EQUIPMENT EFFICIENCY METRICS IN PRODUCTION SYSTEMS A LITERATURE REVIEW AND SURVEY

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Abstract

This paper shows a literature review of efficiency ratios for equipment in production systems. The literature analysis uses the approach of Scientometrics. This methodology gives a good general view of the suggested metrics in the scientific field. The most common used metric for equipment effectiveness is the Overall Equipment Effectiveness OEE ratio. The searching in the scientific databases like Scopus based on this metric. The main focus of the study is to find new developed metrics to measure the efficiency of the whole production system. Several scientometrics methods are used to show and find hot spots in the science map. Some of these visualization and analyzing methods are illustrated like author-paper, Paper citation and keyword network. Additional the results of a survey over the practical use of equipment metrics are stated like OEE, TEEP, first pass yield,

Keywords: *equipment efficiency, production systems*

1. INTRODUCTION

For researchers, it is difficult to get an overview of a new research area.Scientists use search engines and reference listsof scientific papers to find relevant documents.This is anextremelytime-consuming way to find newliterature and topics in the scientific world. For this purpose, the following paper shows aneasy proceduretofind relevant documents and authors per topic. This article shows how to extractscientificinformation's from bibliometric sources. The applied approachuses the Scopus database for basic searching and exporting the results. Topic of interest is the equipmentperformance figure"overall equipment effectiveness". The aim is to find developments of this ratio and basicliterature. Several tools prepare the data for the quantitative analysis. The science of science toolset (Sci²) generates the networks and GEPHI shows and modifies the graphs. The analysis processes generates two types of networks. The author-paper network shows relevant authors and clusters of papers. The paper-citation network helps to search deeper.All results of the analysis are presented as a graph or a list.Finally, a part of themaintenanceawardaustria (MA²) pre-assessment is given. The data shows the deployment of production and maintenance radios in industries.

2. SCIENTOMETRICSANALYSIS OF THE TERM OVERALL EQUIPMENT EFFECTIVENESS

The following investigation uses science mapping methods to analyze the results of a database search. This procedure calledas scientometrics which is a quantitative study based on bibliometric sources.The aim of this method is to find new science areas, geographic andorganizational distributions of research and developments of research fields by time.[1]Science mapping analysis uses a general workflow to get the data from the

database,prepareand analyze them and to generate networks or time slides. The main steps of this process are data retrieval, preprocessing, network extraction, normalization, mapping analysis and visualization.[2]The applied analyzeprocess is according to the process flow for mapping knowledge domainsby Kathy BÖRNER. The main steps of thisprocess are data extraction, unit of analysis, layout and display.The following graphic shows the modified process and the tasks per step.[3]

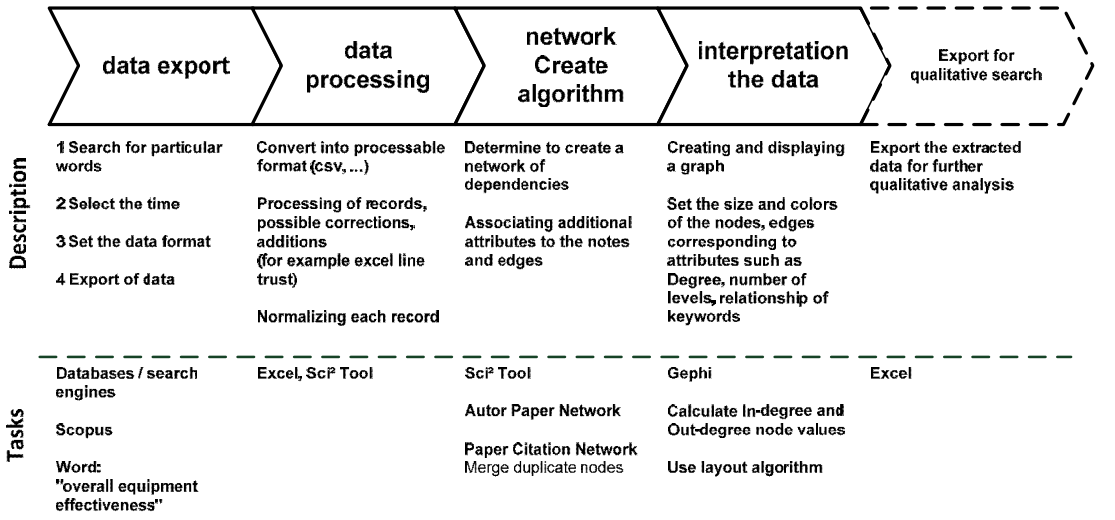

Figure 1. Modified science mapping process

Step 1: Data export

First activity is to search the term “overall equipment effectiveness” in the Scopus database. The settings of the search mask are:

- Search in the articletitle, abstract and keyword
- Search in subject areas:life sciences, health sciences, physical sciences and social sciences &humanities
- Includes all dates and all document types

The search returns 283 documents (1.5.2013). The Scopus integrated export function saves all of these as comma separated values (csv) and the output format is completeformat.

Step 2: Data processing

The exported csvfileincludes errors. For example, columns can be moved so the import into the Sci² Tool is not possible. To prepare the data use excel and sort the list by the last row, so it is possible to see the shifts. It is also essential to choose the correctcsv file format. There are two different formats in English and German. Data processing and saving the csv file uses the English format of csv.It is necessary to set the format to English (USA) in the region and language menu of windows.

Step 3: Network algorithm

To find dependencies between the datasets,it is necessary to generate networks.With the Science of Science Toolset, it is possible to producenetworks basedon these relations.This program is easy to handle and helps to produce and visualize networks.

Sci² Tool[4]

This java based program is a modular toolset to study science. It is possible to analyze datasets temporal, geospatial and topical. Additional it supports the network analysis and visualization of the generated networks.
For the science mapping analysis, it is useful to generatetwo networks.To find clusters and relationships in the scholarly data, an algorithm produce an Author-Paper Network. This algorithm links every paper with other papers over the authors data. So it can be seen which author writes a lot of papers to a subject or with whom. The second algorithm engenders a paper citation network. The Scopus export file has a column with references. This references are the linkage to other papers. Merging duplicate nodes is necessary because the citation styles are not similar. The Sci² Toolset supports all of these algorithms and the merging of duplicate nodes. For the paper citationsnetwork, use the algorithm directed network because there are some format errors in the program.

Step 4: Interpretation the data

When generationthe network with the Sci² Toolset is finishedthere are two ways to visualize the graph. First way is the integrated tool GUESS which is a java based visualization tool. The second way is better and easier to handle. Sci² supports an automatic GEPHIexport function.

GEPHI[5]

GEPHI supports to explore, analyse, spatialize, filter, cluterize, manipulate and export any network. It is an open-source software package which includes an algorithm for layout graphs and modifying visualization properties. Additional it is possible to calculate graph metrics like degree, pagerank, shortest path,…
To prepare the graph for further analysis, it is necessary to calculate the In-Degree and Out-degree of every node of the graph.In-Degree value of a node in a directed network is the count of the in going edges per node. The Out-Degree value counts the outgoing ones. The degree value of a node is the sum of In-Degree and Out-Degree. To visualize the Author Paper Graph use the Out-Degree value for the Size and Color of the Nodes. After that layout the graph with the FRUCHTERMANN REINGOLD Algorithm to get goodvisualization results.[6]For the analysis, two types of the Paper citation networkare used. One with the Out-Degree value for visualization to see which papers influence other papers or get cited. The second type uses In-Degree metrics to find the papers which collects content of other papers.The layout process uses the force atlas algorithm.[5]

Step 5: Export for qualitative research

The last step of the mapping process is to export the results for further qualitative research.GEPHI supports exporting the nodes list with all node parameters. Further qualitative analysis uses Excel fordisplaying.

3. SCIENCE MAPPING RESULTS OF THE TERM OVERALL EQUIPMENT EFFECTIVENESS

This chapter shows a quantitative analysis of the search results of the search term “overall equipment effectiveness” (OEE). This equipment radio is a component of the total productive maintenance (TPM) concept. The main objective of TPM is to improve the OEE value of the used equipment. The OEE is agood figure to measure the six big losses of a machine.[7]The aim of the analysis is to find enhancements of this ratio and basic literature sources.
The Scopus search delivers 283 documents (1.5.2013).These datasets are prepared for further analysis.The following graphics show a short Scopus analysis. The pie chart shows

the document allocation by subject areas and the line chart displays the trend of the documents by time which includes the keyword “overall equipment effectiveness”.

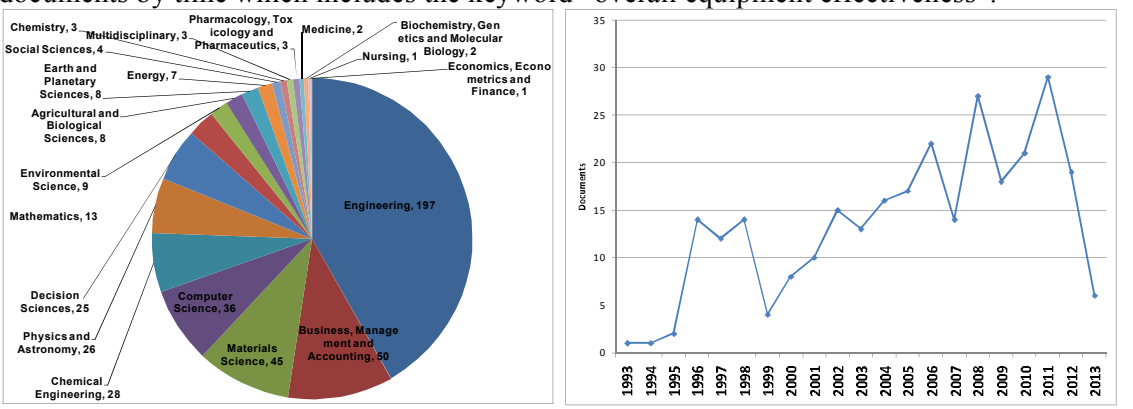

Figure 2. Documents by subject areas and time

The analysis is truly trivial, and it is justobvious the classification of the documents per subject areas and development by the time. The resultsdepend on the content of the bibliometricdatabase. The database does not index all published documents.So they not considered in the analysis.This requires a detailed analysis with an author-paper network and paper-citation network toget more accurate results.

4. AUTHOR-PAPER NETWORK

First network for deeper research is an author-paper network. It shows linkages between authors and papers and count how many papers an author has written.Figure 3 displays the graph with the properties: 815 nodes, 617 edges, directed. Author and paper groups are numbered and colored in the graph. The gray marked cells in Table 1 are the most active authors. They wrote a lot of papers to the topic OEE.

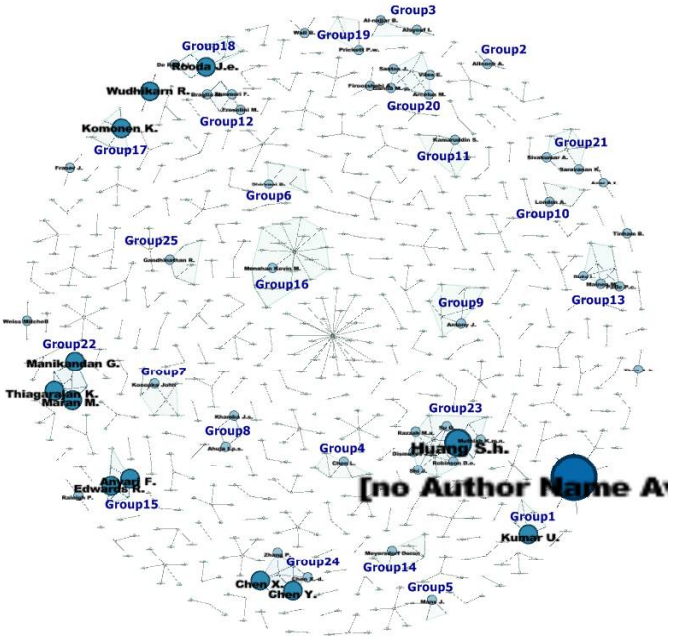

Figure 3. Author-Paper Network with clustering

Table.1 Clustered Authors and their Science activities

Group /Author	number of works	Group /Author	number of works	Group /Author	number of works	Group /Author	number of works
Group 1	**3**	**Group 12**	**6**	**Group 20**	**8**	**Group 24**	**10**
Kumar U.	3	Braglia M.	2	Viles E.	2	Chen Y.	3
Group 2	**2**	Zammori F.	2	Santos J.	2	Chen X.	3
Allcock A.	2	Frosolini M.	2	Arcelus M.	2	Zhang P.	2
Group 3	**4**	**Group 13**	**8**	Garcia M.-p.	2	Chen X.-d.	2
Alsyouf I.	2	Patic P.c.	2	**Group 21**	**4**	**Group 25**	**2**
Al-najjar B.	2	Mainea M.	2	Sivakumar A.	2	Gandhinath	2
Group 4	**2**	Duta L.	2	Saravanan K.	2	**no Group**	**31**
Chen L.	2	Gandhinathan R.	2	**Group 22**	**9**	[no Author	12
Group 5	**2**	**Group 14**	**2**	Manikandan G.	3	Wudhikarn	3
Mans J.	2	Meyersdorf Doron	2	Thiagarajan K.	3	Firoozshahi	2
Group 6	**2**	**Group 15**	**6**	Maran M.	3	Wall B.	2
Shirvani B.	2	Edwards R.	3	**Group 23**	**16**	Tinham B.	2
Group 7	**2**	Anvari F.	3	Huang S.h.	4	Fraser J.	2
Konopka John	2	**Group 16**	**2**	Robinson D.e.	2	Weiss Mitch	2
Group 8	**4**	Monahan Kevin M.	2	Dismukes J.p.	2	Azar A.t.	2
Khamba J.s.	2	**Group 17**	**3**	Shi J.	2	Thun J.-h.	2
Ahuja I.p.s.	2	Komonen K.	3	Su Q.	2	Raleigh P.	2
Group 9	**2**	**Group 18**	**5**	Muthiah K.m.n.	2		
Antony J.	2	Rooda J.e.	3	Razzak M.a.	2		
Group 10	**2**	De Ron A.j.	2				
London A.	2	**Group 19**	**2**				
Group 11	**2**	Prickett P.w.	2				
Kamaruddin S.	2						

5. PAPER CITATION NETWORK

The author-paper network gives an overview over the documents in the database. Indexing of papers in Scopus is notsatisfactory, so deeper research with a paper-citation network is necessary.Table 3 shows the network properties and the steps of merging duplicate nodes. Figure 4 shows the In-Degree network. Large nodes havea high In-Degree value, and the edges represent citation linkages. The node labels just displaying the node number for

better visualization. The Out-Degree network is given in figure 5. Table 3 shows thethirtyone best papers ranked by In-Degree and Out-Degree values. The gray colored cells are some new developments of the OEE value.

Table 1 Network properties paper-citation network

Step	**Nodes**	**Edges**	**Isolated nodes**	**Graph**
Create Paper citation Network	2881	2796	116	directed
Merge duplicate notes Similarity 83%, first 3 letters equal	2232	2766	107	directed

Table 2. Results ofthepaper-citation analysis

	OUTDEGREE NETWORK					INDEGREE NETWORK				
	Id	Autors	Titel	Year	Out	Id	Autors	Titel	Year	In
1	n14	Nakajima, S.	Introduction To Tpm	1988	70	n674	Ahuja, I.p.s., et al.	Total Productive Maintenance: Literature Review And Directions	2008	177
2	n312	Dal, B., et al.	Overall Equipment Effectiveness As A Measure Of Operational Improvement: A Practical Analysis	2000	30	n725	Gibbons, P.m.	Improving Overall Equipment Efficiency Using A Lean Six Sigma Approach	2006	79
3	n325	Ljungberg, O	Measurement Of Overall Equipment Effectiveness As A Basis For Tpm Activities	1998	25	n740	Ahuja, I.p.s., et al.	Total Productive Maintenance Implementation In A Manufacturing Organisation	2008	57
4	n1324	Jeong, K.-y., et al.	Operational Efficiency And Effectiveness Measurement	2001	25	n669	Mathur A., et al.	Performance Measurement In Automated Manufacturing	2011	53
5	n46	Jonsson, P., et al.	Evaluation And Improvement Of Manufacturing Performance Measurement Systems - The Role Of Oee	1999	21	n462	Samat H.a.,et al.	Maintenance Performance Measurement: A Review	2011	49
6	n9	Chan, F.t.s., et	Implementation Of Total Productive Maintenance: A Case Study	2004	11	n1278	Rashid M.m.,et al.	Generic Approach For The Customisation Of The Tpm Programme: Using The Process Transformation Model And	2008	47
7	n182	Raouf, A.	Improving Capital Productivity Through Maintenance	1994	11	n1188	Alsyouf, I.	Measuring Maintenance Performance Using A Balanced Scorecard Approach	2006	43
8	n188	Nachiappan, R.m., et al.	Evaluation Of Overall Line Effectiveness (ole) In A Continuous Product Line Manufacturing System	2006	11	n340	Shahin A., et al.	Developing Decision Making Grid For Maintenance Policy Making Based On Estimated Range Of Overall Equipment Effectiveness	2011	42
9	n844	Hansen, R.c.	Overall Equipment Effectiveness: A Powerful Production/maintenance Tool For Increased Profits	2001	11	n290	Tsarouhas, P.	Implementation Of Total Productive Maintenance In Food Industry: A Case Study	2007	41
10	n10	Tajiri, M., et al.	Tpm Implementation: A Japanese Approach	1992	9	n226	Abdul Samat H.,	Integration Of Overall Equipment Effectiveness (oee) And Reliability Method For Measuring Machine Effectiveness	2012	39
11	n57	Wireman, T.	World Class Maintenance Management	1990	9	n905	Cheng F.-t.,et al.	Advanced E-manufacturing Model: The Significance Of Large-scale, Distributed, And Object-oriented Systems	2010	39
12	n314	Kotze, D.	Consistency, Accuracy Lead To Maximum Oee Benefits	1993	9	n1071	Junker B.h.	Application Of Overall Equipment Effectiveness To Biopharmaceutical Manufacturing	2009	39
13	n741	Huang, S.h., et al.	Manufacturing Productivity Improvement Using Effectiveness Metrics And Simulation Analysis	2003	9	n726	Al-najjar, B.	Total Quality Maintenance: An Approach For Continuous Reduction In Costs Of Quality Products	1996	37
14	n1269	Blanchard, B.s.	An Enhanced Approach For Implementing Total Productive Maintenance In The Manufacturing Environment	1997	9	n204	Wudhikarn R.	Improving Overall Equipment Cost Loss Adding Cost Of Quality	2012	35
15	n318	De Ron, A.j., et al.	Equipment Effectiveness: Oee Revisited	2005	8	n602	Santos J., et al.	Development Of A Wireless Plugandlean System For Improving Manufacturing Equipment Diagnosis	2011	35
16	n413	Mckone, K.e., et al.	Total Productive Maintenance: A Contextual View	1999	8	n139	Buchmeister B., et al.	Analysis Of A Three-stage Supply Chain With Level Constraints	2012	34
17	n661	Scott, D., et al.	Can Overall Factory Effectiveness Prolong Moore's Law?	1998	8	n434	Jeon J., et al.	Measuring Efficiency Of Total Productive Maintenance (tpm): A Three-stage Data Envelopment Analysis (dea) Approach	2011	34
18	n54	Braglia, M., et al.	Overall Equipment Effectiveness Of A Manufacturing Line	2009	7	n1681	Kumar M., et al.	Implementing The Lean Sigma Framework In An Indian Sme: A Case Study	2006	32
19	n181	Swanson, L.	Linking Maintenance Strategies To Performance	2001	7	n1787	Cholasuke C., et al.	The Status Of Maintenance Management In Uk Manufacturing Organisations: Results From A Pilot Survey	2004	32
20	n199	Muchiri, P., et al.	Performance Measurement Using Overall Equipment Effectiveness (oee): Literature Review And Practical	2008	7	n308	Parida, A., et al.	Maintenance Performance Measurement (mpm): Issues And Challenges	2006	31
21	n748	Chand, G., et al.	Implementation Of Tpm In Cellular Manufacture	2000	7	n948	Batumalay K., et al.	Overall Equipment Effectiveness (oee) Through Total Productive Maintenance (tpm) Practices – A Study Across The	2009	31
22	n1260	Hartmann, E.h.	Successfully Installing Tpm In A Non-japanese Plant: Total Productive Maintenance	1992	7	n1826	Chong C.s., et al.	Simulation-based Scheduling For Dynamic Discrete Manufacturing	2003	31
23	n722	Bamber, C.j., et al.	Cross-functional Team Working For Overall Equipment Effectiveness (oee)	2003	7	n631	Azar A.t.	A Novel System For Haemodialysis Efficiency Monitoring	2011	30
24	n439	De Groote, P.	Maintenance Performance Analysis: A Practical Approach	1995	6	n264	Mandahawi N., et al.	An Application Of Customized Lean Six Sigma To Enhance Productivity At A Paper Manufacturing Company	2012	29
25	n526	Tsang, A.h.c., et	Measuring Maintenance Performance: A Holistic Approach	1999	6	n928	Garza-reyes J.a.,	Soriano-meier H., Overall Equipment Effectiveness (oee) And Process Capability (pc) Measures: A Relationship Analysis	2010	29
26	n912	Oechsner, R., et al.	From Overall Equipment Efficiency (oee) To Overall Fab Effectiveness (ofe)	2003	6	n722	Bamber, C.j., et al.	Cross-functional Team Working For Overall Equipment Effectiveness (oee)	2003	28
27	n1335	Robinson, C.j., et al.	Implementing Tpm: The North American Experience	1995	6	n368	Kent P., et al.	Measurement In The Workplace: The Case Of Process Improvement In Manufacturing Industry	2011	27
28	n187	Mckone, K.e., et al.	Impact Of Total Productive Maintenance Practices On Manufacturing Performance	2001	6	n752	Raja P.n., et al.	Overall Line Effectiveness – A Performance Evaluation Index Of A Manufacturing System	2010	27
29	n143	Yamashina, H.	Japanese Manufacturing Strategy And The Role Of Total Productive Maintenance	1995	5	n843	Lad B.k., et al.	A Mechanism For Linking User's Operational Requirements With Reliability And Maintenance Schedule For Machine Tool	2010	27
30	n191	Muthiah, K.m.n., et	Overall Throughput Effectiveness (ote) Metric For Factory-level Performance Monitoring And Bottleneck Detection	2007	5	n1103	Wang, F.k., et al.	Learning Curve Analysis In Total Productive Maintenance	2001	27
31	n273	Konopka, J., et al.	Overall Equipment Effectiveness (oee) And Cost Measurement	1996	5	n1711	Kenyon G., et al.	The Impact Of Lot-sizing On Net Profits And Cycle Times In The N-job, M-machine Job Shop With Both Discrete And Batch	2005	27

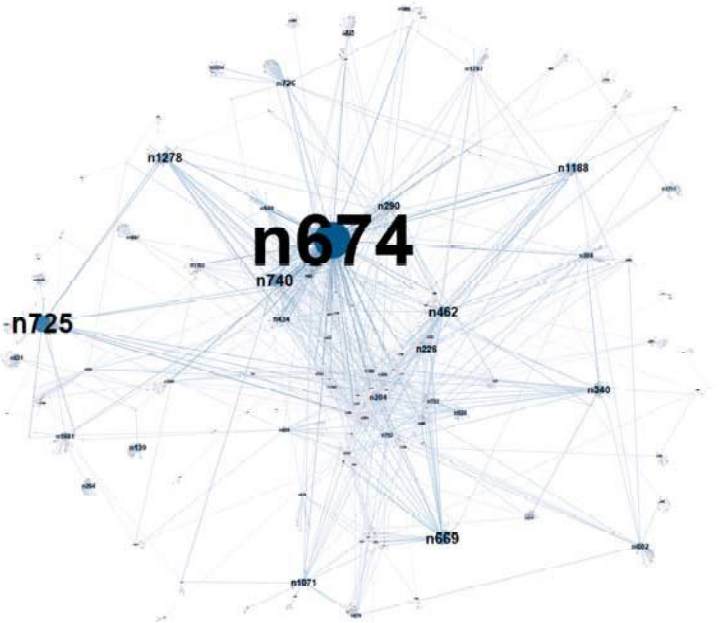

Figure 4. Paper citation network with In-Degree visualization

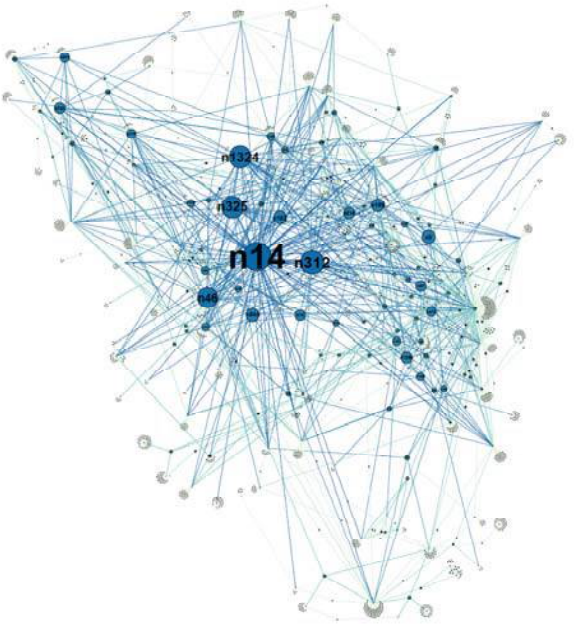

Figure 5. Paper citation network with Out-Degree visualization

To detect all enhancements of the OEE metric, it is necessary to do a qualitative analysis.Following table shows the results of the quantitativescientometrics analysis and the qualitative investigation.

Table 3. Enhancements of the OEE

Metrics	Titel	Year	Author
Overall equipment effectiveness (OEE)	Introduction To Tpm	1988	Nakajima, S.
Capacity Utilization Bottleneck Efficiency System	Overall equipment effectiveness (OEE) and cost measurement	1996	Konopka John, Trybula Walt
Overall Fab Effectiveness (OFE)	Can Overall Factory Effectiveness Prolong Moore's Law?	1998	Scott, D., Pisa, R.
Overall Throughput Effectiveness (OTE)	Manufacturing system modeling for productivity improvement	2002	Huang S.H., Dismukes J.P., Shi J., Su Q., Wang G., Razzak M.A., Robinson D.E.
Overall Fab Effectiveness (OFE)	From Overall Equipment Efficiency (oee) To Overall Fab Effectiveness (ofe)	2003	Oechsner, R., Pfeffer, M., Pfitzner, L., Binder, H., et al.
Overall Throughput Effectiveness (OTE)	Manufacturing productivity improvement using effectiveness metrics and simulation analysis	2003	Huang S.H., Dismukes J.P., Shi J., Su Q., Razzak M.A., Bodhale R., Robinson D.E.
Holistic approach of OEE	A holistic approach to overall equipment effectiveness (OEE)	2003	Loughlin S.
Total Overall equipment effectiveness	Efficiency and effectiveness of wind farms-keys to cost optimized operation and maintenance	2003	Krokoszinski H.-J.
Overall equipment effectiveness (OEE) and equipment effectiveness	Equipment effectiveness: OEE revisited	2005	De Ron A.J., Rooda J.E.
Overall Line Effectiveness (OLE)	Evaluation of overall line effectiveness (OLE) in a continuous product line manufacturing system	2006	Nachiappan R.M., Anantharaman N.
Money based overall equipment effectiveness	Money-based overall equipment effectiveness	2006	Juric Z., Sanchez A.I., Goti A.
Overall equipment effectiveness (OEE) and equipment effectiveness	OEE and equipment effectiveness: An evaluation	2006	De Ron A.J., Rooda J.E.
Overall input efficiency and total equipment efficiency	Overall input efficiency and total equipment efficiency	2006	Sheu D.D.
Maintenance performance measurement	Maintenance performance measurement (MPM): Issues and challenges	2006	Parida A., Kumar U.
Overall Throughput Effectiveness (OTE)	Overall throughput effectiveness (OTE) metric for factory-level performance monitoring and bottleneck detection	2007	Muthiah K.M.N., Huang S.H.
Overall Throughput Effectiveness (OTE)	Automating factory performance diagnostics using overall throughput effectiveness (OTE) metric	2008	Muthiah K.M.N., Huang S.H., Mahadevan S.
OEE and useability	A proposal: Evaluation of OEE and impact of six big losses on equipment earning capacity	2008	Badiger A.S., Gandhinathan R.
Overall Throughput Effectiveness (OTE)	Global efficiency assessment based on component composition of OEE using AltaRica Data-Flow language	2009	Kombe T., Niel E., Pietrac L., Rauzy A.
Overall equipment effectiveness of manufacturing line (OEEML	Overall equipment effectiveness of a manufacturing line (OEEML): An integrated approach to assess systems performance	2009	Braglia M., Frosolini M., Zammori F.
Overall Line Effectiveness (OLE)	Overall line effectiveness - A performance evaluation index of a manufacturing system	2010	Raja P.N., Kannan S.M., Jeyabalan V.
Overall weighting equipment effectiveness	Overall weighting equipment effectiveness	2010	Wudhikarn R.
Overall equipment effectiveness based on market	Methodology and theory evaluation of overall equipment effectiveness based on market	2010	Anvari F., Edwards R., Starr A.
Overall equipment effectiveness and process capability	Overall equipment effectiveness (OEE) and process capability (PC) measures: A relationship analysis	2010	Garza-Reyes J.A., Eldridge S., Barber K.D., Soriano-Meier H.
Enterprise equipment effectiveness	Analysis and improvement of enterprise's equipment effectivenessbased on OEE	2011	Zhu X.
Integrated Equipment Effectiveness	Performance measurement based on a total quality approach	2011	Anvari F., Edwards R.
Integrated Equipment Effectiveness	Maintenance engineering in capital-intensive manufacturing systems	2011	Anvari F., Edwards R.
Stochastic OEE	Stochastic overall equipment effectiveness	2011	Zammori F., Braglia M., Frosolini M.
Overall equipment cost loss	Improving overall equipment cost loss adding cost of quality	2012	Wudhikarn R.
overall resource effectiveness (ORE)	Improvement of manufacturing performance measurement system and evaluation of overall resource effectiveness	2013	Eswaramurthi K.G., Mohanram P.V.

6. SURVEY RESULTS OF EQUIPMENT METRICS

This chapter shows some empirical dataderived from the yearly awarded maintenance award austria(MA²). Firstapplication step of the award is a questionnaire for pre-assessment.The aim of this pre-assessment is to rank the companies by their maintenance performance.As a part of the written pre-assessment, some maintenance metrics and company data arequeried.The following chartshows the results of 28 returning questionnaires. These companies were all candidates of the maintenance award Austria (MA²). Figure 6 shows the results of the pre-assessment. The main part of the participating companies aremainly from metal processing industry and ferrous and non-ferrous metal producing industry and Electrical and Electronics Industry. Most companies need metrics to evaluate the equipment performance becausethey stated to be equipment intensive. It is apparent that few companies usesthe overall equipment effectiveness (OEE) as a holistic ratio for equipment performance measurement.

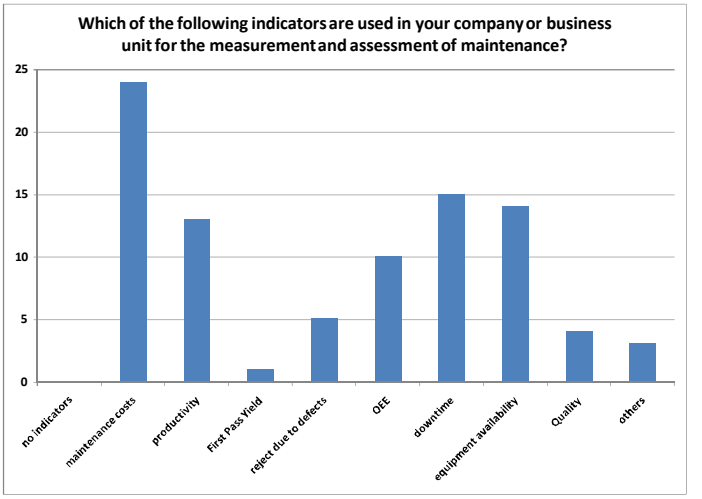

Figure 6 Results of the MA²pre-assessment

7.CON CLUSION AND FURTHER RESEARCH

The overall equipment effectiveness is agood metric to measure losses of equipment. OEE measures the efficiency of a single machine. The proposed method for literature research shows how to find enhancements of the OEE value in bibliometric sources. The developments of thiskey figureaim to measure the performance of the whole production system. Some of them comprise economic and quality parts for assessment. A lot of these approaches are theoretical and should be tested in practice. The empirical part of this paper shows that companies do not use the OEE metrics. Equipment intensive industries calculate their machines performance with simple metrics such as system availability and downtime. Easy to use holistic metric is required to measure the equipment performance of those companies.

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