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Quantifying the Effects of Maintenance – a Literature Review of Maintenance Models

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Abstract

To secure future competitiveness, manufacturing companies have started a digital transformation where equipment and systems become more complex. To handle the complexity and enable higher levels of automation, maintenance organization is expected to take a key role. However, there are well-known challenges in industry to quantify the effects of maintenance, and thereby argue for maintenance investments. To quantify the effects, researchers have developed several models, but their application is limited in industry. This paper presents a structured literature review of existing maintenance models and discusses how to increase their applicability for practitioners in industry.

Keywords: Maintenance; Manufacturing; Model; Value; Effects; Economic; Literature Review

1. Introduction

The availability of new technology and increasing competitiveness have started a digital transformation within the manufacturing industry. New, mainly digital, technology enables more autonomous systems with higher levels of automation, which also imply more complex equipment and systems. The increasing complexity of the systems will make unexpected stops and disruptions even more crucial, and more complex equipment will require more complex repairs of failures, which will affect the duration of the repairs. To reduce the risk and minimize the consequences of unexpected stops and disruptions in digitalized manufacturing, maintenance must take a key role [1, 2].

Even though it has been proven that maintenance plays an important role in production [3] it is a well-known challenge in the manufacturing industry to quantify the effects and value of maintenance. The effects are usually deferred, making it difficult to verify the benefits upfront and argue for maintenance investments. As an example, the benefits of a computerized maintenance system are obvious for maintenance personnel who can use the system to plan and evaluate maintenance actions. However, it is a challenge to prove those benefits for management and the financial department in advance. Several models, methods, concepts, philosophies, and strategies have been developed with the purpose to plan and evaluate the maintenance work, and quantify the effects. Some examples are Value Driven Maintenance (VDM) [4], Life Cycle Cost analysis (LCC) [5], Total Productive Maintenance (TPM) [6] Reliability Centered Maintenance (RCM) [7], and Total Quality Maintenance (TQMain) [8]. Further, maintenance research has been conducted in order to prove improved performance, cost reduction and/or increasing profit, and to demonstrate cost effectiveness of condition based maintenance (CBM) [9-15]. However, the application of maintenance models, methods, concepts, strategies etc. is limited in industry, and despite the knowledge from research, it is still a challenge in industry to quantify the effects and value of maintenance. The practical use of the models has been questioned, and their empirical evidence is limited [16, 17]. This limited empirical evidence, indicates a gap between maintenance research and maintenance practice.

Also, there is a lack of concept clarity, where the same or similar things are described as different models, methods, concepts, philosophies, strategies etc. [16, 17]. Lacking concept clarity and different terminology is making it unclear

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what is what and when to use it. In this paper, the term maintenance model will be used as a common name to refer to the different terminology.

Given the current gap between maintenance research and industry practice, the purpose of this paper is to enable investments in maintenance by increasing the applicability of maintenance models in industry. Compared to previous reviews [16-20], this paper focuses on the economic aspect of maintenance models and their industrial applicability. A scanning of maintenance models in the literature is presented, followed by a structured analysis and categorization of the models. Further, it is discussed how to increase their applicability for practitioners in industry, with the purpose of enabling communication of the value of maintenance and argue for maintenance investments.

2. Methodology

In this paper, a structured literature search and review was done to identify and categorize maintenance models for quantifying effects of maintenance. The following sections will describe the review and the categorization.

2.1. Literature review

The literature search was conducted within Scopus, which is the database that covers journals publishing maintenance research. The search was initiated with a broad focus on identifying maintenance management models. Thereafter, the search was more narrow in its focus, specifically targeting quantification, methods, value and costs. Some key words used in the literature search were:

- Review AND "maintenance management"
- Quantify AND maintenance AND (production OR manufacturing)
- Maintenance AND (production OR manufacturing) AND (method OR value OR cost OR profit)

Papers were selected from both from journals and conferences, and no specific year limited the selection. To determine if a paper was relevant or not, title, abstract, and conclusion were studied. The words model, method, costs, losses, or quantify in combination with maintenance were mainly used for choosing relevant publications. As a complement, interesting publications were identified by tracking references of references.

2.2. Categorization/Grouping of Models

To get an overview of what type of maintenance models that exist, the authors conducted a systematic categorization of the models inspired by the constant comparison method [21]. In a workshop format, the models were reviewed one by one. Based on the purpose of the model and its level of detail, the model could be grouped with other models in an existing category. If the model did not fit with any model in a category, a new category was created. When all models were grouped, the categories were named and described based on a common denominator of the models in the category.

3. Results and Analysis

From the literature search, 35 publications were selected. Fig. 1 describes the number of publications each year from the year 2000. Five of the selected publications were published before the year 2000, and the oldest one in this review is from 1979. From the 35 publications, 24 models could be identified.

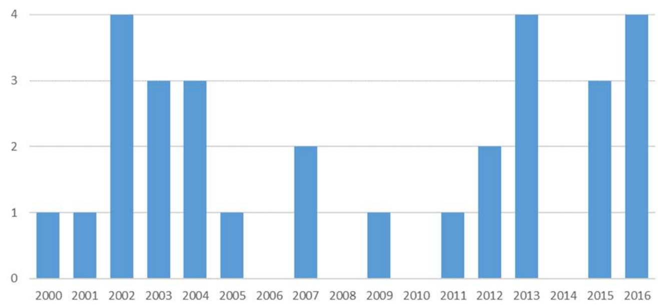

Fig. 1: The graph describes the number of publications per year among the selected publications

3.1. The Models

Following sections will briefly describe the 24 models identified in the selected publications.

3.1.1. Value Driven Maintenance

VDM is a maintenance management model with the aim of adding value and profit to the company [4]. The value drivers in maintenance are described as utilization, resource allocation, cost control, and safety, health, and environment (HSE). Net present value is used in VDM as a measurement of profit calculated by the difference in cash inflows and outflows from the different value drivers. It gives an indication of how much value an investment or project will add to a company, and is used to analyze the profitability of investment suggestions. Studies related to VDM are presented in [22-24].

3.1.2. Life Cycle Cost Analysis (LCC)

LCC analysis is a model which considers an estimation of the overall life cycle cost from cradle to grave [5]. The cost calculations are considering costs such as the cost of corrective maintenance and preventive maintenance (PM) respectively [25]. LCC can be used to compare different alternatives of machine or equipment investments. LCC can also include to evaluate whether the maintenance work should be performed internally or externally.

3.1.3. Life Cycle Profit (LCP)

LCP is a model to estimate how manufacturing equipment can contribute to profit, instead of minimizing its life cycle cost, as in LCC analysis [26]. LCC is particularly adapted to be used within a stable market, while LCP is more suitable for a dynamic market. Costs of maintenance are commonly divided into direct and indirect costs. In LCP a third category is added; non-realized revenue. Non-realized revenue consider loss of income due to maintenance issues causing reduction in sales volume. LCP can be used to investigate how different investments can contribute to profit in a long term. Also, more specific case studies of maintenance profitability have been conducted [10-13].

3.1.4. Sustainability Statement

Sustainability Statement (translated from Swedish terminology) is an economical model developed by a Swedish think tank called Sustainability Circle [27]. The model is divided into four sections; (1) verifiable internalities such as sales, costs sold goods, and investments; (2) non verifiable internalities, for example efficiency and quality losses; (3) verifiable externalities – absence and restored environment; and (4) non-verifiable externalities such as effects on personnel and irreversible environmental damage. It can be used to evaluate the long term effects of decisions and investments related to maintenance.

3.1.5. Cost of Poor Maintenance (CoPM)

CoPM is a model with the purpose to increase the awareness of maintenance improvements among managers and employees, by identify and prioritize different problem areas, and follow up and evaluate maintenance improvements [28]. The CoPM model is built as a matrix with four categories of cost (indispensable corrective maintenance, valid PM, non-accepted corrective maintenance, and poor PM) to visualize the true cost of weaknesses in the performed maintenance. If it is possible to make investments to decrease the weaknesses in performed maintenance, the matrix can be used to compare the costs of the weaknesses to the investments cost.

3.1.6. Cost Deployment

Cost deployment has the objective of mapping the losses in a system, in order to reduce the cost of them [29]. The different steps in the method are to first investigate production losses and categorize them, then identify relationship among the losses and their costs and if there is a known way to reduce the losses. The last step is to estimate the cost reduction and prioritize the reduction of losses accordingly. Breakdowns, short stoppages, and reduced speed are some losses related to maintenance. Cost deployment can be used to identify losses and prioritize investments accordingly.

3.1.7. Waste Reduction (Related to Maintenance)

A working procedure to reduce maintenance-related waste is presented in [30]. The procedure consists of seven steps; (1) investigate needs and requirements, (2) translate needs to need of maintenance and maintenance activities, (3) identify, group, and measure waste related to maintenance, (4) develop solutions, (5) estimate the economic value of solutions, (6) implement cost effective solutions, and (7) follow up implemented solutions. This model can be used to identify possible investment areas with respect to maintenance-related waste, and to follow up the investments.

3.1.8. Total Quality Maintenance (TQMain)

TQMain is a model based on the plan-do-check-act cycle (PDCA) which is used in total quality management (TQM) for improvement of any technical or managerial system [8]. TQMain includes inspections and condition monitoring (CM), with the aim of using components/parts as much as possible and schedule PM outside busy production periods. The measure is overall process effectiveness (OPE), which is a modified version of overall equipment effectiveness (OEE), considering the entire production process. TQMain can be used to assess different investments with respect to OPE.

3.1.9. Model to Describe and Quantify the Impact of Vibration-based Maintenance

The model consists of maintenance investment areas with the finance aspect and technical impacts of the investment at the operative level [14]. The investments are linked to technical impacts and savings accounts, such as less failures, shorter average stop time, fewer short stoppages, and higher quality rate. The investment cost can then be compared to the savings.

3.1.10. A Computerized Model to Enhance the Cost Effectiveness of Production and Maintenance Dynamic Decisions

The purpose of the model is to identify, asses, and control the losses in production time and follow up changes in maintenance and its impact on production time losses [15]. The losses are categorized on operational level and strategic level, and the losses should be documented before and after the maintenance change. The maintenance change can be different maintenance activities, as well as maintenance investments.

3.1.11. Maintenance Function Deployment (MFD)

MFD is a maintenance model with the purpose to identify and quantify company losses, and cost effective measures to reduce the losses [31]. The first step is to identify the output, “whats” that should be achieved to maintain the company´s strategic goals, for example delivery on time. To maintain the “whats”, “hows” needs to be specified with respect to the strategic goals. The “whats” and “hows” are put into a matrix, where effects can be visualized. The listed effects and actions can be used to evaluate how different maintenance investments can contribute to the company´s strategic goals.

3.1.12. CA-Failure

CA-Failures is a model with the purpose to break down a company´s failure database, prioritize the failures, and assess economic losses due to the failures and their impact of the competitive advantages (CA) [32]. For each CA, the economic losses need to be determined for each failure, and further prioritized using Pareto chart. The next step is to assess the costs of actions, and investments needed to prevent the failure to reoccur. The losses due to the failures should then be compared to the investments needed to avoid the failures, to select the most profitable maintenance action.

3.1.13. Fuzzy Multiple Criteria Decision Making Model

A fuzzy multiple criteria decision making (MCDM) evaluation model to select the most efficient and cost effective maintenance approach is suggested by [33]. The first step is to identify the failure causes (criteria) which influences the life length of the equipment or component. Then, an assessment of the capability, and ranking of identified maintenance approaches is done by using a fuzzy inference system and simple additive weighting. The model can be used to weighting different investments with respect to cost effectiveness.

3.1.14. Activity-based Costing (ABC) for Cost Estimation

An application of ABC to estimate maintenance costs is presented by [34]. In ABC, overhead costs are distributed over jobs with respect to their activity scope and complexity. In other cost models, overhead costs are commonly uniformly distributed over all jobs. The purpose is to support decision making processes with non-misleading data. This model can be used to include a more accurate distribution of overhead costs in evaluation of different maintenance applications related to investment suggestions.

3.1.15. Cost Effective Degradation-based Maintenance

A model considering the relationship between the degradation reduction of PM actions, and the cost of the actions is suggested by [35]. The purpose is to find the most cost effective interval for CM with respect to the degradation level. If investing on CM equipment, this model can be used to plan PM actions with respect to cost effectiveness.

3.1.16. Probability Distribution of Maintenance Cost

A model to describe the probability distribution of maintenance cost is presented by [36]. The model considers a system with a stochastic gamma degradation, and shows the probability of the maintenance cost associated with condition-based maintenance activities. The model can be used to not only consider the cost of maintenance activities, put also the probability, to evaluate different investments suggestions, or planning different maintenance tasks.

3.1.17. Cost Model for Maintenance Services

A model presented by [37] aims to be used as performance measurement and decision-making regarding maintenance service pricing, contract negotiations, outsourcing decisions, and life cycle cost management. The model is divided into different categories of costs, such as operating costs, cost of machines and tools, costs of logistics, cost of spare part etc. For each type of cost, the total cost for the service provider and the total cost for the customer are calculated, and should further be used to generate cost savings for the customer and profit for the service provider.

3.1.18. Total Productive Maintenance (TPM)

TPM is a model that focuses on improving the performance-effectiveness in maintenance [5]. The purpose of TPM is to maximize the equipment effectiveness and as a measure, OEE is used [6, 18]. The objective is to eliminate or minimize the 6 losses; breakdowns, set up and adjustment time loss, idling and minor stoppages of equipment, speed reduction for operation, defect and rework losses, and start-up losses [38]. The analysis of OEE can be used to prioritize investments accordingly.

3.1.19. The Eindhoven University of Technology (EUT) Model

The EUT model is a model which describes sub-functions of maintenance using a systems engineering view [18]. It consists of 14 sub-functions that describes the maintenance management function. For each sub-function in the model, major activities and decisions are stated. Some activities and decisions includes LCCs, failure mode, effects and criticality analysis (FMECA), cost calculations of waiting time for spare parts, degree of centralization, and outsourcing.

3.1.20. Reliability Centered Maintenance (RCM)

RCM is a planning approach for maintenance activities by focusing on the functions in a system [7]. There are 4 principles characterizing RCM; preserve functions, identify failure modes that can disrupt the functions, prioritize the functions and select effective PM task according to it [39]. RCM can be used to rank and prioritize which failures to design out.

3.1.21. Terotechnology Model

The terotechnology model was developed for the industry in UK with support from the government. Terotechnology combines management and financial engineering ([40], refers to [41]). The model includes reliability and describes how feedback from installation, commissioning, and operation and maintenance will go back to the design, based on FMECA [18]. This can be used to prioritize which failures to design out.

3.1.22. Kelly´s Philosophy

Kelly mainly regards maintenance as the control of reliability. A ten-point plan from Kelly are described by [18], where the first step is to identify the functions of a maintenance systems. It should be defined as objectives, in order to set up a strategy, to derive maintenance workload and use of resource.

3.1.23. Risk-Based Maintenance

Risk-based maintenance is built up based on answers on five questions related to the system; what can cause the system to fail? How can it cause the system to fail? What should be the consequences if it fails? How probable is it to occur? How frequent an inspection/maintenance of what components would avert such failure? [42]. Risk based maintenance can be used to prioritize failures to invest in or design out.

3.1.24. Simulation and Maintenance

Evaluation of PM and corrective maintenance, and their impact on resource allocation, performance and cost are common applications in maintenance research, as well as planning and scheduling of PM [43]. A literature survey done to report the state of the art in simulation-based optimization of maintenance concludes that much research within this area have focused on optimizing PM frequency to a minimum cost, and suggests more real case studies with multi-objective optimization [44]. Simulation can be used to investigate the long terms effects of investments.

3.2. The Categories

The categorization of the models resulted in six different categories; economic value, categorization of maintenance losses, cost and cost effectiveness associated with maintenance activities, overall management, function oriented planning, and maintenance and simulation. Table 1 presents an overview of the categories and the selected publications. The following sections will describe each category.

Table 1. Overview of the categories and the selected publications.

Category	No. of Models	Model ID	Publications
Economic Value	4	1-4	[4, 5, 10-13, 22-27]
Categorization of Maintenance Losses	3	5-7	[28-30]
Cost and Cost Effectiveness Associated with Maintenance Activities	10	8-17	[8, 14, 15, 31-37]
Overall Management	2	18, 19	[5, 6, 18, 38]
Function Oriented Planning	4	20- 23	[7, 18, 39-42]
Simulation and Maintenance	1	24	[43, 44]

3.2.1. Economic Value

This category includes models of economical type with focus on costs, net present value, or profitability. The models bring up maintenance in a broad long term perspective.

3.2.2. Categorization of Maintenance Losses

The models in this category describe different approaches to map the losses related to maintenance activities. The models describe the working procedure or provide guidelines of how to identify and prioritize the losses in a system, with the aim of reducing the cost of the losses.

3.2.3. Cost and Cost Effectiveness Associated with Maintenance Activities

This category includes models focusing on cost or cost effectiveness of maintenance activities. The working procedure differs between the described models, but all models have a clear objective of assessing suggested or implemented changes in maintenance activities with respect to cost effectiveness.

3.2.4. Overall Management

This category includes models with a broader perspective of how to work with maintenance management. The main objective of the models is to plan and control maintenance activities. The models might include other models to plan with respect to losses, costs, or profit, but does not describe a certain procedure in detail.

3.2.5. Function Oriented Planning

In this category, models related to the function and reliability of the system and its maintenance activities are included. The models focus on how to evaluate different types of failures, and how to plan maintenance activities based on the risks and consequences of the failures depending on how they affect the system's ability to function as expected.

3.2.6. Simulation and Maintenance

This category aims to describe how simulation has been used in previous maintenance research. Some of the areas are planning and scheduling of activities, and to evaluate the impact of PM and corrective maintenance on production performance and cost.

4. Discussion

This paper presents a summary of existing maintenance models for quantifying the effects of maintenance. Even though it has been proven that maintenance plays an important role in the manufacturing industry [3], there is challenge to prove the benefits and justify maintenance investments for management and financial department. Therefore, an overview of maintenance models is presented in this paper, based on a review and categorization of existing literature.

In this study, 24 models were identified. Some of them are describing similar things, but with slightly different matrixes and categories of costs or losses. This lack of concept clarity might be a contributing reason to the low applicability of the models, since it is unclear to practitioners what model to use and when [16, 17]. Applying the majority of the models require a lot of data, which is not always available in practice. Since the empirical evidence is limited, there are no guidelines of making relevant assumptions. To lift the models to a practical context, more empirical research of industrial problems is needed [16, 17].

The categorization in this review was done to cluster the models with respect to their focus, with the aim of improving concept clarity. It followed a structured procedure and fulfilled the purpose of this study. However, it was done internally and further validation is needed.

The purpose of this review is to enable maintenance investments by increasing the applicability of maintenance models for practitioners in industry. To increase the applicability, the models must be presented so that industry can adapt them to their specific needs, making empirical research of real world industrial challenges important. The authors suggest future research in industrial environments for mapping stakeholders and their interest, to enable communication of the value of maintenance and argue for maintenance investments.

5. Conclusion

The manufacturing industry has started a digital transition where maintenance organization is expected to take a key role to enable robust autonomous systems. This paper presents a structured literature review and categorization of existing maintenance models. The goal of the study is to identify models to quantify the effects of maintenance and discuss how to increase their applicability in industry. Six categories of models are presented; economic value, categorization of maintenance losses, cost and cost effectiveness associated with maintenance activities, overall management, function oriented planning, and simulation and maintenance. To increase the models' applicability for practitioners in industry, the authors suggest more empirical research considering maintenance stakeholders and their interest. Stakeholders and decision makers' attention are crucial to enable investments in maintenance in industry practice and facilitate digitalized manufacturing.

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