about processes and procedures, a base case was formed to mirror an average situation for sucker rod management in OMV. During the data gathering, various obstacles were encountered. For example, the lack of tracking technical and cost factors for sucker rods and the strong interdependencies of these factors with parameters that are difficult to measure.

The various concepts describe solutions for overcoming these issues on different levels. First workflow patterns were developed considering different technologies and their combination with one another. The end goal of the work pattern is an improved quality management system for sucker rods, a correct application for classification criteria and a redesign of the system in its key aspects. Using the base case, a business case was developed and calculations for additional economical and technical efforts were applied and evaluated. The results of the ranking matrix show the most beneficial concept. Furthermore, they should give support to decision-makers for weighing their options.

Due to the fact that the application of the RFID system and the non-destructive inspection method are still in a testing or development phase, some technical questions are still open and shall be further investigated. As the projects progress with time, adjustments to the proposed concepts must certainly be made. The RFID system provides not only a solution for better data gathering for classification systems but also for improved inventory management. With wider application and further technical improvements of the system, limiting issues can be addressed and solutions for smart warehouse management with SAP developed.

The application and mechanism of the non-destructive testing device provide in addition to tagging, objectively measured material status data for better classification as well as for an easier understanding of failure mechanisms. The sensitivity and accuracy of the system and the value to the QA/QC inspection of sucker rods are points that should be further investigated and proven.

Transport and storage systems and warehouse management systems open a wide field for research to decide on the most practical one for a changed sucker rod management system. Existing systems and solutions for tubular goods from different companies show high potentials for improvements and on the long run saving and with high confidence it is assumed that existing concepts can be modified to benefit also a sucker rod management system.

In conclusion, the results of this thesis show that with relatively minimal efforts in economic and technical terms, the establishment of a high-level management and quality control/quality assurance system for sucker rods for OMV Austria and especially the pipe yard in Prottes can be initiated. Every well intervention causes additional costs and time for the company. Therefore, it should be a main priority to further look for optimization opportunities. The application of new innovative technologies and the willingness to change and redesign systems will be the first steps towards improvement.

References

Abou El Majd, B. (2014): Multi-level optimal deployment of RFID readers by using particle swarm optimization., 2014.

API (2008a): API 11L Design Calculations for Sucker Rod Pumping Systems, American Petroleum Institute, 2008.

API (2008b): API RP 11BR Recommended Practice for the Care and Handling of Sucker Rods, American Petroleum Institute, 2008.

API (2010): API Specification11B Specification for Sucker Rods, Polished Rods and Liners, Couplings, Sinker Bars, Polished Rod Clamps, Stuffing Boxes, and Pumping Tees, American Petroleum Institute, 2010.

API (2019): Publications Programs Services 2019, American Petroleum Institute, URL: https://www.api.org/~/media/Files/Publications/2019_Catalog/2019_Pubs%20Catalog_final.pdf (Retrieved: 13.02.2020).

ASNT (2019): Introduction to Nondestructive Testing. The American Society of Non Destructive Testing. URL: https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT (Retrieved: 05.09.2019).

Baotou Liande Oil and Mechanical (2019): Sucker Rod with Various Grades and Specs. URL: http://suckerrodchina.com/suckerrod/sucker-rod.html (Retrieved: 17.12.2019).

Beckwith, R. (2014): Pumping Oil: 155 Years of Artificial Lift. In: Journal of Petroleum Technology, Vol. 66, No. 10, pp. 101–107.

Bhagi, P. C. (2012): Magnetic Flux Leakage Testing: Basics. In: Journal of Non-Destructive Testing & Evaluation, Vol. 13, pp. 7–19.

Blair, K. (2000): General Design Principles for DuPont Engineering Polymers., p. 136.

Bradley, H. B. (1987): Petroleum Engineering Handbook. 3., Richardson, TX, U.S.A.: Society of Petroleum Engineers. ISBN 1-55563-010-3.

Campbell, F. C. (2013): Inspection of Metals - Understanding the Basics. ASM International.

Cheremisinoff, N. P. (1996): Polymer characterization: laboratory techniques and analysis. Westwood, N.J: Noyes Publications. ISBN 978-0-8155-1403-9.

Cobalt (2019): Sucker Rod Inspection, Used Sucker Rods Refurbished, Used Sucker Rods for Sale. URL: https://www.cobaltextreme.com/Sucker-Rod-Inspection.html (Retrieved: 28.06.2019).

Drury, J. C. (2018): Magnetic Flux Leakage Technology. In: Silverwing (UK) Limited.

Felemban, E. A.; Sheikh, A. A.; Arabia, S. (2013): RFID for Oil and Gas Industry: Applications and Challenges., 2013.

Forsthoffer, M. S. (2017): More Best Practices for Rotating Equipment. Butterworth-Heinemann. ISBN 978-0-12-811409-4.

Han, W.; Xu, J.; Wang, P. (2014): Defect Profile Estimation from Magnetic Flux Leakage Signal via Efficient Managing Particle Swarm Optimization. In: Sensors (Basel, Switzerland), Vol. 14, pp. 10361–10380.

Hein, N. W. J.; Hermanson, D. E. (1993): A New Look at Sucker Rod Fatigue Life. Proceedings of SPE Annual Technical Conference and Exhibition, januari 1 1993. Society of Petroleum Engineers. ISBN 978-1-55563-481-0.

Hertzberg, R. W.; Vinci, R. P.; Hertzberg, J. L. (2013): Deformation and Fracture Mechanics of Engineering Materials. Fifth edition, Wiley.

Hofstätter, H. (2019a): Artificial Lift Systems -General. Lecture Notes, Mining University Leoben, 2019.

Hofstätter, H. (2019b): Sucker Rod. Lecture Notes, Mining University Leoben, 2019.

Hönig, S. (2012): Specification for Sucker Rods, Pony Rods and Polished Rods, OMV, Internal Document, 18.10.2012.

Janßen, M.; Maier, R. (2019): Feldtaugliche Vor-Ort Prüfung von gebrauchten und mit Protektoren (Centralizer) ausgestatteten Pumpstangen mit der Streuflussmethode.

Kavoussi, F. (2014): Artifical Lift - Sucker Rod Pump, OMV, Internal Document, 10.07.2014.

Li, N.; Becerik-Gerber, B. (2011): Life-Cycle Approach for Implementing RFID Technology in Construction: Learning from Academic and Industry Use Cases. In: Journal of Construction Engineering and Management, Vol. 137, pp. 1089–1098.

Lindemann, T. (2019): Classification of used sucker rods based on parameters influencing rod failure. Dissertation, Mining University Leoben.

Liukkonen, M.; Havia, E.; Montonen, H.; Hiltunen, Y. (2014): Life-cycle covering traceability and information management for electronic product using rfid., p. 65.

Lyons, W. C. (1996): Standard Handbook of Petroleum and Natural Gas Engineering. Gulf Professional Publishing. ISBN 978-0-88415-643-7.

MagnaSafe (2019): Autoclaves for Corrosion Testing & Studies Amar Equipments. MagnaSafe International. URL: https://magnasafe.com/products/corrosion-testing-autoclaves.php (Retrieved: 05.09.2019).

Mahoney, M. W. (2006): Pitfalls in Performance-Data Tracking of Sucker-Rod Pumped wells. Proceedings of SPE Annual Technical Conference and Exhibition, januari 1 2006. Society of Petroleum Engineers. ISBN 978-1-55563-149-9.

Manghani, K. (2011): Quality assurance: Importance of systems and standard operating procedures. In: Perspectives in Clinical Research, Vol. 2, No. 1, pp. 34–37.

Marschall, Ch. (2018): Artificial lift performance indicators. Workshop, OMV, Internal Document, 31.01.2018.

Mitra, N. K. (2012): Principles of Artificial Lift. New Delhi: Allied Publishers. ISBN 978-81-8424-764-0.

Moen, R.; Norman, C. (2009): Evolution of the PDCA Cycle.

Motamedi, A.; Hammad, A. (2009): Lifecycle management of facilities components using radio frequency identification and building information model. In: Journal of Information Technology in Construction (ITcon), Vol. 14, No. 18, pp. 238–262.

Mouritz, A. P. (2012): Introduction to aerospace materials. Reston, VA : Cambridge, UK: American Institute of Aeronautics and Astronautics ; Woodhead Pub. ISBN 978-1-60086-919-8.

Mraz, S. (2015): Mineral Fillers Improve Plastics. Machine Design. URL: https://www.machinedesign.com/materials/mineral-fillers-improve-plastics (Retrieved: 05.09.2019).

MSI Pipe Protection Technologies (2019): Rhino® Tubular Handling Systems from Essentra. Essentra. URL: https://essentrapipeprotection.com/rhino-tubular-handling-systems/ (Retrieved: 14.12.2019).

National Oilwell Varco (2019): Application of Molded and FIield Installed Sucker Rod Guides - Sucker Rod and Tubing Wear Prevention, URL:

http://www.lbcg.com/media/downloads/events/405/cop15-day-two-1020-matt-davison-nov-tuboscope.7007.pdf (Retrieved: 05.09.2019).

National Oilwell Varco (2019): Rod Rotator. URL: https://www.nov.com/Segments/Completion_and_Production_Solutions/Process_and_Flow_Technologies/Artificial_Lift/Rod_Pump_Systems/Rod_Rotators.aspx (Retrieved: 08.08.2019).

National Oilwell Varco (2019): Sucker Rod Inspection Services. URL: https://www.nov.com/products/sucker-rod-inspection-services (Retrieved: 14.02.2020).

Norris (2007): Norris_Brochure Failure Analysis, URL: http://www.perf-chem.com/storage/UserFileFolder/Norris_Brochure_2.pdf (Retrieved: 27.06.2019).

Oberndorfer, M. (2018): Metallurgie und Korrosion für Erdölingenieure. Lecture script, Leoben, 2018.

Obersriebnig, J. (2016): Solutions for Sucker Rod Pump Systems in Sandy Conditions. Dissertation, Mining University Leoben.

Omni-ID (2020): Rugged RFID Tags for the Energy Industry. Omni-ID. URL: https://www.omni-id.com/oil-gas-industry/ (Retrieved: 14.02.2020).

OMV Austria E&P GmbH (2019a): Factsheet OMV Austria Exploration & Production GmbH, URL: https://www.omv.at/services/downloads/00/omv.at/1522140779042/%20Fact_sheet_exploration_production_austria_de.PDF.

OMV Austria E&P GmbH (2019b): GDB - General Database. OMV Austria E&P GmbH.

OMV Austria E&P GmbH (2019c): MTBF submission September 2019 - Excel file extract GDB, 08.10.2019.

Parameswaran Nampoothiri, M. P. (2001): Evaluation of the Effectiveness of API-Modified Goodman Diagram in Sucker Rod Fatique Analysis. Dissertation, Texas Tech University.

Schlumberger (2019): pony rod - Schlumberger Oilfield Glossary. Schlumberger. URL: https://www.glossary.oilfield.slb.com/en/Terms/p/pony_rod.aspx (Retrieved: 12.08.2019).

Shimadzu (2020): Principle of Optical Emission Spectrometry : SHIMADZU (Shimadzu Corporation). URL: https://www.shimadzu.com/an/elemental/oes/oes.html (Retrieved: 14.02.2020).

Stewart, M. (2019): Surface Production Operations. Gulf Professional Publishing. ISBN 978-0-12-809895-0.

Takács, G. (2003): Sucker-Rod Pumping Manual. PennWell Corporation. ISBN 978-0-87814-892-9.

Takács, G. (2015): Sucker-rod Pumping Handbook: Production Engineering Fundamentals and Long-Stroke Rod Pumping. Gulf Professional Publishing. ISBN 978-0-12-417212-8.

Tenaris (2018): Sucker Rods Catalogue, URL: http://www.tenaris.com/~/media/Files/SuckerRods/SuckerRodsTechnicalCatalogue.ashx. (Retrieved: 16.12.2019)

The Weir Group (2019): Rod Rotators Weir Oil & Gas. The Weir Group. URL: https://www.global.weir/products/product-catalogue/rod-rotators/ (Retrieved: 16.12.2019).

Torell, W.; Avelar, V. (2004): Mean Time Between Failure: Explanation and Standards.

Total Materia (2019): Introduction to the SAE-AISI Designation System :: Total Materia Article. Total Materia. URL:

https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=kts&LN=EN&NM=333 (Retrieved: 13.08.2019).

TWI (2019): What are the advantages and disadvantages of eddy current testing? - TWI. TWI. URL: https://www.twi-global.com/technical-knowledge/faqs/faq-what-are-the-advantages-and-disadvantages-of-eddy-current-testing (Retrieved: 18.09.2019).

Varotsis, A. B. (2019): Introduction to Injection Molding | 3D Hubs. 3D Hubs. URL: https://www.3dhubs.com/knowledge-base/injection-molding-manufacturing-technology-explained#what (Retrieved: 05.09.2019).

Weatherford (2006): Sucker Rods, URL: http://uhspe.org/wp-content/uploads/2014/11/Weatherford-Artificial-Lifts-Sucker-Rods.pdf (Retrieved: 05.08.2019).

Weatherford (2016): Sucker Rod Guides, URL: https://www.weatherford.com/en/documents/brochure/products-and-services/production-optimization/sucker-rod-guides/ (Retrieved: 05.09.2019).

Wiederhorn, S.; Fields, R.; Low, S.; Bahng, G.-W.; Wehrstedt, A.; Hahn, J.; Tomota, Y.; Miyata, T.; Lin, H.; Freeman, B.; Aihara, S.; Hagihara, Y.; Tagawa, T. (2006): Mechanical Properties. In: Czichos, H.; Saito, T.; Smith, L. (Eds.): Springer Handbook of Materials Measurement Methods. Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN 978-3-540-30300-8, pp. 283–397.

Zehethofer, G. (2016): Technical Specification and QA/QC for OCTG & Sucker Rod Procurement, OMV, Internal Document, 19.09.2016.

Appendix

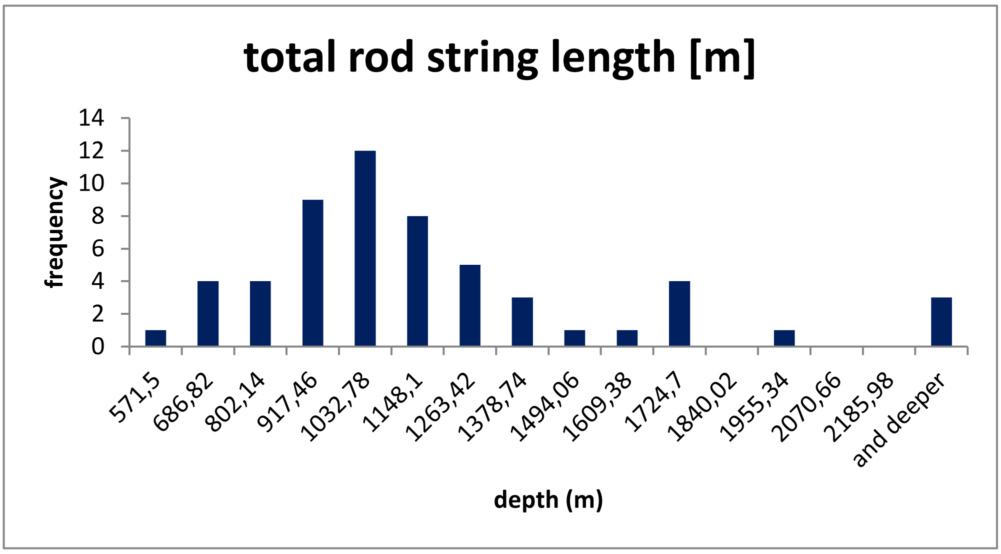

Figure 40: Total rod string length, extract from general database[171]

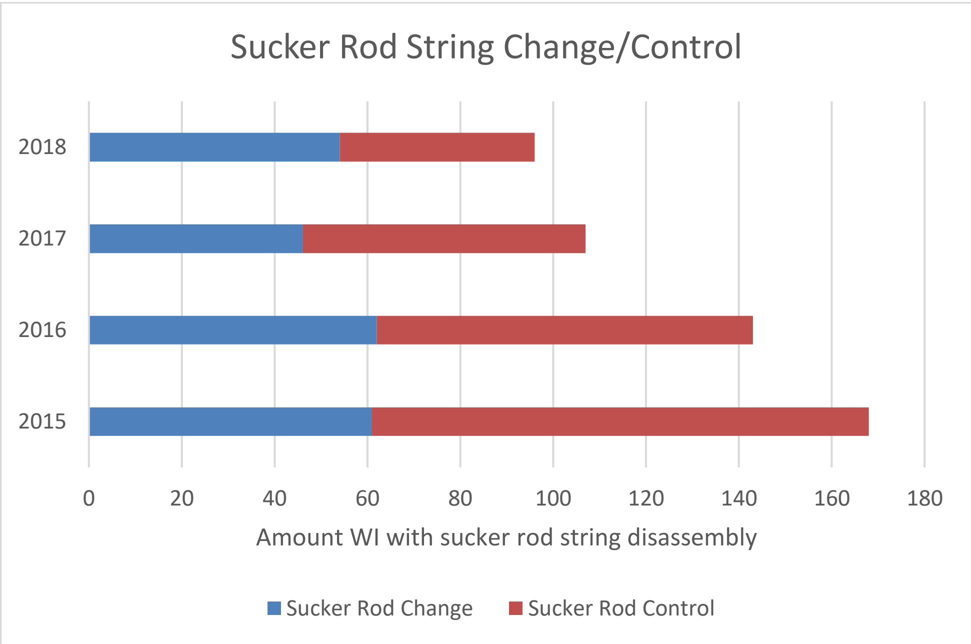

Figure 41: Sucker rod string change and control 2015-2018 extract form general database

[171] Cf. Lindemann, T. (2019)

Concept 1

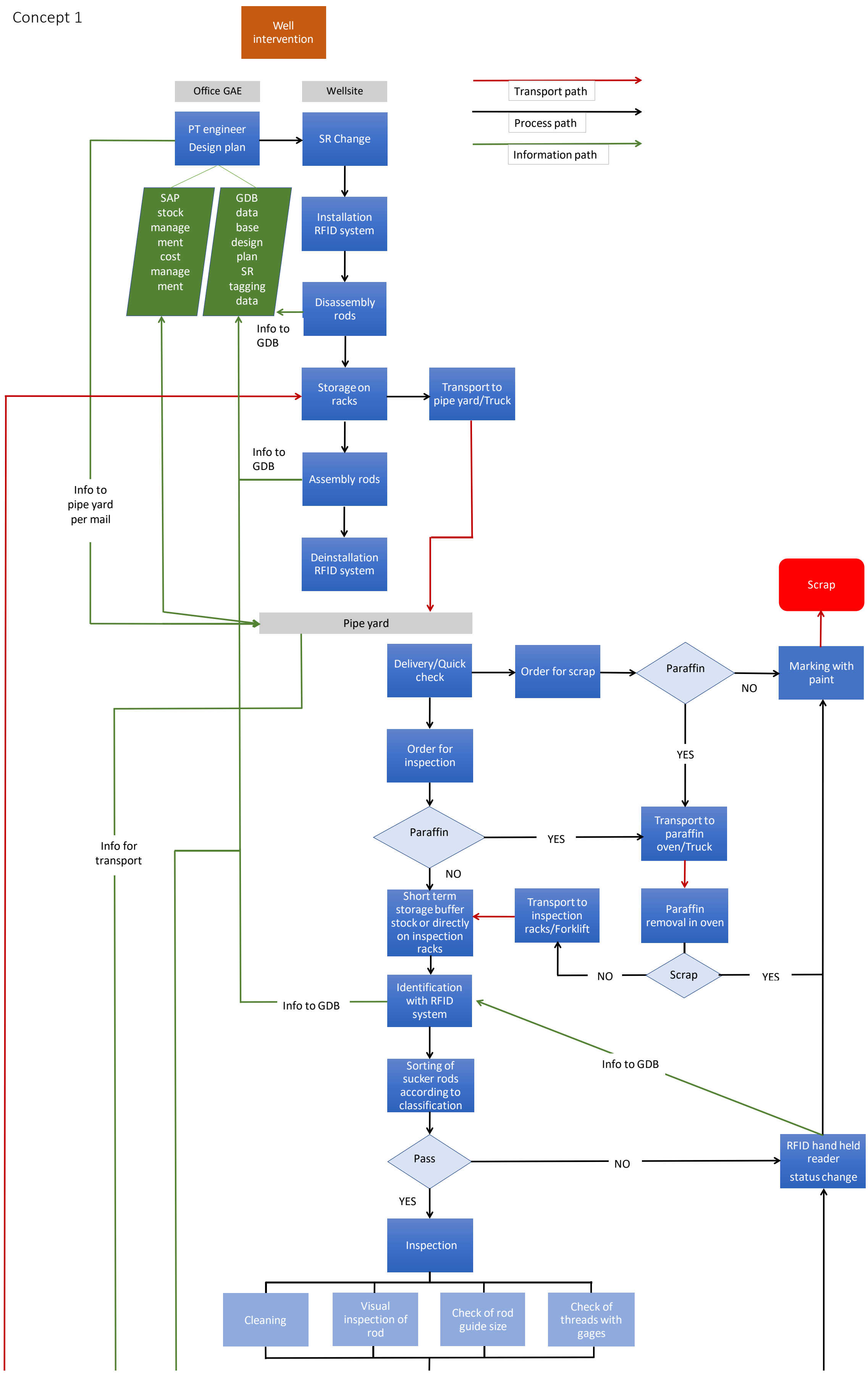

Figure 42: Workflow for concept 1 part 1

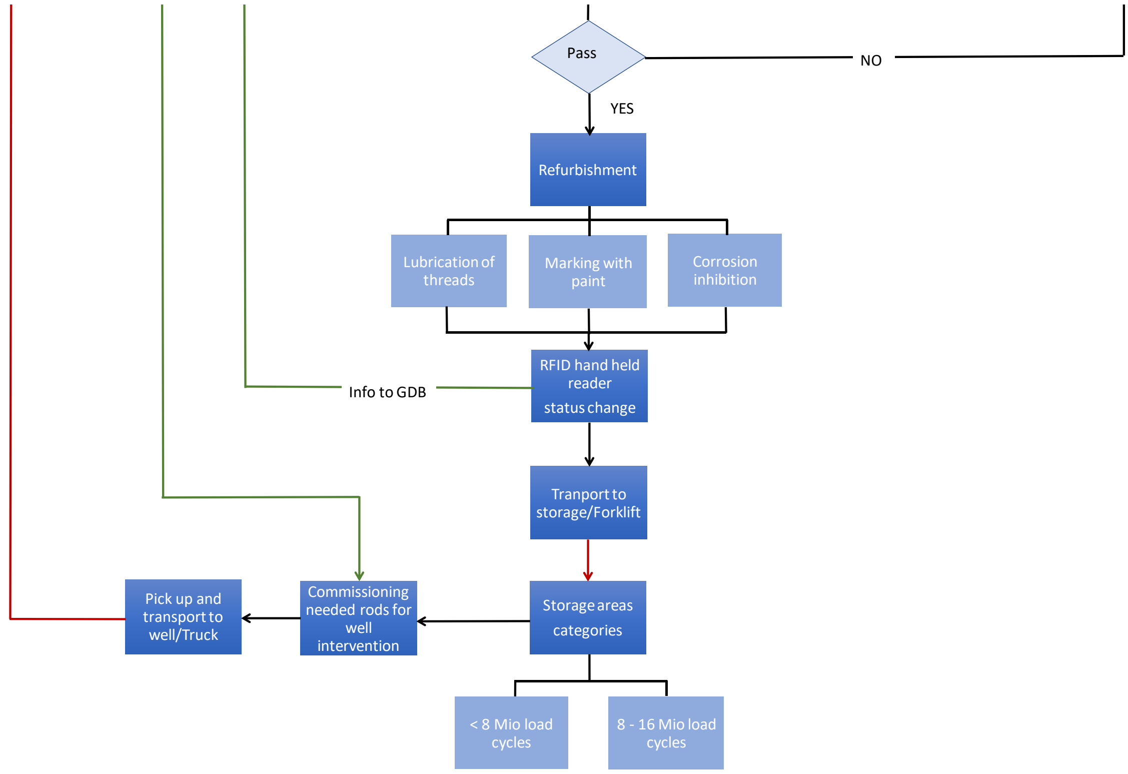

Figure 43: Workflow for concept 1 part 2

Concept 2

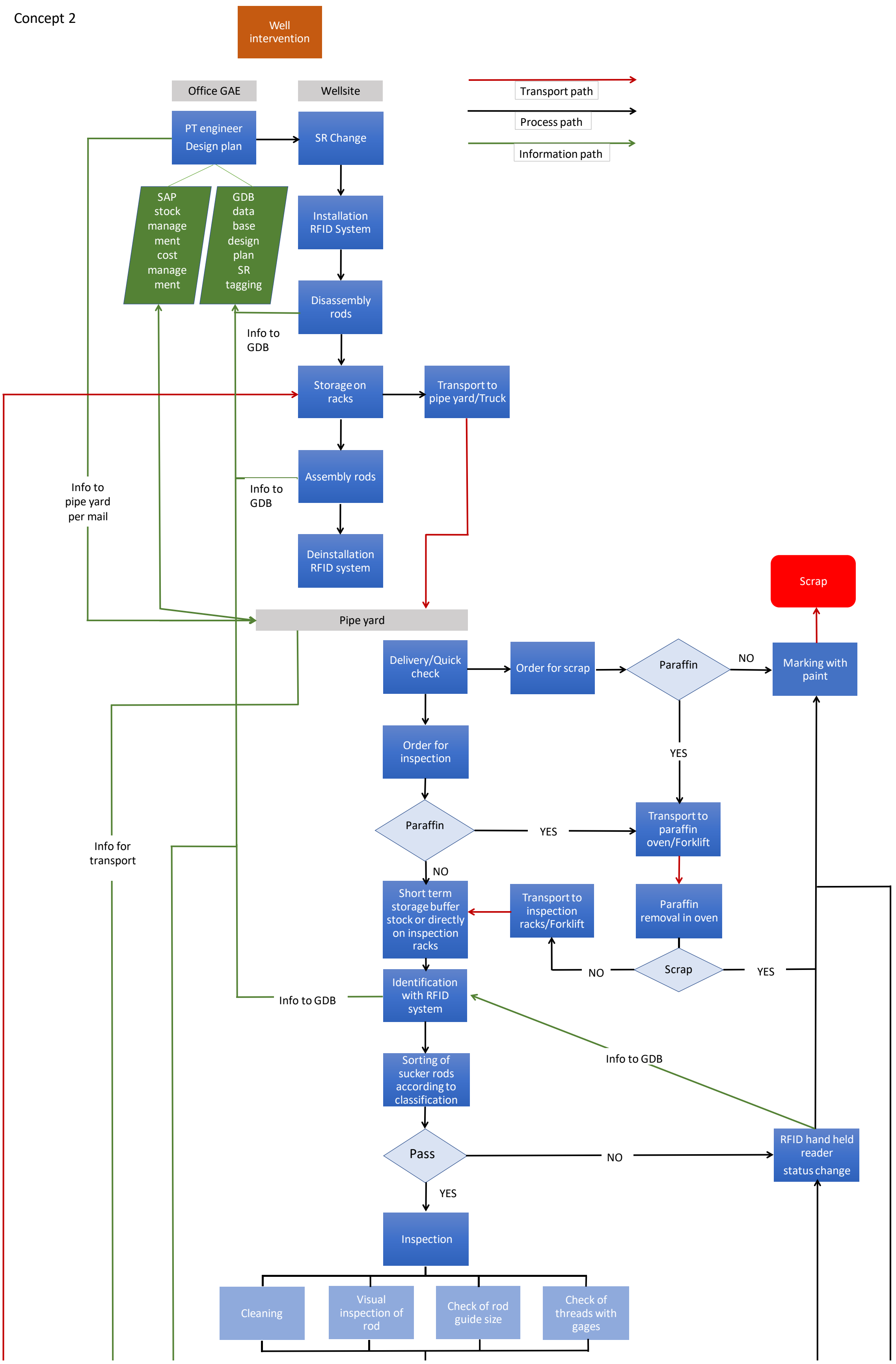

Figure 44: Workflow for concept 2 part 1

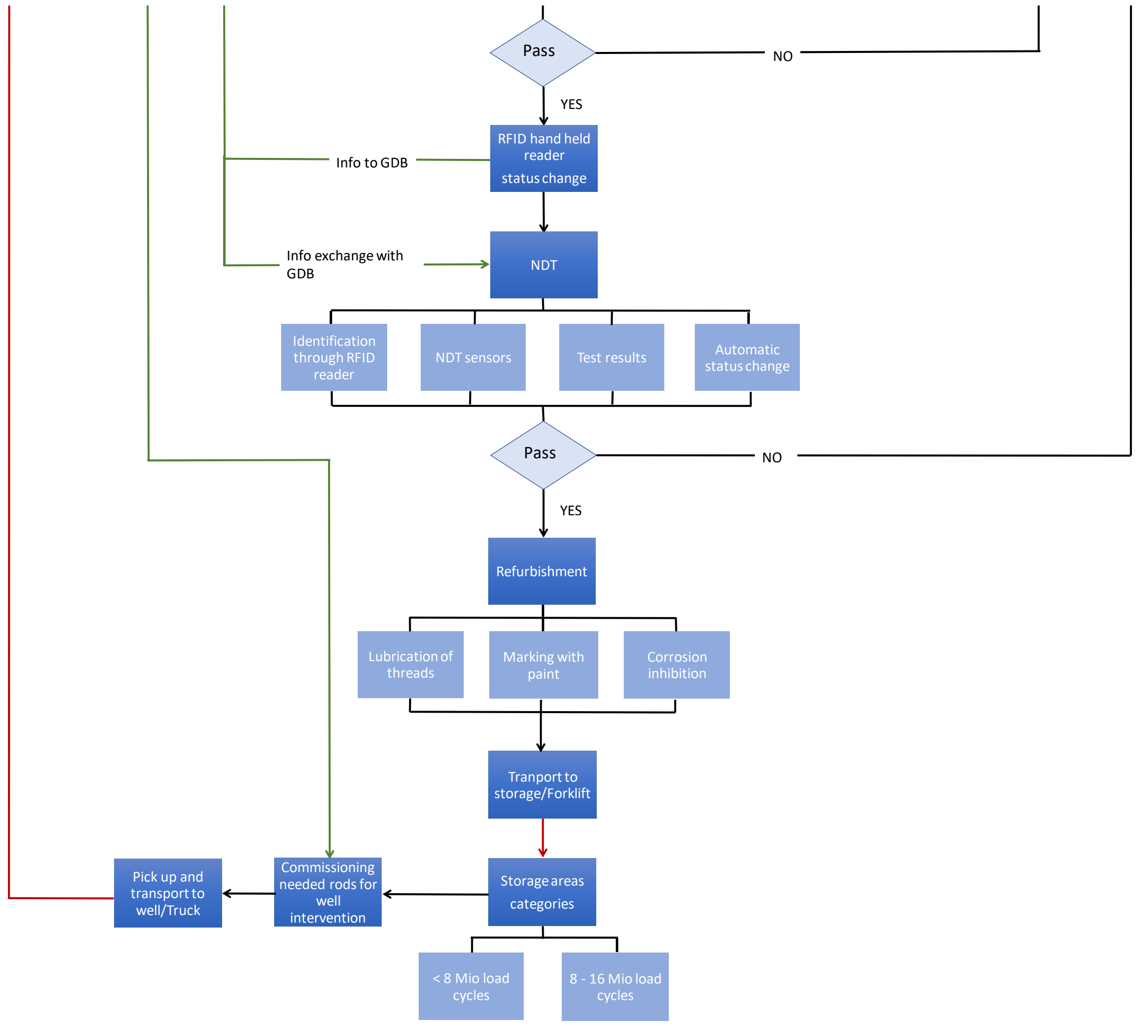

Figure 45: Workflow for concept 2 part 2

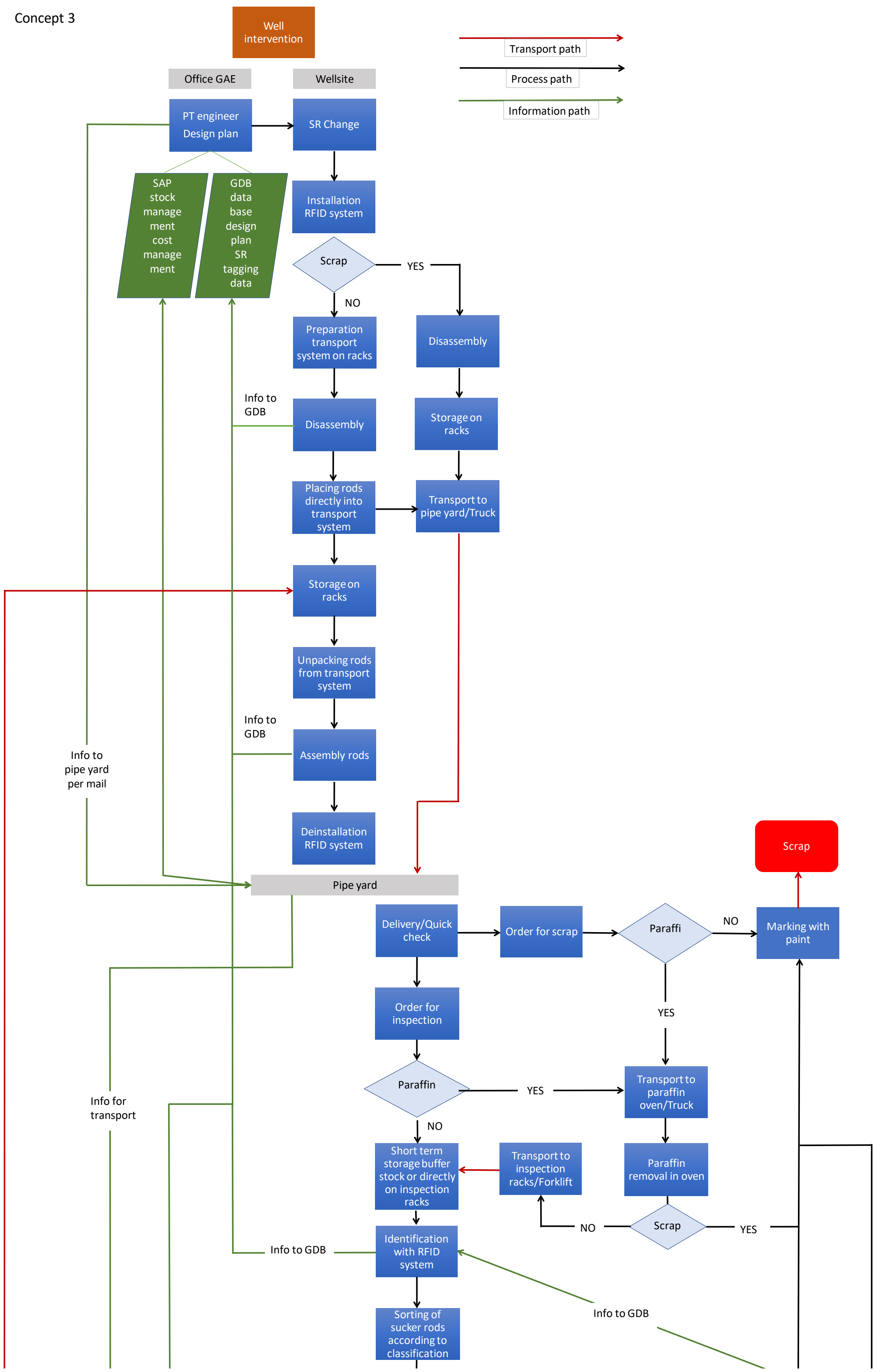

Figure 46: Workflow for concept 3 part 1

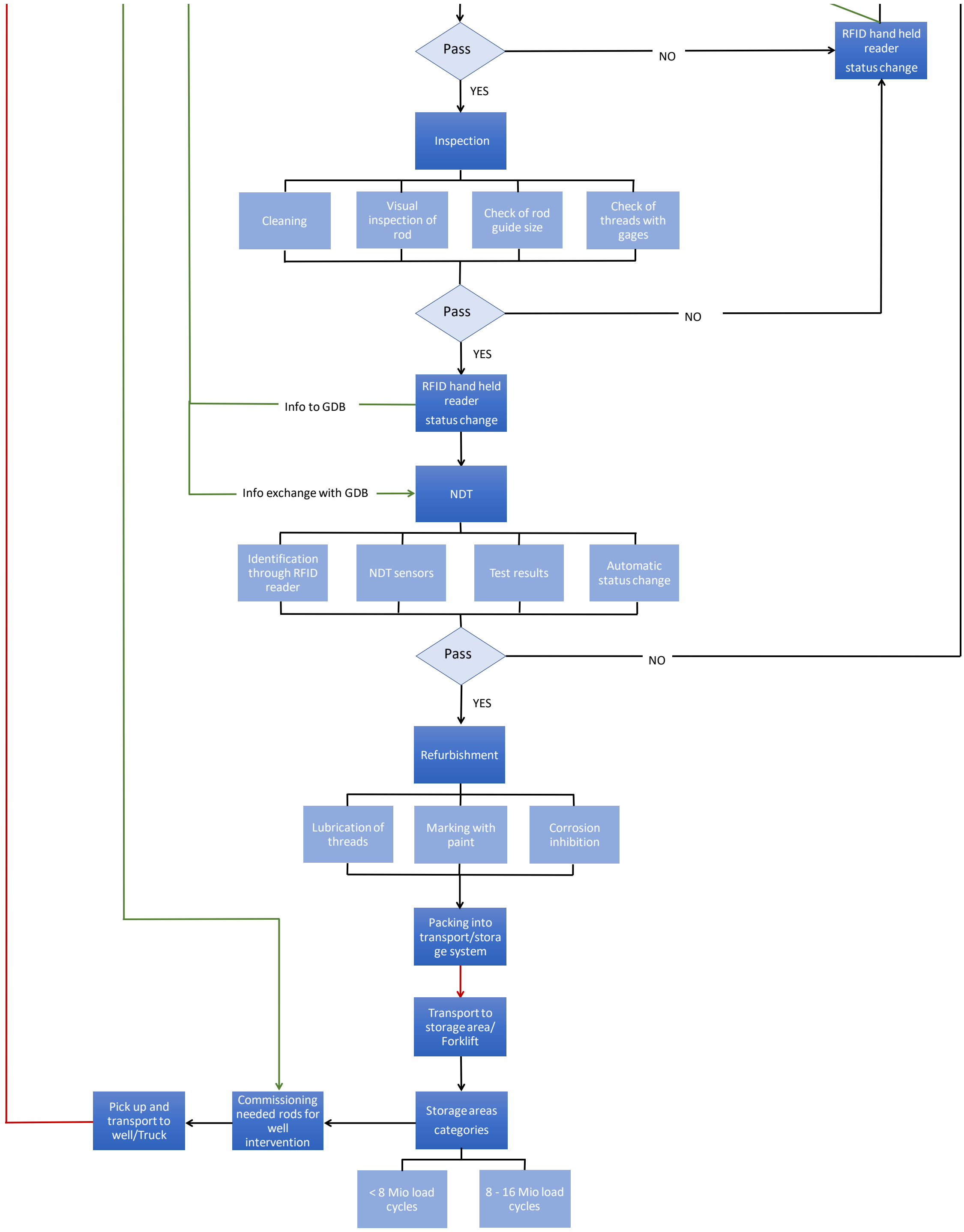

Figure 47: Workflow for concept 3 part 2

Concept 4

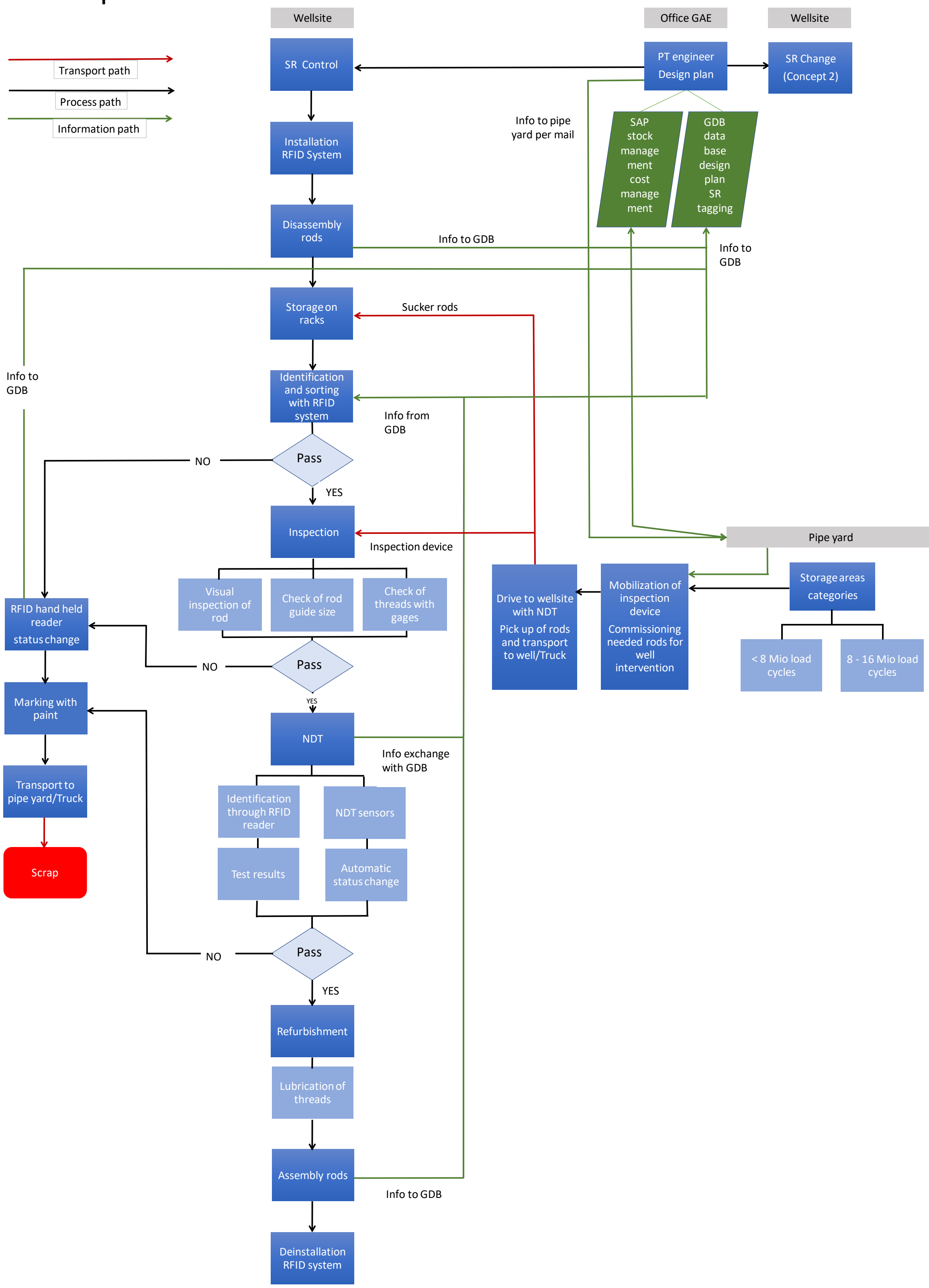

Figure 48: Workflow for concept 4 (sucker rod control)

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Table 17: Calculations base case sucker rod change

SR CHANGE						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base		Nr.	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
Facility costs	EUR				4152,29	
Truck tubular transport	h		8,00	115,00	920,00	avg transport costs between pipe yard and well, loading at pipe yard
Transport (contractor) total	EUR				920,00	
Avg. Costs/SR	**EUR**				**39,02**	
Total well intervention	**EUR**				**5072,29**	
Pipe yard handling and care						
Description	Calculation base	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Paraffin oven	h		10,00	49,04	490,40	removal of paraffin, loading and unloading, facility costs etc
Inspection staff	h/person	2,00	10,50	50,87	1068,27	incl. Personnel costs, maintenance, handling, material costs
Inspection staff (back delivery)	h/person	2,00	2,00	50,87	203,48	excessive rods from wellsite
Office management	h/person	1,00	0,50	38,82	19,41	stock management, invoices, planning
Total pipe yard with paraffin	**EUR**				**1781,56**	
Total pipe yard without paraffin	**EUR**				**1291,16**	
Avg. Costs	**EUR**				**1389,24**	
Costs/SR with paraffin	**EUR**				**13,70**	
Costs/SR without paraffin	**EUR**				**9,93**	
Avg. Costs/SR	**EUR**				**11,82**	
Avg. Total pipe yard					**6461,53**	

Table 18: Calculations base case sucker rod control

SR CONTROL						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base		Nr.	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
Facility costs	EUR				4152,29	
Truck tubular transport	h		4,00	115,00	460,00	avg. transport costs between pipe yard and well, (un)loading at pipe yard
Transport (contractor) total	EUR				460,00	
Avg. Costs/SR	**EUR**				**35,48**	
Total well intervention	**EUR**				**4612,29**	

Pipe yard handling and care						
Description	Calculation base	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Inspection staff (back delivery)	h/person	2,00	2,00	50,87	203,48	excessive rods from wellsite
Avg. Costs/SR	**EUR**				**1,57**	
Total pipe yard	**EUR**				**4815,77**	

Table 19: Calculations concept 1 sucker rod change

SR CHANGE						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base		hours	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
RFID system	h		0,50	830,46	415,23	installation/deinstallation
Facility costs	EUR				4567,52	
Truck tubular transport	h		8,00	115,00	920,00	
Transport (contractor) total	EUR				920,00	average transport costs for SR change
Total well intervention	**EUR**				**5487,52**	
Avg. Costs/SR	**EUR**				**42,21**	
PLUS WI	**EUR**				**415,23**	
Pipe yard handling and care						
Description	Calculation base	Staff	hours	Price EUR/Unit	Result EUR	Comment
Paraffin oven	h		10,00	49,04	490,40	removal of paraffin, loading and unloading, facility costs etc
Inspection staff	h/person	2,00	9,50	50,87	966,53	1 hour less due to RFID sorting
Inspection staff	h/person	2,00	1,50	50,87	152,61	handheld reader, sorting sucker rods
Inspection staff (back delivery)	h/person	2,00	2,00	50,87	203,48	
Office management	h/person	1,00	0,50	38,82	19,41	
Office management	h/person	1,00	0,50	38,82	19,41	additional effort for coordination
Total pipe yard with paraffin	**EUR**				**1851,84**	
Total pipe yard without paraffin	**EUR**				**1361,44**	
Costs/SR with paraffin	**EUR**				**14,24**	
Costs/SR without paraffin	**EUR**				**10,47**	
Avg. Costs/SR	**EUR**				**11,23**	
Plus PY	**EUR**				**70,28**	
PLUS TOTAL	**EUR**				**485,51**	**add. costs due to process changes per WI with inspection**

Table 20: Calculations concept 2 sucker rod change

SR CHANGE						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base		Nr.	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
RFID system	h		0,50	830,46	415,23	installation/deinstallation
Facility costs	EUR				4567,52	
Truck tubular transport	h		8,00	115,00	920,00	average transport costs for SR change
Transport (contractor) total	EUR				920,00	
Total well intervention	**EUR**				**5487,52**	
Avg. Costs/SR	**EUR**				**42,21**	
PLUS WI	**EUR**				**415,23**	
Pipe yard handling and care						
Description	Calculation base	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Paraffin oven	h		10,00	49,04	490,40	removal of paraffin, loading and unloading, facility costs etc.
Inspection staff	h/person	2,00	9,50	50,87	966,53	1 hour less due to RFID sorting
Inspection staff (back delivery)	h/person	2,00	2,00	50,87	203,48	
Inspection staff	h/person	2,00	1,50	50,87	152,61	handheld reader, sorting sucker rods
Office management	h/person	1,00	0,50	38,82	19,41	
Office management	h/person	1,00	1,00	38,82	38,82	additional effort for coordination
Objective Inspection	unit		100,00	7,76	776,00	2 hours
Total pipe yard with paraffin	**EUR**				**2647,25**	
Total pipe yard without paraffin	**EUR**				**2156,85**	
Costs/SR with paraffin	**EUR**				**20,36**	
Costs/SR without paraffin	**EUR**				**16,59**	
Avg. Costs/SR	**EUR**				**17,35**	
PLUS PY	EUR				865,69	
PLUS TOTAL	**EUR**				**1280,92**	**add. costs due to process changes per WI with inspection**

Table 21: Calculations concept 3 sucker rod change

SR CHANGE						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base		Nr.	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
RFID reader installation	h		0,50	830,46	415,23	installation/deinstallation
Sorting sucker rods in and out of transport system	h		1,50	830,46	1245,69	
Facility costs	EUR				5813,21	
Truck tubular transport	h		8,00	115,00	920,00	average transport costs for SR change
Transport (contractor) total	EUR				920,00	
Total well intervention	**EUR**				**6733,21**	
Avg. Costs/SR	**EUR**				**51,79**	
PLUS WI					**1660,92**	
Pipe yard handling and care						
Description	Calculation base	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Paraffin oven	h		10,00	49,04	490,40	removal of paraffin, loading and unloading, facility costs etc
Inspection staff	h/person	2	9,50	50,87	966,53	1 hour less due to RFID sorting
Inspection staff (back delivery)	h/person	2	2,00	50,87	203,48	
Handling	h/person	2	2,50	50,02	250,1	put sucker rods out of transport box, sorting sucker rods
Office management	h/person	1	0,50	38,82	19,41	
Office management	h/person	1	1,00	38,82	38,82	additional effort for coordination
Objective Inspection	unit		100,00	7,76	776,00	2 hours
Sorting into storage system	h	2	1,00	50,02	100,04	
Forklift	h	1	1,00	90,77	90,77	additional effort transporting packaging system
Total pipe yard with paraffin	**EUR**				**2844,78**	
Total pipe yard without paraffin	**EUR**				**2354,38**	
Costs/SR with paraffin	**EUR**				**21,88**	
Costs/SR without paraffin	**EUR**				**18,11**	
Avg. Costs/SR	**EUR**				**18,87**	
PLUS PY	**EUR**				**1153,99**	
PLUS TOTAL	**EUR**				**2814,91**	**add. costs due to process changes per WI with inspection**

Table 22: Calculations concept 4 sucker rod control

SR CONTROL						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
Facility costs	EUR				4152,29	
RFID system	h		0,50	830,46	415,23	installation/deinstallation
Facility costs	h		3,00	830,46	2491,37	elongation due to inspection processes
Inspection Corrosion	EUR/piece		100,00	7,76	776,00	
Inspection threads/refurbishment	h/person	2	9,50	50,87	966,53	
Inspection drive to/back					91,30	1 hour
Truck tubular transport	h		4,00	115,00	460,00	average transport costs for SR control
Transport (contractor) total	EUR				460,00	
Total well intervention	**EUR**				**9352,72**	
Avg. Costs/SR	**EUR**				**71,94**	
PLUS WI	**EUR**				**3672,16**	

Pipe yard handling and care						
Description	Calculation base	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Office management	h/person	1	1,00	38,82	38,82	additional effort for coordination
De-Mobilisation	job		1,00	587,82	587,82	mobilisation of non-destructive testing unit
Inspection staff (back delivery)	h/person	2,0	2,00	50,87	203,48	
Avg. Costs/SR	**EUR**				**4,82**	
PLUS PY	**EUR**				**626,64**	
PLUS SRC	**EUR**				**4298,80**	**add. costs due to process changes per WI with inspection**

Table 23: Calculations concept 4 sucker rod change

SR CHANGE						
Avg .Costs SR String (130 pieces)						
Well Intervention/ Sucker Rod string installment and transport						
Description	Calculation base		Nr.	Price EUR/Unit	Result EUR	Comment
Diesel for intervention jack	h		5,00	10,46	52,29	5 hours average time
Technical services	h		5,00	130,00	650,00	5 hours average time
Jack and facilities	EUR				702,29	
FacilitiesOMV	h		5,00	690,00	3450,00	5 hours average time
Jack staff	EUR				3450,00	
RFID system	h		0,50	830,46	415,23	installation/deinstallation
Facility costs	EUR				4567,52	
Truck tubular transport	h		8,00	115,00	920,00	
Transport (contractor) total	EUR				920,00	
Total well intervention	**EUR**				**5487,52**	
Avg. Costs/SR	**EUR**				**42,21**	
PLUS WI					415,23	

Pipe yard handling and care						
Description	Calculatio	Staff	Nr.	Price EUR/Unit	Result EUR	Comment
Paraffin oven	h		10,00	49,04	490,40	removal of paraffin, loading and unloading, facility costs etc.
Inspection staff	h/person	2,00	9,50	50,87	966,53	1 hour less due to RFID sorting
Inspection staff (SR back from	h/person	2,00	2,00	50,87	203,48	
Inspection staff	h/person	2,00	1,50	50,87	152,61	handheld reader, sorting sucker rods
Office management	h/person	1,00	0,50	38,82	19,41	
Office management	h/person	1,00	1,00	38,82	38,82	additional effort for coordination
Objective Inspection	unit		100,00	7,76	776,00	2 hours
Total pipe yard with paraffin	**EUR**				**2647,25**	
Total pipe yard without paraf	**EUR**				**2156,85**	
Costs/SR with paraffin	**EUR**				**20,36**	
Costs/SR without paraffin	**EUR**				**16,59**	
Avg. Costs/SR	**EUR**				**17,35**	
PLUS PY					865,69	
PLUS SRCH					**1280,92**	**add. costs due to process changes per WI with inspection**

Table 24: Concept 1 calculations per year

Assumptions for calculations per year		20% Paraffin	Inspection 60%	Scrap 40%
WI/year	125	25		
SR change	50	10	30	20
SR change + (former control)	75	15		

Costs SR Change			
AVG SRCH/yr	€	60 809,13	
Additional costs for transport	€	27 600,00	
Additional costs for paraffin	€	7 356,00	
SUM Process PLUS/YEAR	**€**	**105 341,64**	PLUS 10% MISC
PLUS OPEX/YEAR	**€**	**36 448,51**	
AVG Costs WI	€	74 968,00	
Saving process	€	453,44	
SUM Savings WI	**€**	**75 421,44**	

WI saved	Add. operating costs	Savings due to reduction of sucker rod breaks	Savings deferment
0	€ 141 790,15	-	-
1	€ 141 790,15	€ 106 778,44	€ 31 357,00
2	€ 141 790,15	€ 213 556,88	€ 62 714,00
3	€ 141 790,15	€ 320 335,32	€ 94 071,00

Table 25: Concept 2 calculations per year

Assumptions for calculations per year		20% Paraffin	Inspection 60%	Scrap 40%
WI/year	125	25		
SR change	50	10	30	20
SR change + (former control)	75	15		

Costs SR Change			
AVG SRCH/yr	€	145 853,28	
Additional costs for transport	€	34 500,00	
Additional costs for paraffin	€	7 356,00	
SUM Process PLUS/YEAR	**€**	**206 480,20**	PLUS 10% MISC
PLUS OPEX/YEAR	**€**	**117 948,51**	
AVG Costs WO	€	74 968,00	
Est. savings/year	€	74 968,00	
Saving process	€	1 280,92	
SUM Savings WI	**€**	**76 248,92**	

WI saving	Add. operating costs per year		Savings due to reduction of sucker rod breaks		Savings deferment	
0	€	324 428,71	€	-		
1	€	324 428,71	€	107 605,92	€	31 357,00
2	€	324 428,71	€	215 211,84	€	62 714,00
3	€	324 428,71	€	322 817,76	€	94 071,00
4	€	324 428,71	€	430 423,68	€	125 428,00

Table 26: Concept 3 calculations per year

Assumptions for calculations per year		20% Paraffin	Inspection 60%	Scrap 40%
WI/year	125	25		
SR change	50	10	30	20
SR change + (former control)	75	15		

Costs SR Change			
AVG WI/yr			
AVG PGW/yr	€	317 827,18	
Additional costs for transport/yr	€	34 500,00	
Additional costs for paraffin/yr	€	7 356,00	
SUM PLUS/YEAR	**€**	**395 651,50**	PLUS 10% MISC
PLUS OPEX/YEAR	**€**	**122 948,51**	
AVG Costs WI	€	74 968,00	
Saving process	€	2 814,91	
SUM Saving WI	**€**	**77 782,91**	

WI saving	Add. operating costs per year	Savings due to reduction of sucker rod breaks	Savings deferment
0	€ 518 600,01	€ -	€ -
1	€ 518 600,01	€ 109 139,91	€ 31 357,00
2	€ 518 600,01	€ 218 279,81	€ 62 714,00
3	€ 518 600,01	€ 327 419,72	€ 94 071,00
4	€ 518 600,01	€ 436 559,62	€ 125 428,00
5	€ 518 600,01	€ 545 699,53	€ 156 785,00
6	€ 518 600,01	€ 654 839,44	€ 188 142,00
7	€ 518 600,01	€ 763 979,34	€ 219 499,00

Table 27: Concept 4 calculations per year

Assumptions for calculations per year		20% Paraffin	Inspection 60%	Scrap 40%
WI/year	125	25		
SR change	50	10	30	20
SR change + (former control)	75	15		

Costs SR Change		
AVG WI/yr		
AVG PGW/yr	€ 317 827,18	
Additional costs for transport/yr	€ 34 500,00	
Additional costs for paraffin/yr	€ 7 356,00	
SUM PLUS/YEAR	**€ 395 651,50**	PLUS 10% MISC
PLUS OPEX/YEAR	**€ 122 948,51**	
AVG Costs WI	€ 74 968,00	
Saving process	€ 2 814,91	
SUM Saving WI	**€ 77 782,91**	

WI saving	Add. operating costs per year	Savings due to reduction of sucker rod breaks	Savings deferment
0	€ 518 600,01	€ -	€ -
1	€ 518 600,01	€ 109 139,91	€ 31 357,00
2	€ 518 600,01	€ 218 279,81	€ 62 714,00
3	€ 518 600,01	€ 327 419,72	€ 94 071,00
4	€ 518 600,01	€ 436 559,62	€ 125 428,00
5	€ 518 600,01	€ 545 699,53	€ 156 785,00
6	€ 518 600,01	€ 654 839,44	€ 188 142,00
7	€ 518 600,01	€ 763 979,34	€ 219 499,00

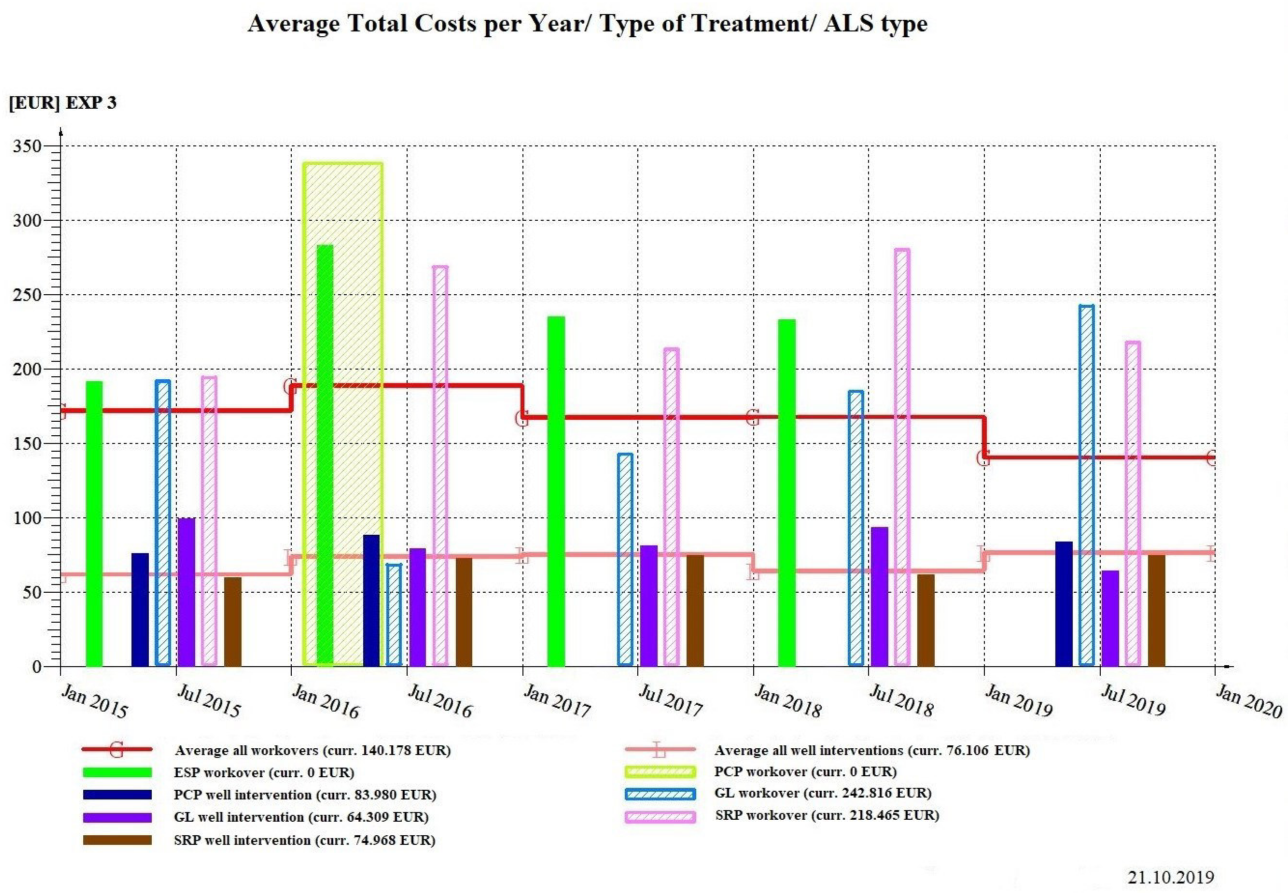

Figure 49: Average total costs for well interventions, extract from general database of OMV

Table 28: Costs for RFID-system, NDT method and transport and storage system

RFID	
CAPEX	
Equipment costs	€ 60 000,00
Certification	€ 5 709,48
Handheld Reader	€ 4 516,60
Server connection	€ 10 821,80
Miscalleneous 10%	€ 8 104,79
SUM	**€ 89 152,67**
Additional OPEX	per year
Avg. SRs with rod guides purchase per year (pieces)	€ 8 328,00
Surcharge tag	€ 26 327,89
Surcharge rod guide molding	€ 5 205,00
Antenna	€ 1 107,72
Antenna cable	€ 494,40
Miscalleneous 10%	€ 3 313,50
SUM	**€ 36 448,51**

Non-destructive testing	
CAPEX	
Container	€ 3 000,00
Equipment	€ 2 000,00
Server connection	€ 10 000,00
Inspection workbench	€ 1 000,00
RFID reader	€ 3 000,00
Miscallenous 10%	€ 1 900,00
SUM	**€ 20 900,00**
Additional OPEX	per year
Energy costs	€ 1 500,00
Staff (1 person)	€ 80 000,00
SUM	**€ 81 500,00**

Transport and storage system	
CAPEX	
Equipment	€ 20 000,00
SUM	€ 20 000,00
Additional OPEX	per year
Spare parts	€ 5 000,00
SUM	€ 5 000,00

Table 29: Grading Limits for Ranking Matrix

Grading Limits					
Criteria/ Points	5	4	3	2	1
Add. process costs per inspection	€ 0-600	€ 620-1 200	€ 1 200-1 800	€ 1 800-2 400	€ 2 400-3 000
Add. process and operating costs per year	€ 0-105 200	€ 105 200-210 400	€ 210 400-315 600	€ 315 600-420 800	€ 420 800-526 000
Required saved sucker rod breaks per year	1	2	3	4	5
QA/QC level	3,2-4	2,4-3,2	1,6-2,4	0,8-1,6	0-0,8
Capital expenditures	€ 0-26 000	€ 26 000-52 000	€ 52 000-78 000	€ 78 000-104 000	€ 104 000-130 000
Add. time (hour) for wellsite per year	0-58	58-116	116-174	174-232	232-290
Add. time (hour) for pipe yard per year	0-150	150-300	300-450	450-600	600-750
Additional staff (OMV)	0-0,2	0,2-0,4	0,4-0,6	0,6-0,8	0,8-1