RECOGNIZED DEVELOPMENT TRENDS AND FUTURE VISIONS OF MAINTENANCE STRATEGIES IN PROCESS INDUSTRY

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Tämän diplomityön tavoite on tutkia kunnossapidon metodologioiden trendejä prosessiteollisuudessa vuosien 2000–2020 välillä. Prosessiteollisuuden tulevaisuuden visioita tarkastellaan ja niiden yhteyttä nykyisiin trendeihin arvioidaan.

Kirjallisuuskatsauksen ensimmäinen osuus koostuu vian ja vikaantumisen sekä kunnossapidon määritelmästä. Toinen osuus metodologioiden määritelmistä sekä strategian valintaprosessista. Viimeinen osio koostuu trendin määritelmästä sekä visioiden esittelystä.

Kahdesta aiemmasta tutkimuksesta hyödynnettyjä lähteitä taulukoidaan ja niistä analysoidaan jokaisen metodologian käyttöastetta. Tutkimusväli 2000–2020 jaetaan neljään osaan, jotka toimivat aikajanana trendien määrittelylle. Jokainen metodologia pisteytetään systemaattisesti lähdekohtaisesti. Nämä pisteet muunnetaan suhteellisiksi käyttöasteiksi, jotta saavutetut tulokset ovat luotettavia jokaisella ajanjaksolla.

Yleisimmät strategianvalintakriteerit ovat taloudelliset, tekniset, toteutuskelpoisuuteen sekä turvallisuuteen vaikuttavat tekijät. Huoltostrategioista luotettavuuskeskeinen kunnossapito on ainoa, jolla on nouseva trendi. Huoltotyypeillä ei ole aikaan verrattuna havaittavia trendejä. Huoltomenetelmiä dominoi aikaan perustuva jaksotettu kunnossapito sekä ei-ennustava ja ennustava kuntoon perustuva huoltomenetelmä. Tulevaisuuden visiot ovat oletettavasti vahvasti kytkeytyneet näihin edellä mainittuihin menetelmiin.

ABSTRACT

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Recognized development trends and future visions of maintenance strategies in process industry

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101 pages, 48 figures, 7 tables and 8 appendices

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Keywords: Maintenance, process, industry, trend, vision, methodology, strategy, type, method

The objective of this master's thesis is to investigate the trends of maintenance methodologies during the years 2000 – 2020 in the process industry. Future visions of maintenance in process industry were also analyzed to see how the trends of today's industry and the visions are related to each other.

The literature review consists of the definitions of fault, failure, and maintenance. The second part consists of the methodologies' definitions and strategy selection process. The final part explains the definition of a trend and introduces the visions shortly.

Sources from two studies are collected and distributed into different tables to see the application rates of each methodology. The survey period of 2000 – 2020 is split into four periods which act as the timeline for the trends. Each maintenance methodology is graded with points systematically per source. These points are converted into relative application rates to achieve accurate results for each period.

The most common strategy selection factors are economic, technical, feasibility and safety. From maintenance strategies reliability-centered maintenance is the only one with increasing trend. Maintenance types have no relation to time. Maintenance methods are dominated by the top three methods which are time-based interval, non-predictive and predictive condition-based maintenance. Future visions are presumably highly associated with these forementioned methods.

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Big thanks to all my friends from LUT and all around the world. Special thanks to those that had my back when life took unexpected turns. Prost!

Tom Lokkila

Tikkurila, 12.5.2023

SYMBOLS AND ABBREVIATIONS

AB	Age-based maintenance
AHCSM	Analytical hierarchy constant sum method
AHP	Analytical hierarchy process
AI	Artificial Intelligence
AM	Additive manufacturing
AR	Augmented reality
Auto	Autonomous maintenance
CBM	Condition-Based Maintenance
CM	Corrective Maintenance
DOM	Design-out maintenance
FMEA	Failure mode effect analysis
FMECA	Failure mode effect and criticality analysis
FOA	Field of application
IM	Improvement
IoT	Internet of Things
MCDM	Multi-criteria decision model
MSI	Maintenance Significant Items
MTBF	Mean time between failure
MTTR	Mean time to repair
NPd	Non-predictive
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer

OM	Opportunity maintenance
OPE	Overall Process Effectiveness
Pd	Predictive
PHM	Prognostic Health Management
PM	Preventive Maintenance
RBM	Risk-Based Maintenance
RCM	Reliability-Centered Maintenance
SLU	Skill level upgrade
SSF	Strategy selection factor
TBI	Time-based interval
TBM	Time-based maintenance
TIM	Technical Integrity Management
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TPM	Total Productive Maintenance
TQMain	Total Quality Maintenance
VR	Virtual reality
CRP_M	Combined relative percentage of all periods of certain methodology
CRP_{STM}	Combined relative percentage per period for either strategy, type, or method
K	Criticality index
M_p	Production loss risk multiplier
M_s	Safety risk multiplier
M_e	Environmental risk multiplier
M_q	Quality cost risk multiplier
M_r	Repair or consequential risk multiplier

Met	Sum of points for certain methodology in a specific period
P	Unit's or function's weighting in risk assessment
RP	Relative percentage of certain methodology in a specific period
S	Number of periods/splits
u	Uncertainty value
W_p	Production loss weighting factor
W_s	Safety risk weighting factor
W_e	Environmental risk weighting factor
W_q	Quality cost weighting factor weighting factor
W_r	Repair or consequential cost weighting factor

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1 Introduction

The need for maintenance is an issue in any manufacturing or process line. In today's industry the units seem to become more complex and develop faster than the maintenance methodologies that should be used to keep them functioning.

Optimal maintenance methodologies will give a competitive advantage if done correctly. However, implementation of any maintenance methodology on factory or process level can be costly and irreversible. Which is why one should consider the possibilities and risks systematically before deciding the best alternatives. Maintenance methodologies can differ depending on the field of application; therefore, field specific background knowledge should be investigated as well. (Martin, H., Mohammed, F., Lal, K. & Ramoutar 2020, p. 425.)

Interesting statistics can be found regarding maintenance and its differences between research and the process industry. According to Järviö (2017, p. 163) as much as 40% of planned maintenance is unnecessary and possibly even harmful. As much as 80% of the total number of failures do not have time related failure modes but random. From the remaining 20% only 10-20% can be predicted (Järviö 2017, p. 82, 84).

As much as 80% of companies in Swedish industry base their maintenance process decisions on experience and knowledge. 30% base the decision on mathematical models, 10% on using risk analysis tools such as failure mode effect and criticality analysis (FMECA) and only 2% use multi-criteria decision models (MCDM). (Alsyouf 2004, p. 38.)

However, there is a lot of research that focuses on the selection process of the maintenance methodologies, but for some reason this does not translate to company level. The research though does not seem to give much thought to what is being compared. The methodologies which are sometimes unclearly defined are being thrown around and everything seems to be comparable with each other but that is not the case. There is a clear gap in understanding the differences between the maintenance methodologies which this thesis tries to give answers for.

1.1 Research objective, structure, and goals

In this thesis a maintenance methodology analysis is applied by using source data from earlier research. The goals are to recognize trends on every level of maintenance that is defined in this thesis as the following: strategy, type, and method. The fourth level, which would be the maintenance action or service, is left out. This is because the services are highly application dependent and can vary a lot. In addition, some visions are investigated that could explain the trends of today's industry.

First the fault and failure definition of component is explained in literature review as it is the baseline reason why maintenance is needed in the first place. The second part of the literature review introduces the different maintenance types, strategies, and the selection process of those items. However, the selection process itself is a vast topic on its own which is why it is not covered as accurately as it could be with mathematical models. The final part of the literature review consists of the definition of a trend and introduces the latest visions in the field of maintenance. Based on the information from literature, the trend analyzing tool and results are concluded.

The scope of this thesis is limited to the analysis of the maintenance methodologies and their application rates throughout the years 2000 – 2020. Future maintenance visions are shortly investigated to see possible relations with the trends of today's methodologies.

1.2 The research problem and questions

Maintenance as a field seems to be in disarray, it is difficult to pinpoint the problems as the topic is too dependent on the field in which maintenance is applied. There are standards but they are not connected well enough with the methodologies or the actual maintenance actions. This might be the result of lack of resources, inexperienced personnel, outsourcing or other likewise factors. In the end everything revolves around maximizing the profits in any given industry. Maintenance is no exception, the amount of unnecessary maintenance actions can be due to the manufacturers, outsourcing services and other factors that aim to maximize the profits of companies which base their income on maintenance. Investigating the topic from a critical point of view in relation to time could give insight into how the field has changed during the years 2000-2020. It would also help to understand the possible reasoning behind the dominant methodologies and visions in maintenance. Following research questions are based on this overview of the research problem,

Q1. How the focus of discussion and the research objectives of the maintenance methodologies and their applications have changed during the past two decades and why, and what are the recognized trends of these changes?

Q2: What are the recognized development visions of the maintenance methodologies and the assisting tools for the future and what would be their contribution to the current maintenance methodologies?

2 Fault and failure of an item

Fault is the reason maintenance is needed in the first place. Therefore, it is important to acknowledge what causes the need for maintenance. In this chapter, the definition of fault and failure is explained. In addition, root causes for failures are shown and classification of different failure models are compared.

2.1 Definition of fault and failure

Fault is a state in which a component cannot execute the required function as it is supposed to do. Excluding the situation where the unit or system is not in use because of maintenance or lack of other resources such as fuel or energy. The required function is explained in detail in the definition of maintenance, Chapter 3.1. Faults can be identified as abnormal functionality like efficiency or quality loss. In worst case scenario, the function cannot be completed in any form or way. (Järviö 2017, p. 71.)

The following can happen when a fault occurs,

- Disturbance: In this case the item is not broken but it causes immediate need for maintenance and loss of production. The maintenance can be just resetting the machine, cleaning, or changing settings. The interval for a fault can be identified with the data collected from disturbances.
- Damage: The item is broken, and the consequences are similar in disturbance. It requires more effective actions of maintenance. From damages it is possible to identify the intervals for faults and the life cycle of the item.

(Järviö 2017, p. 71.)

Failure is an occurrence which puts the item under failure in a state of fault. In standards the term “failure” is categorized purely as a quick instance that results in interruption of operation – the required function cannot be completed after this instance. For some reason standards consider failure purely as quick instance. Slow degradation that leads to failure is not included in standardized terms. There are upcoming and non-standardized terms that are core elements of maintenance strategies such as Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM). These terms define the slow degradation of an item instead of quick instance. Deterioration describes the slow degradation of an item due to a combination of normal wear and hidden faults. As a result, the item cannot function as normal anymore and its efficiency lacks noticeably compared to a new identical item. (Järviö 2017, p. 71.)

In TPM the following terms are often applied. Chronic failure is often a hidden fault that noticeably hinders the function of an item, and it happens repeatedly. Sporadic failure is sudden and has a larger impact on the required function. Chronic failure can be fixed permanently by changing the environmental factors for example. Whereas sporadic failure requires corrective maintenance. (Järviö 2017, p. 72.)

2.2 The causes of faults and failures

Originally the cause for failures have been deemed as mistakes in production or design of units. Through comprehensive research this claim has been concluded as misinformation. The baseline for every machine is that the design is “perfect” in a sense that no failures will occur. This includes everything from materials to production and proper operation. Therefore, one can conclude that every failure is the result of some development mechanism. And fault is the result of failure. (Järviö 2017, p. 85, 76.)

One of the main reasons for machine failure is the operators’ lack of interest in keeping the machine in good condition. The operator might notice something wrong with a machine, but the infrastructure of reporting, communication and task management sets the worker up to choosing the easier option and not caring for the machine. Reporting and communication might be too counter-intuitive. If responsibilities are completely separated between operator and maintenance personnel, the operator might justify the misuse of the machine. Additionally, the knowledge of both operators and maintenance personnel often lack the proper knowledge of symptoms that can lead to failures. In worst case scenario maintenance work can lead to more failures as the initial symptom of a machine has been misunderstood. (Järviö 2017, p. 85.)

Aging of components and machines will cause minor degradation of components, which leads to ineffective output. Additionally, environmental factors can be crucial depending on the application. These forementioned factors become root causes if the unit cannot sustain its function due to the environment. The unit might be used in a different environment than what was originally intended. For example, dirt, dust, humidity, and other factors can cause massive problems over time if they are not considered during the design process. (Järviö 2017, p. 85.)

Nowadays maintenance is more focused on the preparation work. This contains figuring out the root causes and propagation of failure modes. This is arguably the most important part of the field of maintenance as preventing the need for maintenance is more desirable than completing the maintenance tasks effectively. The only possibility of improving the reliability of an item is to work on the root causes mentioned above. If the focus is only on improvement of the design of an item or equivalent factor, true reliability is never reached. With the forementioned problems solved, there has been reported a case in which the number of maintenance activities dropped by 98%. (Järviö 2017, p. 76, 85.)

2.3 Classification of failure models

Traditional mindset includes only one failure model that is based on time. A brand-new item has more problems as it is settling in as part of the process. The same phenomenon occurs as the item is close to the end of its life cycle. The time in-between is the part in which the occurrence rate of failures is stable. This is shown in Figure 1 below.

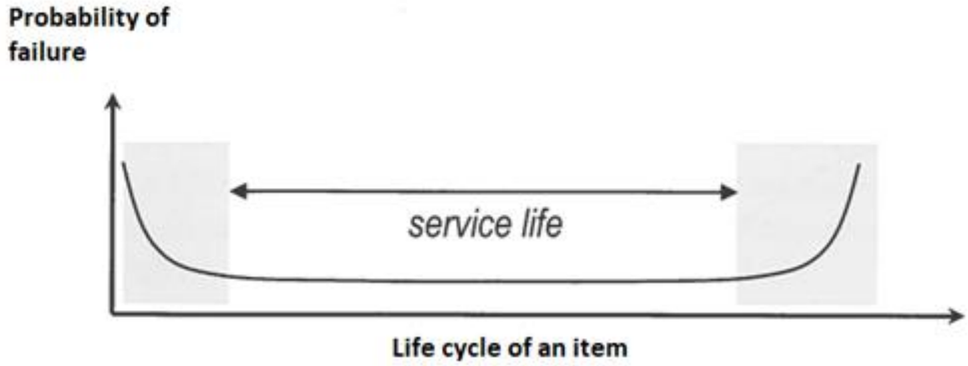

Figure 1. Traditional model of the lifecycle of an item (Järviö 2017, p. 80) (Modified picture)

Maintenance is performed only during the service life-section that is defined above. That is because there is too much variance during the so-called infant mortality of an item. To name a few – incorrect installation, unprofessional instructions or maintenance that is not performed properly. In the end of the lifecycle the rising number of failures might become more expensive than investing in a new item. (Järviö 2017, p. 80.) Reasons are not mentioned for the rising number of failures at the end of the life cycle.

Time-based models themselves are not valid in many cases. For example, a company called “SKF” executed a study of failure modes regarding bearings. Zero cases could be identified as time-based failure excluding failures from normal wear. Below is Figure 2, in which the first three models A, B and C are time-based and the models D, E and F show that the failure modes are random. The model G is a new model that has been identified with computers’ peripherals. (Järviö 2017, p. 81.)

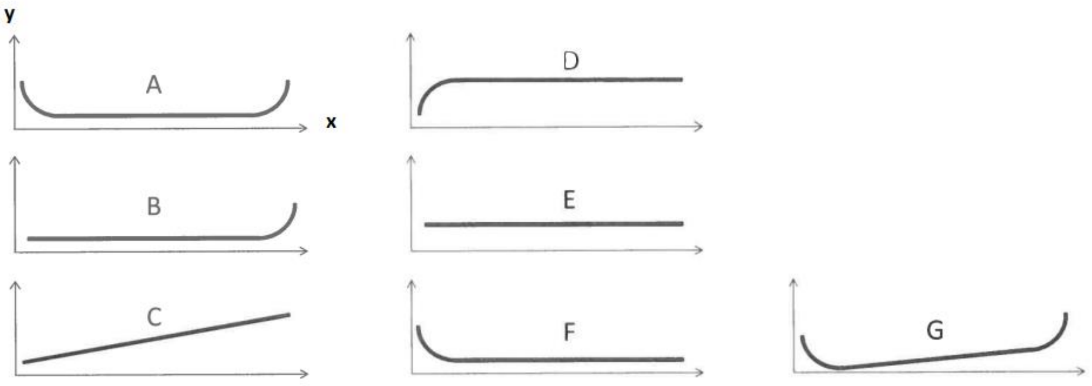

Figure 2. Failure models of items. X-axis: age of an item, wear rate etc. Y-axis: Probability of failure. (Järviö 2017, p. 81) (Modified figure)

According to Järviö (2017, p. 82) as much as 80% of failures follow the models D, E or F. From the rest 20%, only around 10% of failures can be predicted, which would mean that designing a maintenance strategy purely on preventive maintenance is not a sensible option. These values are not studied in the process industry but in airplane industry. However, according to experts in the field industrial production and process engineering follow the same failure models as in airplane industry. The distribution of models in airplane industry, which can be compared directly to process industry, are shown in Table 1 below.

Table 1. The occurrence of failure models (Järviö 2017, p. 82)

Model	UAL	Broberg	MSP	Submepp
A	4 %	3 %	3 %	2 %
B	2 %	1 %	17 %	10 %
C	5 %	4 %	3 %	17 %
D	7 %	11 %	6 %	9 %
E	14 %	15 %	42 %	56 %
F	68 %	66 %	29 %	6 %
Field of study:	Civil airplanes	Civil airplanes	Ships	Submarines

As can be seen from Table 1, the field of civil airplanes, which corresponds to process industry – has the most failure models in category F. As components become more complicated the more difficult it becomes to define the failure model for a unit. In most cases the unit's complexity is too high to determine the failure model. This often leads to a case where the probability factor of the failure model is constant – this means that the failure model falls into category F. (Järviö 2017, p. 83.)

John Moubray, who is a known RCM expert in the field of maintenance, has set average values for faults that can be predicted. Values are shown in Table 2.

Table 2. Fault distribution by predictability (Järviö 2017, p. 84)

Can be predicted	10 – 20 %
Can be found via symptoms	30 – 40 %
Cannot be predicted	40 – 60 %

As these are just guideline values, the expected values can vary from what is shown in Table 1. Based on Table 1 over 40% and likely higher number of faults cannot be predicted. Therefore 40-60% of preventive maintenance is excessive. (Järviö 2017, p. 84.)

2.4 Key points of chapter 2

With the forementioned information in mind, it is possible to analyze the resulting trends of different methodologies and question the reasonings behind the application rates. The trends are not informative by themselves if there is no background information on what factors the failure models are based on. When the failure models and their incidence rate are acknowledged, it's possible to evaluate and question the application rate of different methodologies.

3 Maintenance in process engineering

In this chapter the definition of maintenance is explained. Various maintenance strategies, types and methods are introduced. In addition, the selection process of a maintenance strategy and its contents is presented.

3.1 Definition of maintenance in process industry

The definition of maintenance according to the standard (SFS-EN 13306, 2017:en) is “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”.

At the production system level administrative and managerial actions can include improvement of cost effectiveness and operational factors, managing subcontractors, inventories, health, and safety factors of personnel. On unit level it includes maintenance costs, maintainability of unit and so on. (Järviö 2017, p. 17.)

The required function being a single or combination of functions which must execute correctly for the application being able to fulfil its requirements. Retaining the function is executed by preventive maintenance and restoring the function includes corrective maintenance. (Ben-Daya, Kumar & Murthy, 2016, p. 12.)

The maintenance planning process can be divided into following terms:

- Maintenance strategy
- General maintenance plan
- Maintenance task analysis

Maintenance strategy is the top-level term that defines the objective of maintenance. It determines the selection from personnel resources, general maintenance plans, locations, materials to equipment data management. The general maintenance plan is concluded from the maintenance strategy which acts as a baseline for maintenance. General maintenance plans take into consideration all required environmental factors, resources and supporting functions. Maintenance task analysis concludes more specific details regarding the general maintenance plan. These details are the pre-determined maintenance activities and their required resources on system, sub-assembly, or component level maintenance. (PSK 6021 p. 16.) Additional note that should be acknowledged; the standard PSK 6800 defines “maintenance plan” as the same piece of information as PSK 6021 defines “maintenance task analysis”. Whereas “general maintenance plan” has a completely different definition in PSK 6021.

A structural model can be designed of a plant that helps to distinguish the differences between levels that maintenance can be made on (Kelly, 2006, p. 55). The hierarchy model is essential to identify all the equipment and divide it correctly into systems, sub-assemblies, and components. One can see the levels from Figure 3 below.

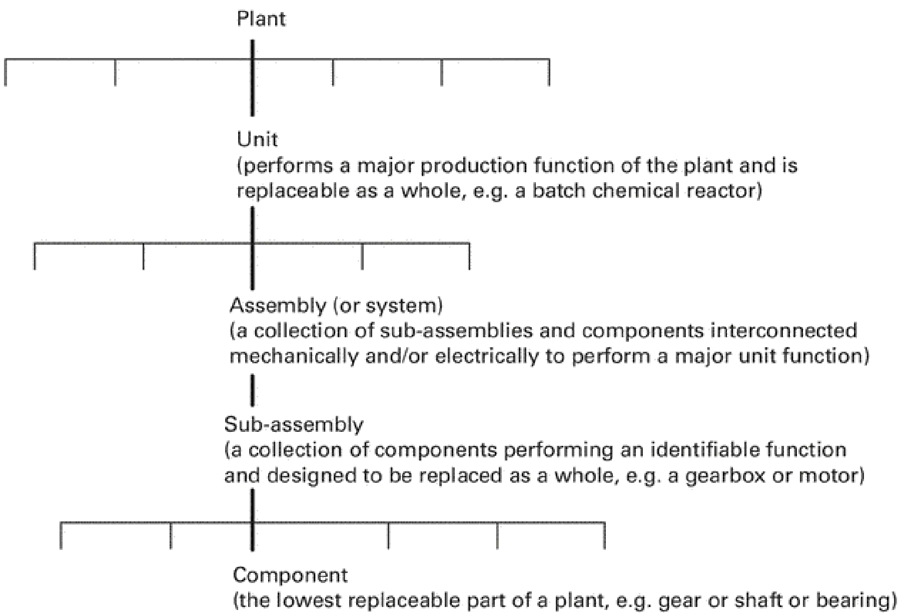

Figure 3. Structural model of a plant (Kelly, 2006, p. 55)

The plant level is self-explanatory, it is the top level for which maintenance strategy is implemented. For all the levels below “plant” a general maintenance plan or task analysis can be implemented.

A process flow diagram is helpful for compiling the overall picture of the process. The structural model divides the plant into different units and smaller parts but gives no information regarding the co-operation between units or systems. Process flow diagram fills this gap in information and is a mandatory step to complete to understand the characteristics of the plant. When the characteristics are known, selection of maintenance strategy becomes much easier. (Kelly, 2006, p. 59.) Below from Figure 4 one can see the basic principle of a process flow diagram.

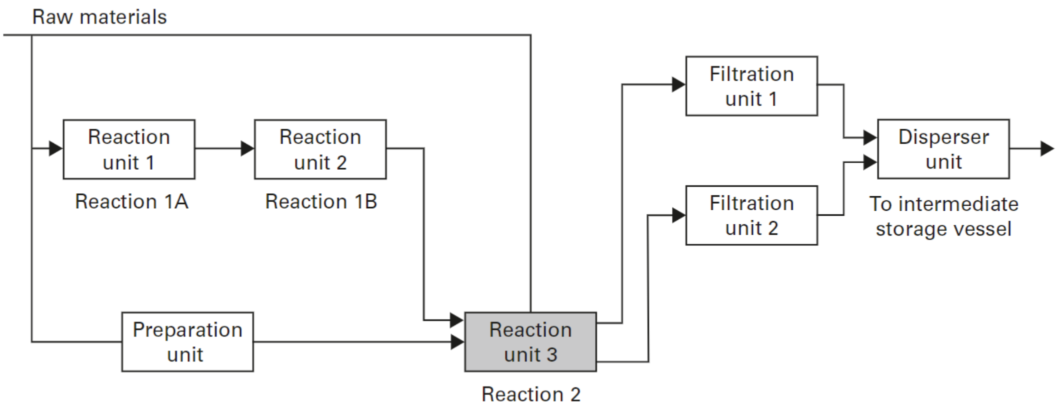

Figure 4. Process flow diagram example (Kelly 2006, p. 59)

Figure 4 is simplified and could be done on a more detailed level. One should carefully consider the level of accuracy when creating the process flow diagram. Too detailed process flow diagram will make it hard to truly understand the process in full. However, a diagram that is described too generally might lack critical information. The goal is to understand the most critical factors between systems, not every single factor. This makes it easier to determine the most suitable maintenance strategy, type, or task analysis.

3.2 Condition audit in process industry

Condition audit is a standardized process and part of the selection process of a maintenance plan. The goal of condition audit is to acquire as broad and accurate understanding of the plant processes. It acts as a tool for collecting initial data. This data reveals overall picture of the plant process and near complete list of required maintenance actions. The actions should consider environmental effects and cost estimates. By doing this it is possible to estimate some guidelines for the expenses and timings of the maintenance actions. The objective of a maintenance plan is to stretch the life cycle profit to its maximum limit. (PSK 6202, p. 4, 15.)

3.3 Categorization of maintenance terms: strategies, types, and methods

In this sub-chapter the distinctions between different terms regarding maintenance are made. There is an abundance of different strategies, types, and methods some of which are not classified. In this chapter a collective list is made from multiple sources of information.

Following definitions are made to be clear on the differences of methodologies:

- Maintenance strategy is the top level that determines the selection of everything from personnel resources, general maintenance plans, locations, materials, and equipment data management. For example, Reliability Centered Maintenance is a strategy. This is a standardized term. (PSK 6021 p. 16.)
- Maintenance type is the second level of maintenance. It is the basic principle of how one can execute maintenance, for example, preventive maintenance is a maintenance type. This is a standardized term. (SFS-EN 13306, 2017:en.)
- The maintenance method is the third level of maintenance: One type of maintenance, such as preventive maintenance, can be performed with multiple different methods. For example, time-based interval maintenance. This is not a standardized term.
- The maintenance action is the fourth level of maintenance, this includes the actual service of an item. This level is excluded from the investigation of this thesis as was mentioned in introduction. This might be standardized term; no source was found.

The terms are shown in Figure 5 below to give visual interpretation of how the terms form the levels of maintenance. In literature many authors refer to maintenance strategies which are methods by the definition of this thesis.

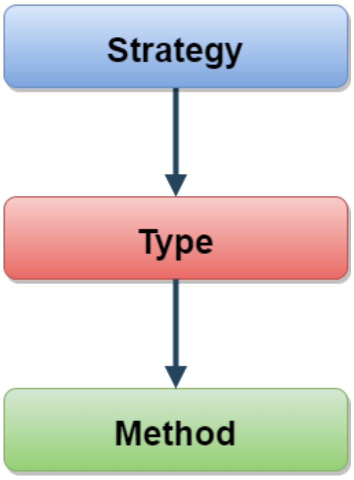

Figure 5. The hierarchy of terms to reach completion of maintenance actions.

The terms and definitions regarding maintenance can vary a lot between research studies, books, or other sources. Maintenance is generally categorized into three types which are improvement, preventive and corrective maintenance (Mobley, 2004, p. 9; Patil et al., 2022, p. 680; SFS-EN 13306, 2017:en, p. 58). A book by Velmurugan & Dhingra (2021, p. 38) suggests that there are even as many as six types, them being shown in Appendix 1. This is probably just poor categorization as some of these types are included in the forementioned sources as well but are defined as methods instead. Another book by (Ben-Daya, Kumar & Murthy, 2016, p. 76) does not include improvement as a maintenance type at all and the methods are almost identical with different names. None of the sources agree on one uniform sub-categorization besides the main types, meaning there is some room for interpretation. This interpretation is shown in Figure 6 below. The abbreviations are as follows in Figure 6; Total Productive Maintenance (TPM), Risk Based Maintenance (RBM), Reliability Centered Maintenance (RCM). The general maintenance plan and task analysis do not belong in the three main levels of maintenance and were explained in Chapter 3.1.

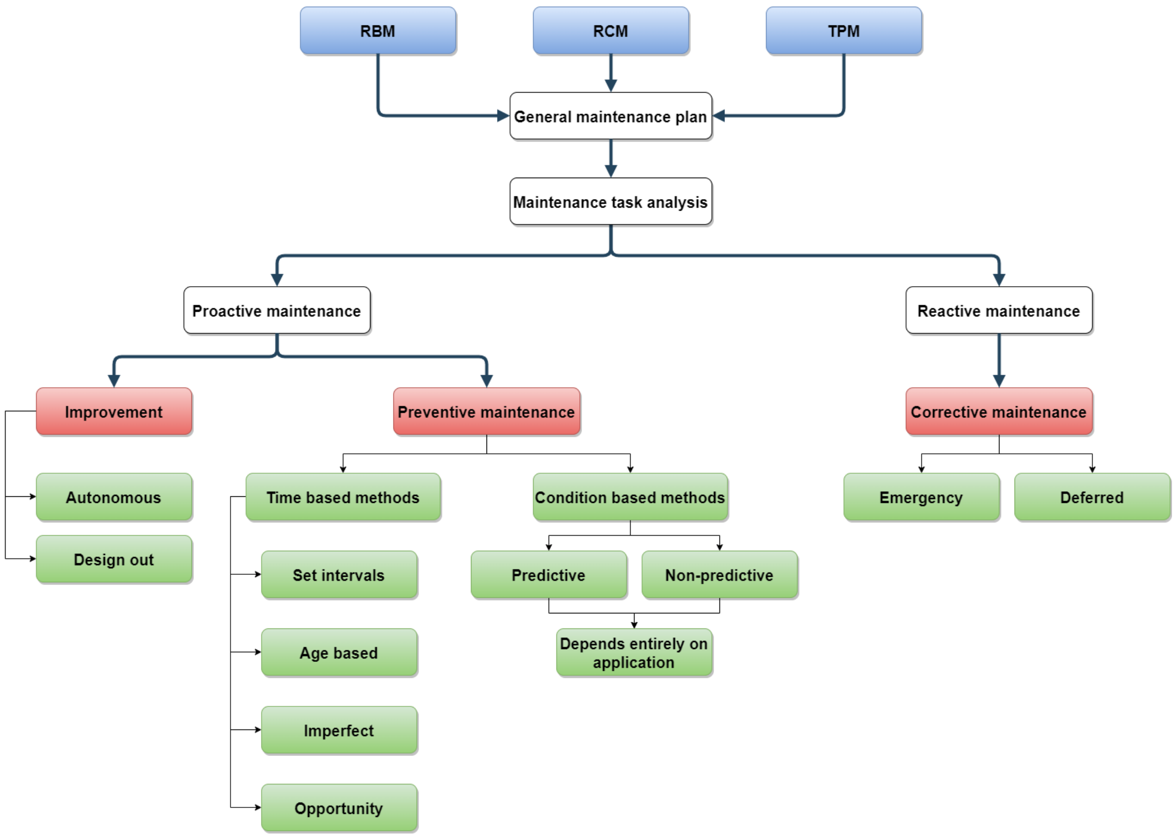

Figure 6. My interpretation of Appendix 1

This gives an overall explanation of how the terms are defined in the field of maintenance. Not every strategy, type or method is included in Figure 6 as there are simply too many of them. First a maintenance strategy is chosen, based on the strategy a general maintenance plan can be determined. From the general maintenance plan a maintenance task analysis is conducted which contains the specific types and methods that are used. The task analysis is then distributed into proactive and reactive maintenance types. Then the three types of maintenance are divided into methods which are approximately the same in all sources. The standard (SFS-EN 13306 2017:en) specifies maintenance types in nineteen different types and does not define methods at all. However, other source materials often define the methodologies as strategies or methods which is why the interpretation was made for this thesis.

Original Equipment Manufacturer (OEM) recommendations are usually part of every maintenance plan. They should be available in the operations and maintenance manuals that are supplied with the delivered equipment. OEM is not a maintenance type or method itself but acts as important support material when creating a maintenance task analysis. (Velmurugan, Dhingra, 2021, p. 41). While the warranty might be cancelled if the OEM recommendations are not followed, the guidelines are rather excessive and can be partly a reason that causes breakdowns to happen in the first place.

3.3.1 Improvement

In improvement the goal is to try and improve the maintenance of a system in a way that breakdown will not happen unexpectedly. This can be achieved with two methods: autonomous (Auto) and design-out maintenance (DOM).

In design out maintenance a component or system is redesigned in a way to prevent the root causes for failures. To give an example, a bearing could be swapped from normal into a bearing that has lubrication for its life. Another method could be to add a lubrication system that prevents the bearing from breaking down thus possibly preventing follow-up problems in the process. This maintenance method is noteworthy in cases where the component is in a poorly accessible location. (Mobley, 2004, p. 8.)

In autonomous maintenance all personnel working with a specific system are trained in their respective levels to maintain the system. Co-operation with the production and maintenance department enables the possibility to exclude the need for external or additional maintenance technicians. (Patil et al., 2022, p. 681.) This method is seen as a key component in Total Productive Maintenance which will be discussed later in its own chapter.

3.3.2 Preventive maintenance

Preventive maintenance (PM) aims to prevent the breakdown of a component thus minimizing unscheduled downtime of a system or unit (Mobley, 2004, p. 9). In other words, it extends the life cycle of the system by reducing the probability of failure and degradation (Velmurugan, Dhingra, 2021, p. 38; Patil et al., 2022, p. 679).

The risk of failure still exists even when using a PM method (Niemann, Pisla, 2020, p. 30). Generally PM methods are purely time or condition-based and the maintenance actions can vary from visual inspections, servicing, lubrication, calibration testing to component replacement (Ben-Daya, Kumar & Murthy, 2016, p. 77).

Time-based maintenance (TBM) activities are executed in a way in which different type of time intervals are used to determine the need for service. These methods are individually explained below in this chapter. Poorly chosen intervals can lead to too frequent activities, hence resulting in increased costs for labor, spare parts, and repair (Niemann, Pisla, 2020, p. 30). When planning to use TBM methods, one should acknowledge that they are effective only in cases where the failure mechanism is associated with time (de Almeida et al., 2015, p. 218).

In general units that have simple functions or are complex but have a dominant failure mode can have time-related failures. The most common units that fall into this category are in contact with the product that is being manufactured. Another common feature is that the units are subjected to rough environmental factors such as fatigue, corrosion, oxidation, and evaporation. (Moubray, 1997, p. 133.)

In Figure 7 below, it is shown that as TBM has no feedback loop, it is not possible to execute the maintenance activity with optimal timing.

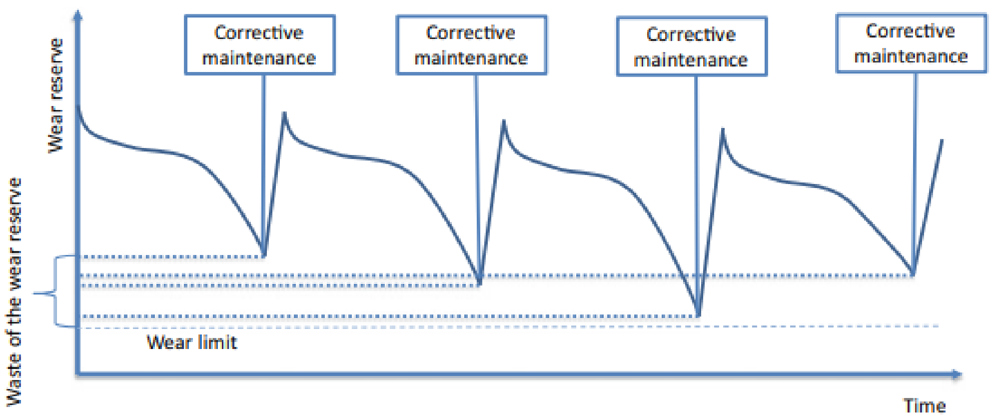

Fig. 3.5 Process of wear reserve during preventive maintenance (Modified acc. [3])

Figure 7. Process of wear reserve during preventive maintenance (Niemann, Pisla, 2020, p. 30)

As can be seen from Figure 7, TBM methods cannot take into consideration the wear of components. Think of an example in which a component is replaced every 6 months. The operator clearly identifies there is no need for replacement yet. The swap must be made in any case as running the system with the same component for another 6 months might result in failure.

Constant interval maintenance is one of the more common TBM methods in which predetermined intervals are chosen by studying the risk failure optimization and PM costs of the system (Patil et al., 2022, p. 679). Utilization of mathematical models is recommended to maximize the optimization possibilities (Velmurugan, Dhingra, 2021, p. 39).

Age-based maintenance utilizes the component's age after installation as benchmark for the maintenance activities. The component is set to be serviced at a certain age which acts as a parameter for when the activity is performed. If the component breaks before the set age is reached, the parameter is optimized accordingly. (Kothamasu, Huang & VerDuin, 2006, p. 1014.)

Imperfect maintenance takes into consideration the fact that the component or unit will not be in "factory new"-state but rather in "field-tested" that has been in use for some time (Patil et al., 2022, p. 679). This method can be extremely heavy regarding workload as it requires in-depth information of the system to build the mathematical models from scratch. (Cheng, Zhou & Li, 2018, p. 252-253.)

Opportunity-based maintenance is a method in which maintenance activities are performed by evaluating the situation on certain levels ranging from component to plant level. For example, if a component fails one can come to the assumption that the same component will probably fail in another identical system soon. This makes it tempting to swap the same component on all identical systems. Another form of this method is to perform all maintenance activities during process shutdown. Systems that are determined as the most critical at that point of time or happen to have spare parts are serviced. (Bevilacqua, Braglia, 2000, p. 73; Borges, internet article; Patil et al., 2022, p. 680.)

Condition-based maintenance (CBM) is in many sources (de Almeida et al., 2015, p. 233; Velmurugan, Dhringra, 2021, p. 38) regarded as its own type of maintenance but under the SFS-EN 13306:2017:en standard it is identified as sub-type of preventive maintenance. It can be divided into predictive and non-predictive maintenance, predictive taking into consideration the evolution of the degradation of components.

CBM is “a philosophy or attitude that, simply stated, uses the actual operating condition of a plant equipment and systems to optimize total plant operation” (Mobley, 2004, p. 4-5). There are disturbances and differences between factories and facilities which makes it hard to set universal guidelines for a specific system (Kothamasu, Huang & VerDuin, 2006, p. 1014). The problem with traditional PM methods such as TBM related, is that excess work and spare parts are used. CBM offers a solution in which the process parameters can be analyzed. This enables the decision; should one execute quick corrective maintenance actions before failure occurs or make long term predictions and trends to solve root causes for breakdowns (Velmurugan, Dhringra, 2021, p. 39).

In CBM the condition of the system is tracked with various measuring devices which depend entirely on the application that is being monitored. Some of the more common nondestructive methods are:

- Vibration monitoring
- Process parameter monitoring
- Thermography
- Tribology
- Visual inspection

(Mobley, 2004, p. 6)

Below is Figure 8 illustrating the possibility of perfect prediction timing for executing a maintenance activity just at the wear limit of a component. Curative maintenance means some small maintenance activity that prolongs the need of corrective maintenance for a component.

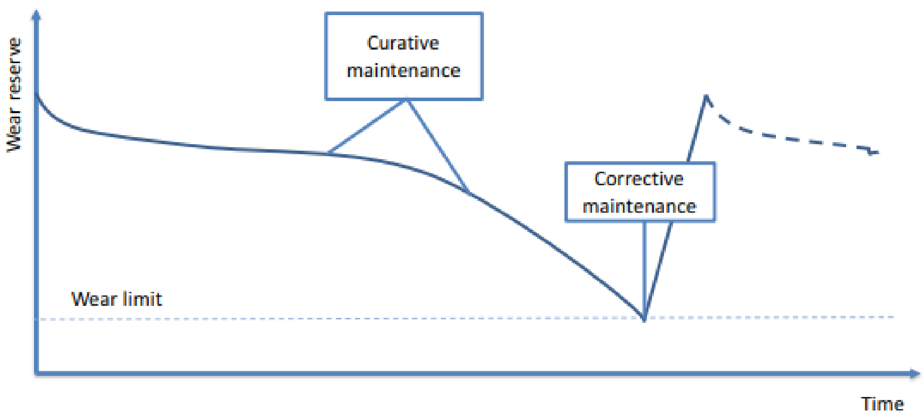

Figure 8. Process of wear reserve during condition-based maintenance (Niemann, Pisla, 2020, p. 31)

3.3.3 Corrective maintenance

Corrective maintenance (CM), also known as run-to-failure maintenance is the traditional way of maintaining products. It is divided into deferred and emergency corrective maintenance, where emergency should be the last possible solution to avoid serious consequences. Deferred corrective maintenance is a viable method given that there is no possibility of harm to anyone’s health or critical damages for equipment. For emergency corrective maintenance certain procedures can be expected. (Kothamasu et al. 2006, p. 1013; Mobley, 2004, p. 6; Niemann, Pisla, 2020, p. 29.)

It should be noted that corrective maintenance can cost as much as ten times the amount of preventive maintenance cost, depending on the application (Järviö 2017, p. 15).

3.4 Maintenance strategies

In this sub-chapter a few maintenance strategies are introduced to gain insight between the differences of the lower-level methodologies. There are more strategies than what are presented, presumably the most common ones are chosen.

3.4.1 Reliability-centered maintenance

Reliability-centered maintenance (RCM) is a maintenance strategy that can be utilized for either a single unit or a complete plant. It is designed to be used for systems in which failure, be it partial or complete, breakdown is not an acceptable outcome (Järviö 2017, p. 165). It is emphasized that in RCM "The driving element in all maintenance decisions is not the failure of a given item, but the consequence of that failure for the equipment as a whole" (Kelly 2006, p. 140).

It starts by studying which processes maintenance is needed the most. When all processes are examined thoroughly one can check which processes impose the most severe consequences in a case of failure. After putting the processes in sequence to a list one must find out what kind of units or machines are included. To start off a small sample is completed, for example a specific process and its sub-processes and not the complete plant process. RCM is strictly a tool for determining maintenance requirements, methods, and actions. Unlike TPM, which includes co-operation between the designers, system operators and other personnel. (Järviö 2017, p. 165.)

The goal in RCM is to create a strategy that helps to analyze the costs of maintenance while maximizing the efficiency of production. To reach this goal one must prioritize the focus on the systems that need maintenance the most. Environmental factors, costs and safety are the most common factors that are evaluated during RCM creation process for each system or unit. (Järviö 2017, p. 167.) RCM should answer the following problems:

1. What are the functions that are occurring during operation of the machine?
2. What are the functional failures that can happen?
3. What is the cause for each functional failure?
4. What is the total effect on the system after specific functional failure?
5. What are the consequences of failure?
6. What proactive actions can be taken to prevent a specific failure from happening?
7. What default actions can be taken if no suitable PM method is found for specific failure?

(Järviö 2017, p. 168; Mobley, Higgins, & Wikoff 2008, p. 2.35-2.39.)

To answer these questions efficiently, the basic principle of RCM creation process is shown in Figure 9 below. Maintenance Significant Items (MSI) are the most critical units that require the most care (Kelly 2006, p. 141). Failure Mode Effect and Criticality Analysis (FMECA) is just an option shown in Figure 9. Other options include reductionist mathematical models like Failure Mode Effect Analysis (FMEA), Risk Benefit Analysis and holistic models such as Root Cause Analysis. The difference being that holistic models utilize historical data which in some cases might be more beneficial in some cases. It is noteworthy that all available mathematical models are fragile to their creator. For example, people might value some things differently such as risk of injury or even death. Therefore, it is important to have some critical thinking towards these models. (Järviö 2017, p. 181.)

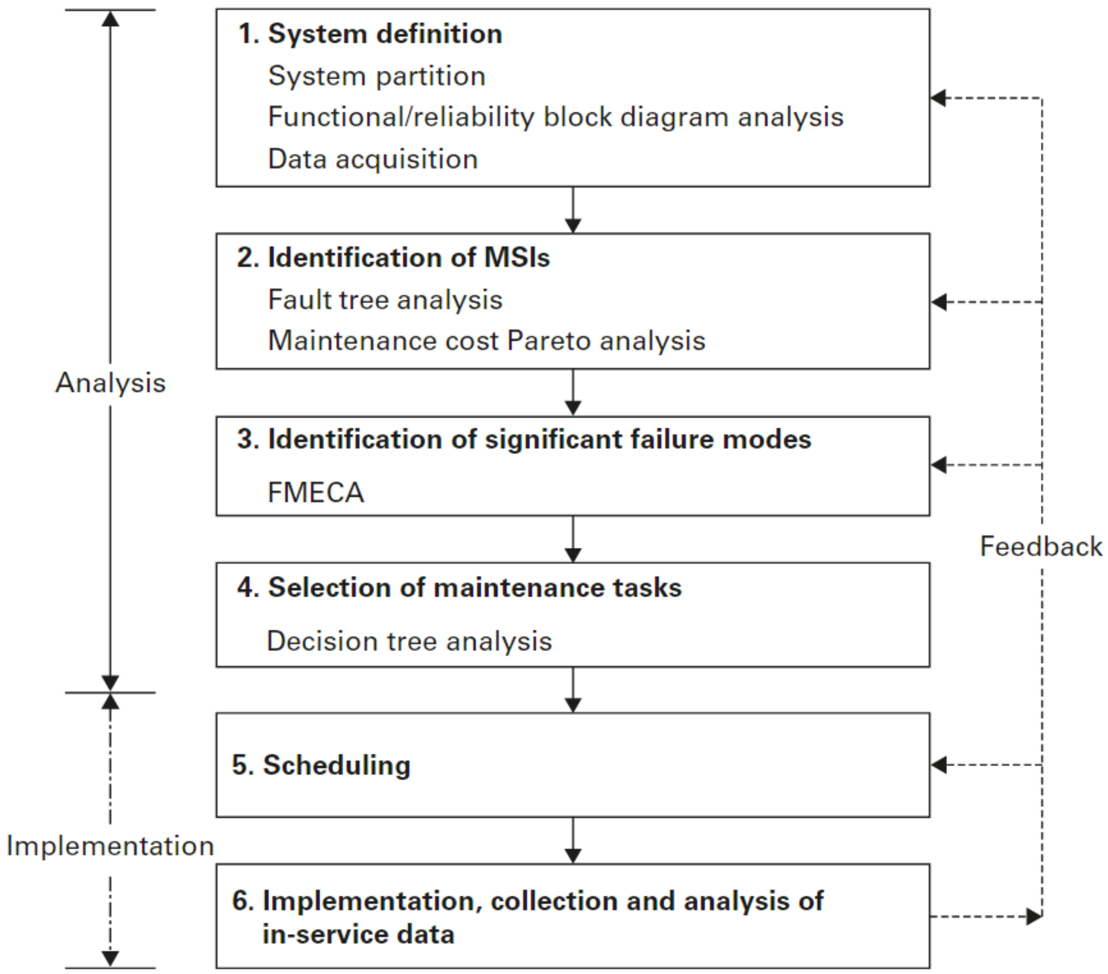

Figure 9. Basic structure of RCM creation process (Kelly 2006, p. 141)

As can be seen from Figure 9, RCM is in a constant process of updating as time goes by. A maintenance plan is often done only for the initial needs of the production and process requirements. However, these factors will almost certainly change during the lifecycle of a factory. In that case the maintenance plan does not meet the expectations of production anymore. Therefore, RCM offers a solution to keep the plan updated. (Järviö 2017, p. 163.)

3.4.2 Risk-based maintenance

"Risk-based maintenance (RBM) methodology is designed to study all the failure modes, determining the risk associated with those failure modes, and developing a maintenance strategy that minimizes the occurrence of the high-risk failure modes" (Arunraj & Maiti, 2007, p. 654). Risk-based maintenance can be summed in two simple steps, risk assessment and maintenance planning based on the risk assessment. The goal of this strategy is like RCM as it's trying to focus maintenance resources towards the most critical units. The most critical units being the ones that have the largest impact on production, environmental or other factors. These factors have different weightings depending on how important they are to the production process. (Arunraj & Maiti, 2007, p. 656; PSK 6800, p. 3-5.)

RBM can be completed with either quantitative or qualitative risk assessment. The quantitative method should be applied only when it's practical. The practicality can be assessed by evaluating the validity of initial data and estimating the cost effectiveness of the strategy. Qualitative risk assessment can be used when the risks are low and well known. Additional requirements are that the major risks are simple to describe, and their likelihood of occurrence is predictable. There are multiple ways of creating an RBM strategy but many of them are fragile in terms of uncertainty and sensitivity analysis. (Arunraj & Maiti, 2007, p. 656, 660.)

There is also a standardized process to create an RBM strategy. Using standardized processes helps to avoid the uncertainties of strategies that are not officially approved. One standard process, "PSK 6800 – Criticality classification of equipment in industry" is introduced to give more detailed information regarding the process. The process has seven main steps that are explained below in Figure 10.

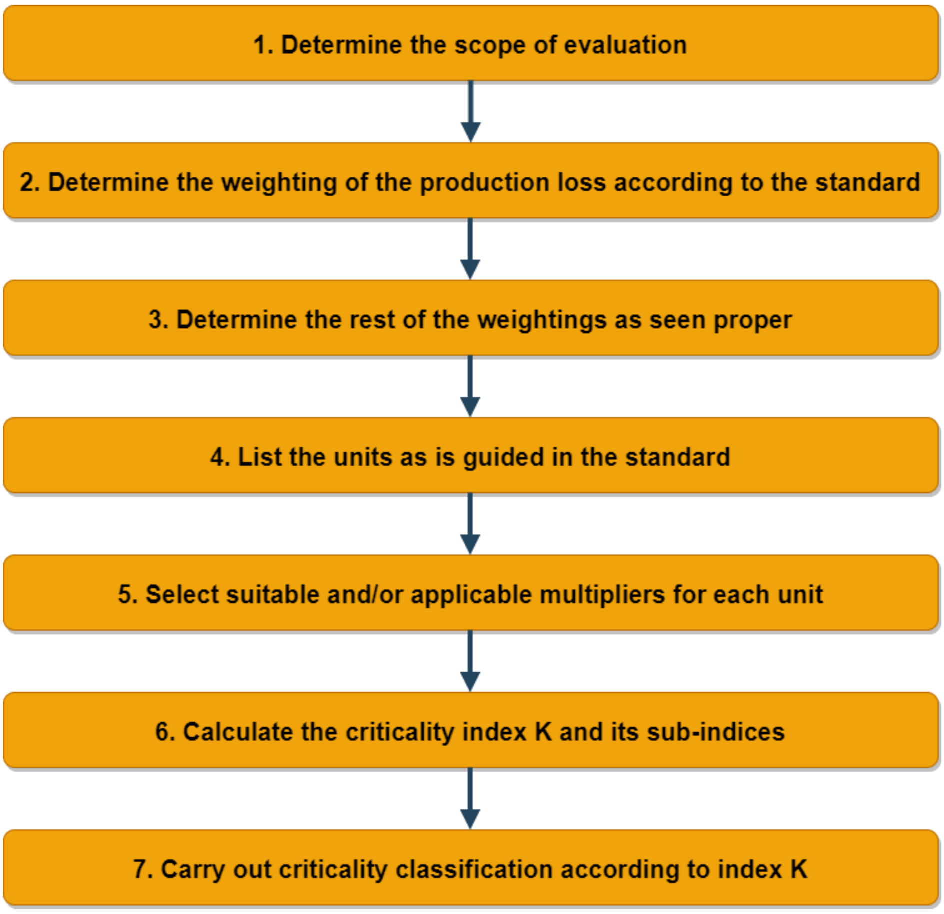

Figure 10. Description of one RBM method according to standard (PSK 6800 p. 3)

As can be seen from Figure 10, first the units that belong in the scope of the risk assessment are identified. Then weighing factors and multipliers are determined as well as possible for the system under evaluation. The final steps output a value for criticality index K for each unit. This index is compared to the pre-set limit for criticality classification. If a unit exceeds this limit, it is identified as a critical unit. Critical units should be focused on more when creating the maintenance task analysis.

If specific sub-indices are the determining factors, one should perform the “step 7.” with the selected sub-indices instead of index K. For example, if a unit’s risk is purely based on quality cost and environmental risks, the corresponding sub-indices should be used. (PSK 6800, p. 3.)

Step 1: First the structural model should be created as explained in Chapter 3.1. Then it’s possible to determine the scope of the evaluation.

Step 2: Determining the weighting of production loss. The weighting of a unit is determined by the value it produces in the process. When there are multiple units in one production line, the weighting of 100% is shared between the units. Units can be connected parallel or in series, if the units are connected in series the weightings are shared evenly between those units. A unit that causes complete shutdown of the process will have a weighting of "100". (PSK 6800, p. 4-6). Figure 11 below illustrates this step.

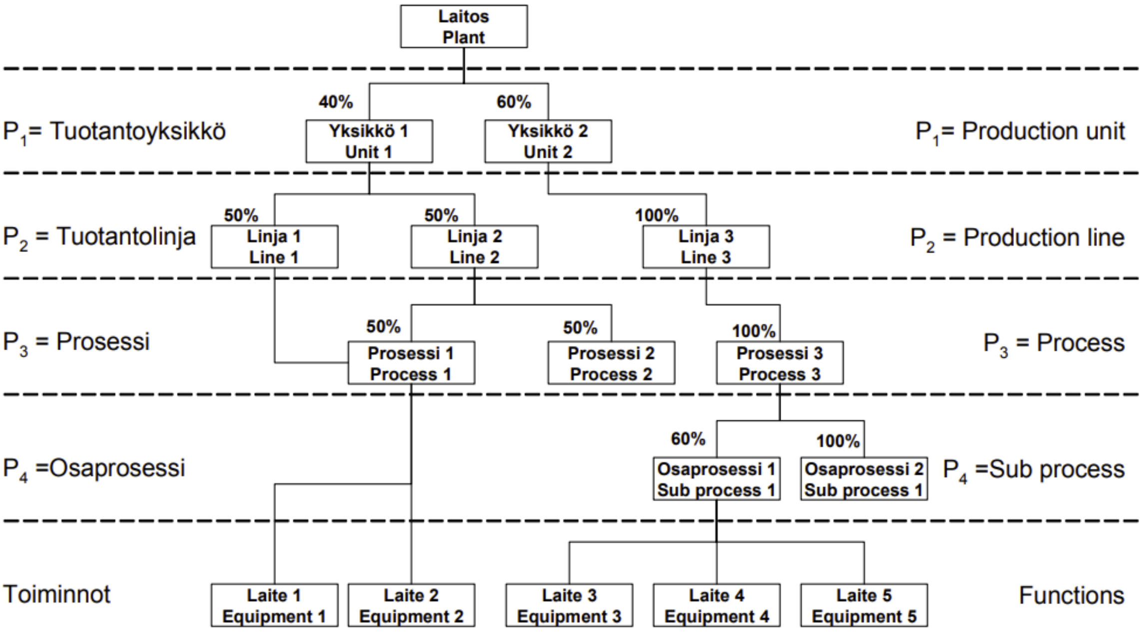

Figure 11. Example weighting factors of units (PSK 6800, p. 5)

After this determining the values for each unit, one can calculate the weighting factor for production loss with following equation:

$$W_p = P_4 \times P_3 \times P_2 \times P_1 \tag{1}$$

The risk assessment method of standard PSK 6800 does not consider the impact of variation regarding market factors such as price and demand. They can be inserted in Equation (1) as variable factors if needed. (PSK 6800, p. 4.)

Step 3: Determining the rest of the weighting factors. In total the sum of all risk factors should add up to 100. This can be seen from Figure 12 below.

Object	Weighting factor [W]	Time between failures [p]	Multiplier [M]	Selection criteria
Safety and environmental impacts	Safety risks $W_s = 30$	1 = Long time between failures, eg. over 5 years 2 = Quite long time between failures, eg. 2 to 5 years 4 = Quite short time between failures, eg. 0.5 to 2 years 8 = Short time between failures, eg. 0 to 0.5 years	$M_s = 0$	No safety risk
			$M_s = 2$	Minor safety risk
			$M_s = 4$	Moderate safety risk
			$M_s = 8$	Major safety risk
			$M_s = 16$	Serious safety risk
	Environmental risks $W_e = 20$		$M_e = 0$	No environmental risk
			$M_e = 2$	Minor environmental risk
			$M_e = 4$	Moderate environmental risk
			$M_e = 8$	Major environmental risk
			$M_e = 16$	Serious environmental risk
Production impacts	Production loss $W_p = 0 \ldots 100$		$M_p = 0$	Non-operation of equipment has no impact on the sub-process or department
			$M_p = 1$	Non-operation of equipment stops the sub-process or department momentarily (eg, ≤3 h)
			$M_p = 2$	Non-operation of equipment stops the sub-process or department for a short time (eg. ≤10 h)
			$M_p = 3$	Non-operation of equipment stops the sub-process or department for a considerable time (eg. 10 to 24 h)
			$M_p = 4$	Non-operation of equipment stops the sub-process or department for a long time (eg. >24 h)
	Quality cost $W_q = 30$		$M_q = 0$	Non-operation of equipment does not cause quality costs to the end product.
			$M_q = 1$	Non-operation of equipment causes quality costs on the end product equivalent to a momentary production loss (eg. ≤1 h)
			$M_q = 2$	Non-operation of equipment causes quality costs on the end product equivalent to a short-term production loss (eg. ≤3 h)
			$M_q = 3$	Non-operation of equipment causes quality costs on the end product equivalent to a major production loss (eg. 3 to 8 h)
			$M_q = 4$	Non-operation of equipment causes quality costs on the end product equivalent to a long-term production loss (eg. >8 h)
Repair or consequential costs	Repair or consequential cost $W_r = 20$		$M_r = 0$	Repair or consequential costs are not significant in relation to other losses.
			$M_r = 1$	Minor repair or consequential costs equivalent to a momentary production loss (eg. ≤2 h)
			$M_r = 2$	Medium repair or consequential costs equivalent to a short-term production loss (eg. ≤10 h)
			$M_r = 3$	High repair or consequential costs equivalent to a major production loss (eg. 10 to 24 h)
			$M_r = 4$	High repair or consequential costs equivalent to a long-term production loss (eg. >24 h)

Figure 12. Unit level criticality factor table (PSK 6800, p. 8)

The sum of weighting factors for safety, environmental, quality cost and repair or consequential cost adds up to 100. All the weighting factors given in Figure 12 are just informative and must be checked before applying the strategy in any application. The production loss has its own weighting as was shown in Step 2.

Step 4-5: One should list the units in a form shown in Appendix 2. Then apply a multiplier for each object and unit separately. The guidelines for multipliers are shown in Figure 12.

Step 6: From the table shown in Figure 12 one can get the values for all parameters that are needed to define the index K. Index K is calculated for every unit that is connected to the relevant production process.

The equation for K is as follows:

$$K = p \times (W_s \times M_s + W_e \times M_e + W_p \times M_p + W_q \times M_q + W_r \times M_r) \qquad (2)$$

The sub-indices can be calculated by using the equation:

$$K_x = p \times (W_x \times M_x) \qquad (3)$$

In which the “x” is one of the five factors that are shown in the criticality factor table above. For example, the equation of quality cost would take form:

$$K_q = p \times (W_q \times M_q) \qquad (4)$$

An important note is that the criticality index of safety and environment are subjective to the field that the RBM is used for. For example, a risk that manifests in chemical plant has larger impact when compared to some other field of industry. (PSK 6800, p. 9.)

Step 7: At this point a criticality index K should be defined for each unit. Carry out criticality classification according to the K-indices. These index values are compared to a pre-set limit value. If the limit value is exceeded, the unit will be classified as a high-risk item. Therefore, it’s possible to focus the maintenance resources on these high-risk units. It is good to note that choosing the limit value and the weightings require expert knowledge of the systems. Otherwise, the results of RBM are not accurate.

3.4.3 Total productive maintenance

Total productive maintenance (TPM) is a broad topic, and it has as many definitions as there are authors of the topic. The most basic interpretation of it would be something like this; It’s more than a strategy, it’s a philosophy that the whole company must agree to in all hierarchies for it to work. Production and maintenance are not differentiated in terms of who is responsible for a specific machine being in operative condition. The goal is to reach maximum efficiency of systems and machines by slowing down or preventing degradation of components through various maintenance methods and cooperation between departments. The overall number of maintenance activities is minimized through applying autonomous maintenance, planned maintenance and maintenance reduction. Maintenance reduction can be applied with predictive and condition-based maintenance methods. Products and services are meant to exceed the customers’ expectations by reaching so called world-class manufacturing system in terms of quality and cost. (Díaz-Reza, García-Alcaraz & Martínez-Loya, 2019, p. 5-6; Mobley et al. 2008, p. 2.41; Järviö, 2017, p. 150.)

TPM is a challenging strategy to implement as there are many factors that must be taken into consideration. It should be based on solid concepts that can be applied to that specific environment. Cultural differences are an important factor and cannot be excluded as implementing TPM from one culture to another is neigh impossible. In addition, every factory or process line has its own unique features that must be kept in mind when deploying TPM. (Díaz-Reza et al, 2019, p. 11; Järviö, 2017, p. 150.)

The concepts of TPM are often described as a pillar approach. The number of pillars depends on the application at hand, what country the application is in and what the work culture is in that country. Some studies have five pillars, some have even ten pillars, but the main principle originated from Japan has eight pillars. These pillars are introduced below in Figure 13. (Díaz-Reza et al, 2019, p. 11.)

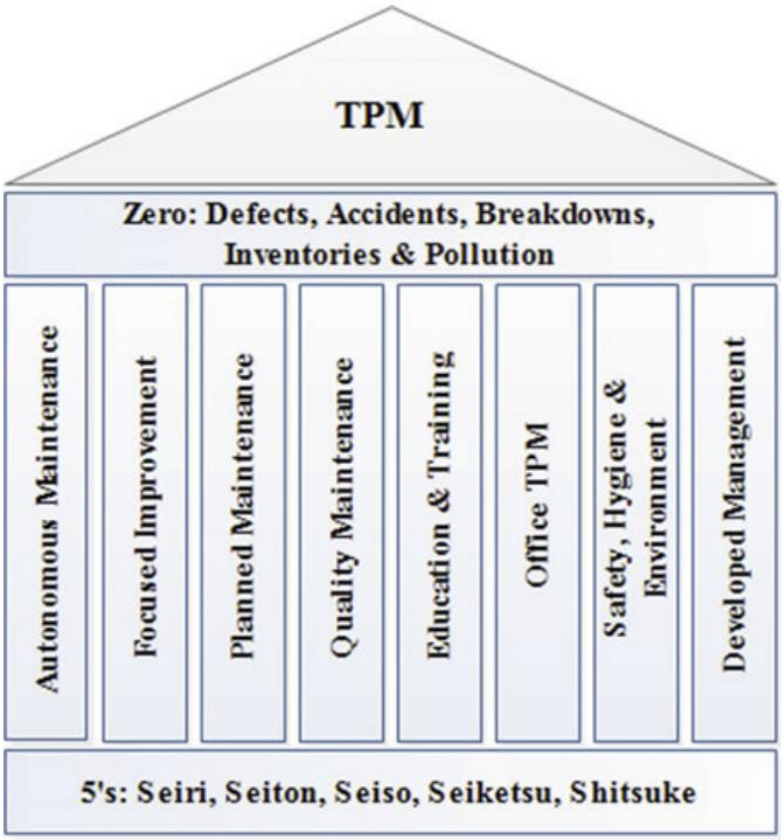

Figure 13. The main concept pillars of TPM (Díaz-Reza et al, 2019, p. 11)

The pillars are introduced shortly below to give an understanding of the scale of TPM. The point is to just understand the basic principle why these concepts are important in TPM. The foundation for TPM is the 5S method which at the same time acts as the first pillar; “Autonomous Maintenance”.

Seiri (Sort): Remove all unnecessary equipment from the work environment.

Seiton (Straighten): The necessary equipment is marked and put in the correct location.

Seiso (Sweep): Keep the workstation always clean.

Seiketsu (Standardize): Definition of what is clean is given for each workstation.

Shitsuke (Sustain): Overall mentality of workers that the plan is respected, and no external supervision is needed to sustain these rules.

(Díaz-Reza et al, 2019, p. 12-13; Järviö, 2017, p. 119-121.)

The second pillar is “Focused improvement”, which means implementing small improvements but on large scale continuously over time. This results in increased Overall Equipment Effectiveness (OEE) which is the main measurement of TPM. It will be explained in detail later in this chapter. (Díaz-Reza et al, 2019, p. 12-18.)

The third pillar is “Planned maintenance”, which refers to all maintenance methods that are planned in one way or another. It is a crucial part of the TPM to help and understand the correct ratio of planned and unplanned maintenance. (Díaz-Reza et al, 2019, p. 12-18.) This is shown in Figure 14 below.

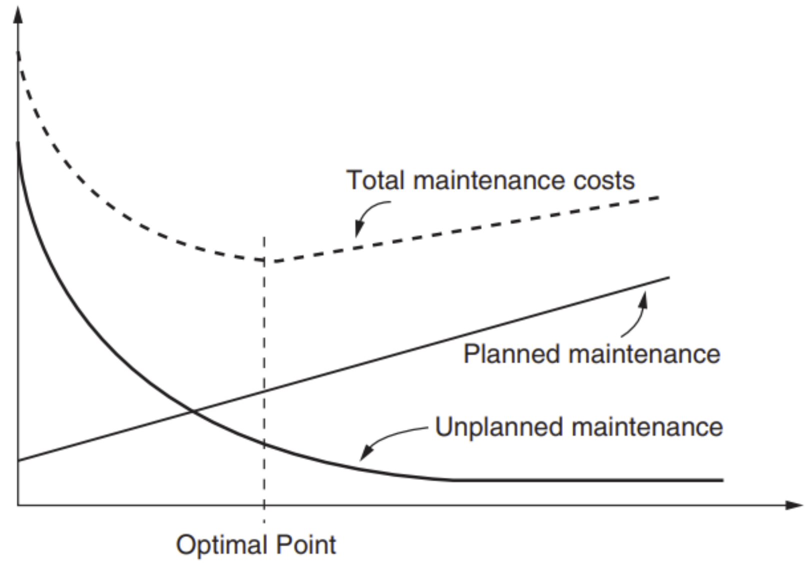

Figure 14. Ratio of PM and CM effects to costs (Mobley et al. 2008, p. 2.43)

Fourth pillar is “Quality maintenance”, which aims to keep the machines or systems in prime condition that are directly affecting the product or process quality. This is achieved through monitoring that differs based on the application. (Díaz-Reza et al, 2019, p. 12-18.)

Fifth pillar is “Education and training”, which means the process of implementing the idea of TPM to every level of the company. The goal is to motivate and make people want to work by the TPM ideology by showing them how it will help in their respective job tasks. (Díaz-Reza et al, 2019, p. 12-18.)

Sixth pillar: “Office TPM”. This pillar is the administrative organization that focuses on minimizing the process and production losses. Office TPM optimizes the strategies that are formed in the previous pillars. (Díaz-Reza et al, 2019, p. 12-18.)

Seventh pillar: “Safety, Hygiene and Environment”. This pillar maintains the policy of zero work related accidents, diseases, and environmental hazards. An example of this would be posters or some other promotional content that would motivate the workers to pay more attention to these attributes in their work. (Díaz-Reza et al, 2019, p. 12-18.)

The eighth pillar: “Developed management”. This organization is responsible for commissioning new equipment and tracking of standards, machines, and maintenance records. (Díaz-Reza et al, 2019, p. 12-18.)

The main measuring method of TPM is the Overall Equipment Efficiency that can be described as follows:

$$OEE = Availability \times Performance\,rate \times Quality\,rate$$

- Availability is the difference between the actual and predicted availability of a machine or system.
- Performance rate describes the difference between the expected and actual performance of a machine or system.
- Quality measures the expected amount of production output and compares it to the actual output that includes products with defects.

These parameters can be acquired by following equations:

$$Availability = \frac{Required\ availability - Downtime}{Required\ availability} \times 100 \tag{5}$$

$$Performance\ rate = \frac{Theoretical\ cycle\ time \times units\ output}{Actual\ cycle\ time} \times 100 \tag{6}$$

$$Quality = \frac{Production\ output - defects}{Production\ output} \tag{7}$$

(Díaz-Reza et al, 2019, p. 14-15.)

The data required for the calculation of OEE is collected by respective personnel that are responsible for the operation of the machine or system. By collecting enough initial data and determining thresholds for each parameter it is possible to prevent breakdowns. (Mobley et al. 2008, p. 2.46.)

Implementation of TPM is not a quick process. According to Mobley et al. (2008, p. 2.53) it takes 3-5 years to implement on factory level. However, Järviö (2017, p. 150) explains that the minimum implementation time is 10 years that is non-officially standardized by the Japan Institute for Plant Maintenance. Nevertheless, the results of TPM can be measured as early as a few months after implementation. This is achieved by deploying pilot projects to targeted departments in the factory (Järviö, 2017, p. 150).

3.5 Selection process of maintenance strategies

Comparing different strategies is crucial as implementing a maintenance strategy can be expensive and even irreversible in some cases (Martin et al., 2020, p. 425). The financial aspect of maintenance is often the most interesting compared to other factors. It is extremely hard to estimate the cost of maintenance even with historical data available from previous process lines (Mobley, 2002, p. 29). “Around one-third of gross maintenance costs is wasted due to improper or unnecessary maintenance actions. Therefore, the selection of a suitable maintenance strategy is a key concern while planning maintenance activities for the system” (Patil et al., 2022, p. 676). However, qualitative factors should not be ignored during the selection process.

3.5.1 Multi-criteria decision model

Multi-criteria decision model is an approach that can be applied in numerous ways. It is used for problems that include multiple objectives with multiple criteria. The objectives can sometimes conflict with each other, and one objective can have multiple results. Variable is determined for an objective whose performance is measured thus making it possible to compare the outcomes of different scenarios. There are multiple methods on how to create an MCDM and they are unique for the application at hand. (de Almeida et al., 2015, p. 1-2.)

Important thing to keep in mind is that MCDM approaches are just one option, there are also other mathematical models, frameworks, and risk-based analysis approaches (Patil et al., 2022, p. 684). MCDM seems to be one of the most used approaches in maintenance related topics.

MCDM can be used to either select a strategy or modify the strategy itself. For example, RCM strategy can be modified with MCDM. In this thesis the focus is on the models that are used to select a certain strategy. According to de Almeida et al. (2015, p. 18) more than 180 papers were published between 1978 and 2013 regarding MCDM and maintenance. The most common criteria that were found between these studies were following:

- Cost
- Reliability
- Availability
- Time
- Weight
- Safety and risk

(de Almeida et al. 2015, p. 18.)

While these criteria are common factors, another study (Patil et al., 2022) that has reviewed the field of MCDM broadly suggests a slightly different view. This view takes into consideration the feasibility and social sides of applying a successful maintenance strategy. As was discussed in Chapter 3.4.3 regarding TPM, the mentality of personnel towards the maintenance strategy is a crucial factor in terms of success. Patil et al. (2022) have also considered the difference of quantitative and qualitative factors. Quantitative factors are the factors that can be measured with certainty into accurate numerical value. These factors are, for example, the maintenance cost or productivity. Qualitative factors cannot be measured as accurately as they are relative to the person that interprets them. In Figure 15 below the abbreviations are as follows: Mean time to repair (MTTR), Mean time between failure (MTBF).

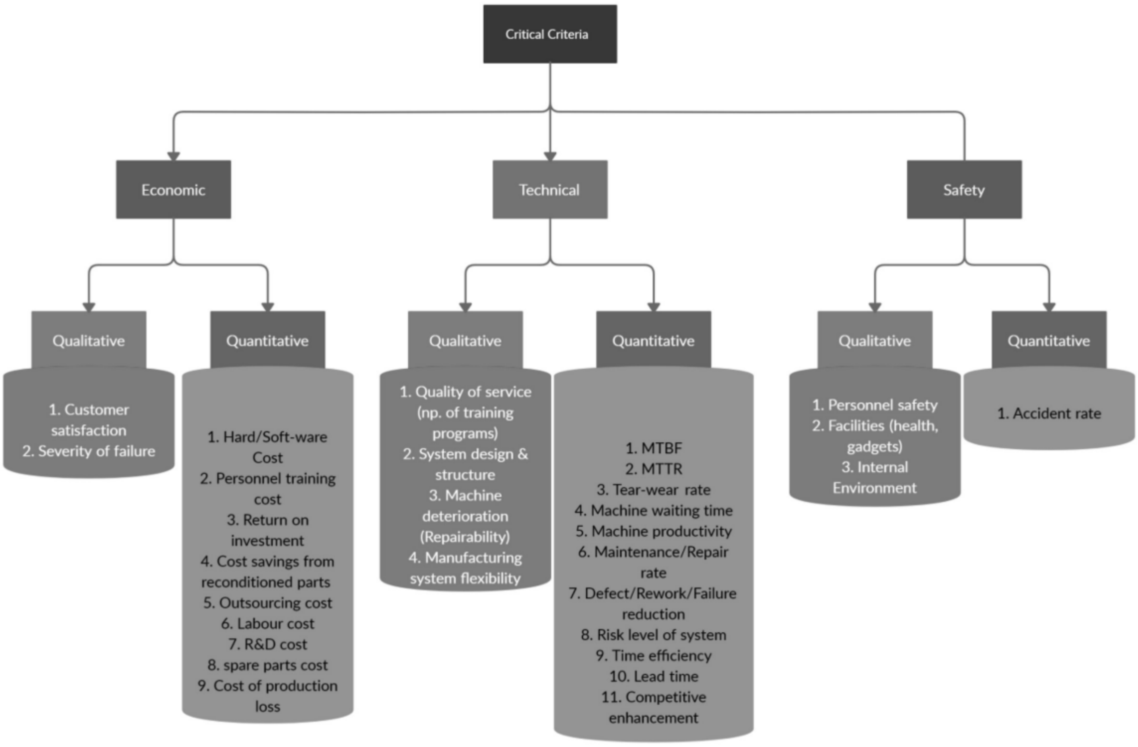

Figure 15. Critical factors in MCDM (Patil et al., 2022, p. 682)

MCDM criterion is distributed roughly the same way in the study by Patil et al. (2022) and Almeida et al. (2015). Both include factors regarding economy, safety and the availability or reliability of units. For some reason Patil et al. (2022) have included the time, weight, and risk in the quantitative factors of technical factors. By this one can conclude that both studies share the same critical factors but are distributed differently. Patil et al. (2022) has the additional environmental, feasibility and social factors which are shown in Figure 16 below.

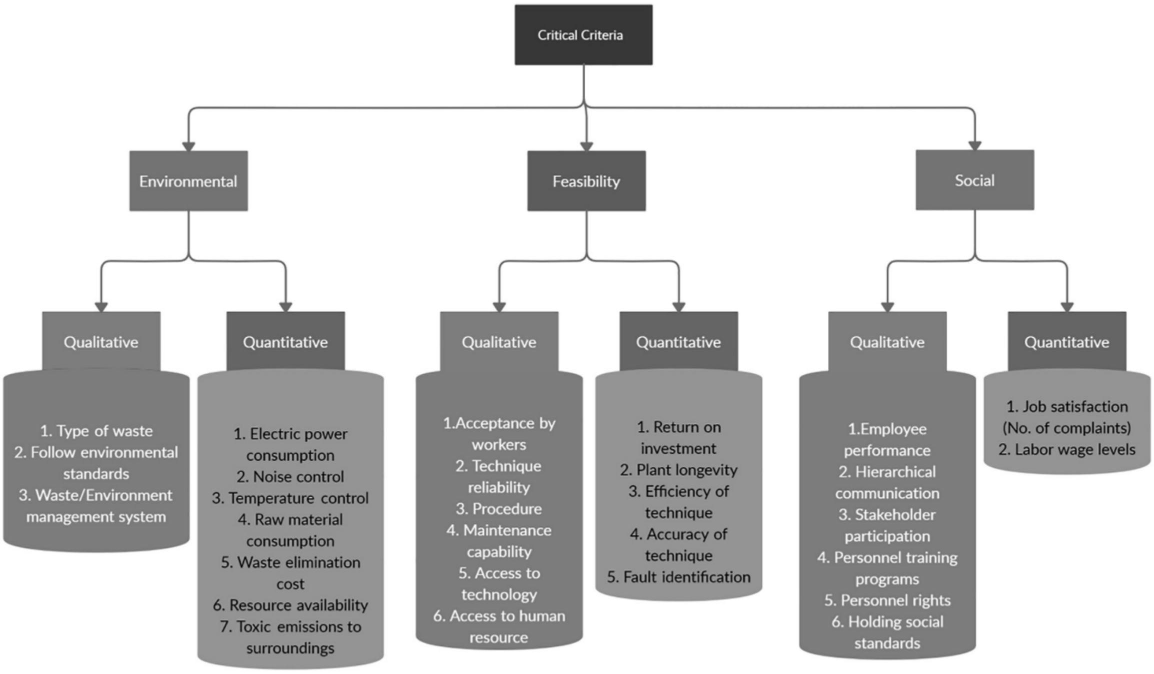

Figure 16. Critial factors of MCDM (Patil et al., 2022, p. 683)

From Figure 16, it is possible to concretize the qualitative and quantitative factors of environmental, feasibility and social views. These factors are often overlooked whilst feasibility is one of the core components of successful strategy. If a strategy is not properly implemented and accepted by the workers, the theoretical savings on costs will not likely materialize.

One commonly used model is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). In this method one solution is divided into positive and negative categories. “The Euclidean distance approach is used to evaluate the relative closeness of the alternatives of ideal solutions” (Patil et al., 2022, p. 684). The idea is to see which solution is relatively closest to the ideal whilst being as far away as possible from the negative solution. For the process line of this thesis the most potential MCDM approaches would be AHP and TOPSIS. These are purely based on personal evaluation between what has been used in different industries of application. The evaluation has been done by studying the research by Patil et al. (2022, p. 687).

One of the most common MCDM-based models for maintenance strategy selection is Analytical hierarchy process (AHP). It utilizes pairwise comparison based on eigenvectors. “Eigenvectors are defined as the special set of vectors associated with a linear system of equations" (Patil et al., 2022, p. 684). With AHP it is possible to simplify a complex model into a hierarchy in which each level can be inspected separately (Martin et al., 2020, p. 426).

To give more insight into how the AHP works, Figure 17 below divides the main factors which are the base of the whole approach. Depending on the model the main factors can vary.

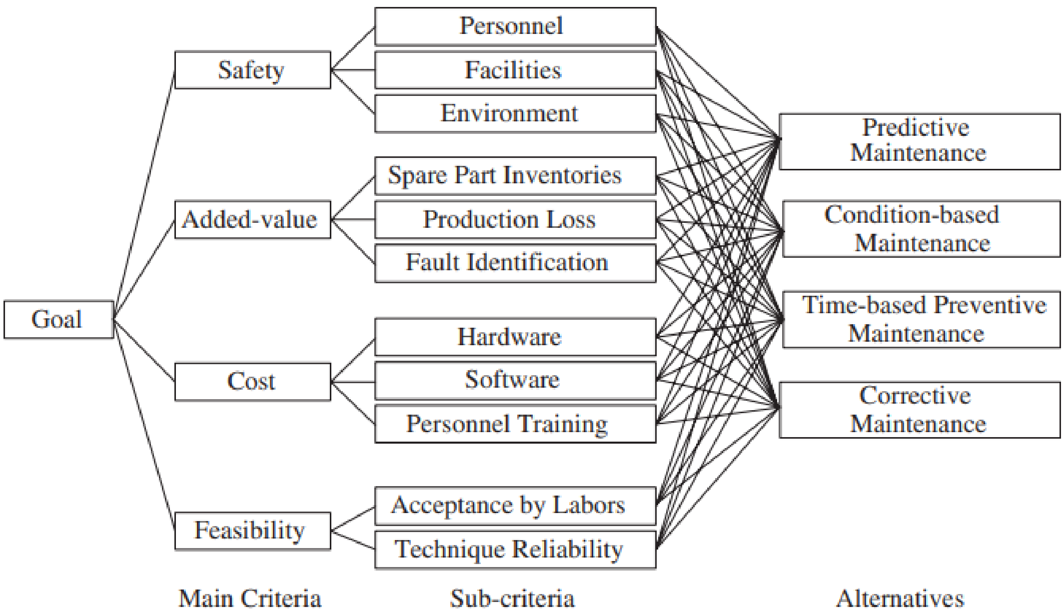

Figure 17. Hierarchy structure of the fuzzy analytic hierarchy process (Wang, Chu & Wu 2007, p. 158)

As can be seen from Figure 17, in this approach the chosen main factors are safety, added value, cost and feasibility. These factors are distributed into separate factors which have a weighting that depends on the creator and the user of the model. In the end one can acquire a numerical value for each strategy, type, or method, depending on what is under comparison.

In literature one study was found (Martin et al. 2020) that was related almost purely to maintenance strategy selection that was utilizing AHP related process – Analytical hierarchy constant sum method (AHCSM).

AHCSM is like AHP, the difference between these two is that AHP can result in inaccurate ratio scaling. There is also the uncertainty in mapping human judgement which can lead to loss of information. This loss then leads to wrong ratings for the factors are calculated. AHCSM tries to minimize these errors by, for example, quantifying the scores. This aids in a way that the comparison matrices result in more accurate values. (Martin et al., 2020, p. 426.)

To start off the AHCSM, one must select the different maintenance strategies that will be compared, such as TPM, RCM and RBM. Then main attributes are decided for the AHCSM analysis. These attributes are dependent on the field of industry and can vary. For example, a steel fabrication company has used the following:

- Productivity
- Quality
- Reliability
- Cost
- Safety and work environment
- Morale
- Inventory
- Flexibility

(Martin et al., 2020, p. 427)

These attributes have multiple sub-attributes for which a normal relative value and a desirability index are calculated. The process of calculating these relative values and indices is rather complex with multiple steps. The initial step is to choose values for all attributes, then compare one attribute to another with pairwise comparison matrix. This iteration is done until all attributes are compared with each other. After this there will be multiple iterations of matrices and equations, which in the end, result in the normal relative values and desirability indices. The indices are then summed up and can be visualized. Example visualization is shown in Figure 18 below. In the Figure abbreviations are as follows: Reactive or breakdown maintenance (RBM), Preventive maintenance (PM) and predictive or condition-based maintenance (PCBM). Note that the abbreviations related to this figure do not apply in the thesis except for PM.

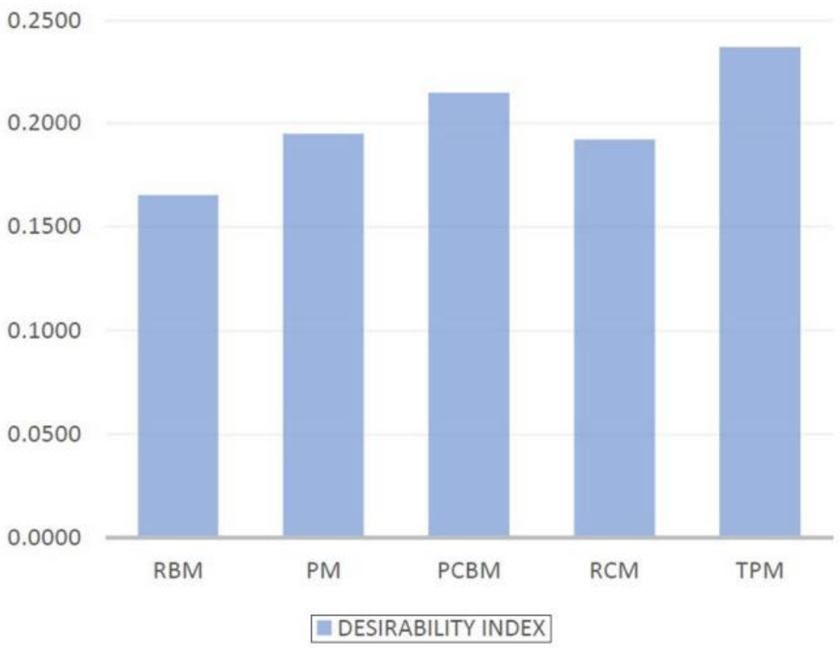

Figure 18. Example desirability indices (Martin et al., 2020, p. 427)

The calculations made in the source study resulted in the following. In this example the TPM strategy was deemed as the best option and PCBM as the second best.

3.5.2 Key points of chapter 3

This chapter presented the definitions of maintenance, the most common methodologies, and the selection process for these methodologies. The key thing to take away from this chapter is to acknowledge the difference between the definitions of maintenance, those being the strategy, type, and method. These definitions and strategy selection factors of the maintenance methodologies will be used actively in this thesis.

4 Trends and visions in process engineering

There will be a trend analysis in which maintenance methodologies' application rates are analyzed in relation to time. This chapter explains the theory behind trends and how they are formed mathematically. The mathematical models will not be used as it is out of the scope of this thesis, instead the trends will be analyzed visually. Some of the more commonly found visions in the field of maintenance are introduced shortly as well.

4.1 Definition of a trend

Temporal trend is a systematic and continuous increase or decrease of a measurable parameter that is compared to another parameter. Usually, X-axis is a time axis and a parameter's relation are analyzed against it. Other variables can be used instead of time as well. There is a possibility that the two variables are not related to each other, which is why trends should be analyzed carefully and with sufficient base data. Trends can be divided into linear and non-linear. (Şen, 2017, 2017, p. 3-5.) The resulting geometries from the linear and non-linear ideal trends can be seen in Figure 19 below.

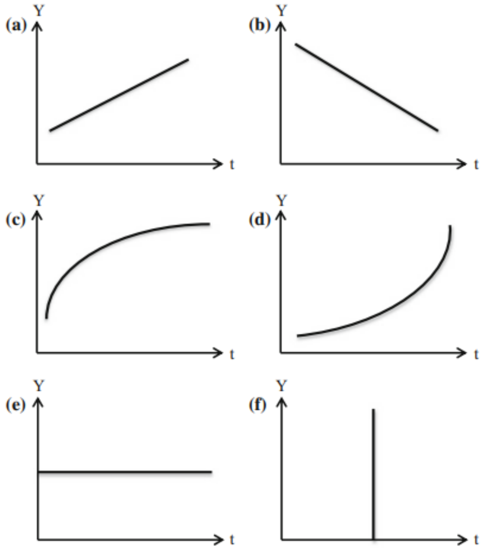

Figure 19. Relationship of a dependent variable Y and independent variable time, t (Şen, 2017, 2017, p. 5)

The graph (a) and (b) represent the direct-linear and inverse-linear relationships. Graphs (c) and (d) represent the direct-nonlinear and inverse-nonlinear relationships, (e) and (f) represent no relation. In this thesis the most probable relations are either (a), (b) or (e) but the non-linear options are still possible. Trendlines can be visualized roughly by eye if the trend is clear, but to get the best possible results one should use mathematical expressions. The trendline can be described as simply as the following equation for an increasing or decreasing straight line:

$$Y = a \pm bt \tag{8}$$

Where a is the initial Y-value, b is the angle of the slope and t is time.

There will be variance in the results, no trendline will ever be as the ideal trendline. The variable Y's values will not increase or decrease with smooth changes which can be seen. This is the variance that will occur in any case, small data pool size can affect massively in the maximum variance value. The variance peaks between the trendlines are called the uncertainty factor. The uncertainty factor can be implemented in the mathematical expression of the trendline to get a complete and more accurate presentation of the trendline. When added, the previous equation for the linear trendline becomes as follows: (Şen, 2017, 2017, p. 6-10.)

$$Y_i = a + bt_i + u_i \tag{9}$$

Where the time series has value Y for each specific point in time. The index is i = 1, 2, …, n, where n is the number of samples and u is the uncertainty factor. Example of this method is shown in Figure 20 below. (Şen, 2017, 2017, p. 6-10.)

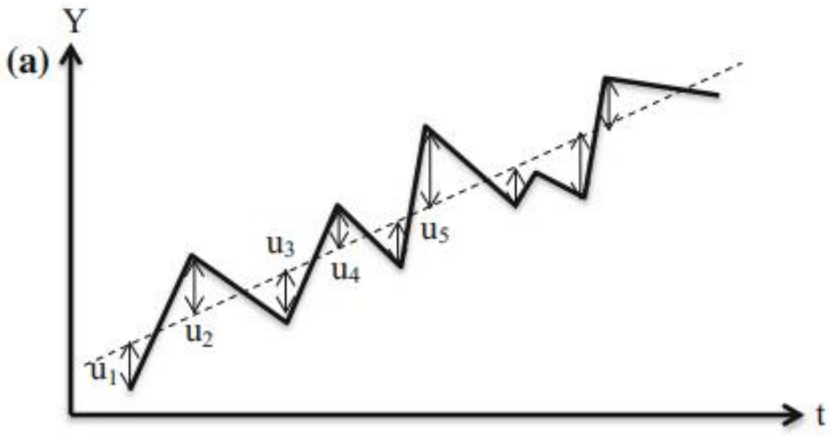

Figure 20. Uncertainty of results in trend lines (Şen, 2017, 2017, p. 10)

For each Y-value there is corresponding uncertainty factor, the total sum of uncertainty is zero. However, this simplified uncertainty is not sufficient as the deviations might be far away from the trendline and still result in zero value. In deterministic case the uncertainty each amount is equal to zero, which is not possible in any natural or artificial time series. Complete deterministic uncertainty is calculated with absolute values, but one should use the minimum method. In which case the summation of errors is as small as possible. This is achieved by squaring each uncertainty value and then calculating the error in the trendline. The equation is as follows:

$$\sum_{i=1}^{n} u_i^2 = minimum \tag{10}$$

(Şen, 2017, p. 11.)

The forementioned mathematical equations would result in the most accurate trend lines. However, in this thesis the accuracy of visual analysis is enough to make conclusions.

4.2 Visions in process engineering maintenance

The purpose of this sub-chapter is to raise up what kinds of visions in maintenance development are mostly discussed in different media inside the commercial and industrial communities. Not everything will be included but the ones that appear in the searches the most.

4.2.1 Augmented reality and virtual reality in maintenance

Augmented reality (AR) utilizes the environment of the end user which is enhanced with digital information. For example, maintenance technician could use a phone camera to define the environment that includes a unit that must. Digital information is added in the environment which is supposed to be helpful for the technician. In virtual reality (VR) everything is artificially created. For example, immersive training and remote maintenance are introduced as the main applications for this technology. (Infraspeak team, 2022; Prometheusgroup, 2022.)

4.2.2 Internet of things in maintenance

Internet of Things (IoT) is visioned to be a way to automate and centralize data collection. Many units that have sensors or other measurable parameters that are utilized for maintenance purposes can be fused with IoT services. The collected data can be used for updating predictive maintenance models or creating new ones. Thus, the timing of specific maintenance activities can be scheduled in a more accurate way. (Global electronic services inc., 2018; StartUs-insights, 2022; Artesis, 2022.)

4.2.3 Decentralized maintenance

Decentralized maintenance is more of a business model than it is a maintenance methodology. It focuses on minimizing the maintenance costs by utilizing tools such as AR and real-time updated databases that are provided, for example, with IoT. This allows for smaller teams of people to do the same work as there is no need for a local maintenance team in every factory or process location. (Infraspeak team, 2022; Global electronic services inc., 2018.)

4.2.4 Digital twin in maintenance

Digital twin is a virtual model of the real-world unit. Digital twins are becoming more complex and whole units can be modeled with realistic simulations instead of single components. They allow for simulations of the real unit which allows for data collection of the maintenance related parameters. These again can be used for the predictive maintenance models and improvement design of the unit. Digital twins can also be used for risk assessment in certain scenarios. (StartUs-insights, 2022; MaintenanceCare, 2022.)

4.2.5 Artificial Intelligence in maintenance

Artificial Intelligence (AI) is machine learning that can be done with data that is collected from the units in manufacturing. Real-time data, service records and equipment conditions can be the inputs for machine learning. By giving more and more data as time goes by the results are continuously evaluated to optimize the needed maintenance actions. (StartUs-insights, 2022; Artesis, 2022.)

4.2.6 Additive manufacturing in maintenance

Additive manufacturing (AM) is considered as an option to minimize the need for spare parts. This is more of a business model than maintenance methodology. It is not related to the maintenance actions that could be taken but focuses more on inventory management and other sections of maintenance. This could allow for longer life cycles for certain units as they would not be dependent on the OEM if they decided to discontinue certain spare parts or units from their production. (Global electronic services inc., 2018; Prometheusgroup, 2022.)

4.3 Key points of chapter 4

Now that the definition of a trend is set, it is possible to identify the trends in the upcoming results. The visions are taken into consideration as they might explain some of the reasons behind the trends of the methodologies in today’s industry applications.

5 Trend analyzing tool

In this chapter the tools for analyzing maintenance trends are introduced. Any mention of term “methodology” in the results refers to either a maintenance strategy, type, or method. The trendlines in graphs are applied by visual analyzing and the mathematical expressions will not be used as those are not in the scope of this thesis.

5.1 The introduction of the trend analyzing tool

The tool consists of two different table types that present information of the used maintenance strategies, types and methods for each source listed. As was shown earlier in this thesis, the order from top to bottom goes strategy, type, and method. This tool distributes the maintenance strategies and types into one table and the methods into a separate table. The upper level-table that consists of the strategies and types is called “Core”-table. The lower-level table that consists of the methods is called “Support”-table.

Baseline strategies are chosen as listing all of them in the tables would be impossible. Other strategies are also included if encountered during the research. The baseline types and methods are almost the same as introduced earlier in this thesis. The exceptions and reasoning for these decisions are explained below. There are more maintenance methods than what are listed earlier in this thesis which are also included in the table if encountered.

There are two main studies which are used as main sources for data tables: (Patil et al., 2022, p. 688-690) and (Shafiee, 2015, p. 390-392). The sources from the forementioned studies are thoroughly reviewed.

Sources are from the years 2000 to 2020 and are divided into splits of five years. Therefore, there will be splits from 2000 – 2005, 2006 – 2010, 2011 – 2015 and 2016 – 2020. There will be two tables of data per split to be able to compare the data from different points of view. These are the Core and Support tables. Four Core tables that contain upper-level data regarding maintenance strategy, types, and methods. The other four Support tables contain more specific maintenance data regarding the maintenance methods. Each table contains a list of sources which present the used or considered maintenance strategy, type, and methods in corresponding studies. In the last step the data of all Core and Support tables are put together and visualized in graphs to analyze the long-term trends in maintenance of process industry.

5.1.1 The Core table structure:

The first three columns are included under “General information” which contains the source of information, field of application (FOA) and the strategy selection factors (SSF). The SSF are the forementioned factors which are: economic, technical, safety, environmental, feasibility and social. The next four columns are included under “strategy” column. In this thesis RBM, RCM and TPM were chosen as the main strategies for investigation. The next three columns include the maintenance type, which is PM, CM, or Improvement (IM). The last three columns contain the core maintenance methods. Cell with a value means the corresponding methodology is applied or studied as an option in the corresponding source (row). Empty cell means that the methodology is not considered as an option or applied in the source. The core table template is shown below in Table 3.

Table 3. The core data table

General information			Strategy				Type			Core Method		
Source	FOA	SSF	RBM	RCM	TPM	Other	PM	CM	IM	TBM	CBM	Other
Source 1												
Source 2												
Source n + 1												

5.1.2 The Support table structure:

The Support data table contains the specific maintenance methods. The source data corresponds to the upper-level table. Therefore, both tables have the same sources of data, the difference is the data represented. Where the Core table presents methods in TBM, CBM, or other methods, the support table distributes those core methods into more specific methods.

The time-based methods include the time-based interval (TBI), age-based (AB), and opportunity maintenance (OM). In this thesis the constant interval maintenance was introduced, however as the intervals are not constant in all scenarios, the method is changed into TBI in this thesis to avoid possible misinformation. The term TBI is not standardized, only to be used in this thesis.

Condition-based methods are distributed into Non-predictive (NPd) and Predictive (Pd). The methods of Improvement-column are classified as design-out maintenance (DOM), autonomous maintenance (Auto) and other types of improving (Other IM). The fourth method-column contains the rest of the methods which are not commonly used or discussed in literature. An important note here is that as the sources do not classify the terms the same way as this thesis, some interpretations must be made. For example, if the source mentions TPM as its maintenance strategy but no methods for Improvement-section, there will be a mark for Autonomous method in the support table. Meaning that Autonomous methodologies are used in that source. This is because Autonomous maintenance is a crucial part of TPM, and it is part of TPM even when not explicitly mentioned.

The standard SFS-EN 13306:2010 points out that the OM can be either corrective or preventive maintenance (p. 39). This is irrelevant regarding this thesis unless the relation between OM and PM or OM and CM are studied. The support table template is shown in Table 4 below.

Table 4. Support data table of specific methods used or discussed in source papers.

Core Method	TBM			CBM		IM			The rest
Specific method	TBI	AB	OM	NPd	Pd	DOM	Auto	Other	Name of method:
Source 1									
Source 2									
Source n +1									

From the table one can see the core methods, which are then distributed into specific methods. Sources are the same as in Core tables. Now one can see that IM was mentioned in Core table as a type and in Support table as a core method. This is because there is no clear distinction of core method and type in the case of IM. Therefore, they are not separate definitions but act as one IM type and core method.

5.1.3 Visions' table structure

As the visions cannot be explicitly defined under any of the categories defined in this thesis they are evaluated independently. The template table for visions can be seen below as Table 5.

Table 5. Vision table structure

General information			Methodologies					
Year	Author	Source	AR / VR	IoT	Decentralized	Digital twin	Artificial intelligence	AM

The visions will have the same point system as the core and support tables which will be explained in the next chapter.

5.1.4 The point system

As the definition of maintenance terms is different to the sources, interpretations are done on different levels. This is to ensure that every methodology will be taken into consideration. It was noted early on that the source list from Patil et al. (2022) and Shafiee (2015) has interpreted the sources differently and not accurately enough. From now on if there is a mention of a "source table", it refers to the forementioned studies that have listed the methodologies in their respective data tables. "Original sources" refer to the sources listed in these forementioned studies’ source tables. In some cases, the source table includes a methodology that is not mentioned as part of a literature review in original research. These errors and missed methodologies will be found out with the point system. The point system is shown in Table 6 below.

Table 6. Point system for analysis.

Point(s)	Description
1	The source table, original source and the interpretation done from the point of view of this thesis all agree that the methodology is applied in the original source
0,75	The methodology is applied in original source but is not mentioned in the source table
0,5	The methodology is only mentioned, not applied. It is listed in the source table
0,25	The methodology is not mentioned in the original source but is still listed in the source table

An important note here is that most of the source data research is maintenance methodology selection related studies. This means that many sources consider multiple options, therefore multiple methodologies can get full points in one category. This is because there can be multiple methodologies of same category under comparison in the source study. For example, one source study can include a selection process between TPM, RCM, CBM and PM. The same study can also mention CM and OM but not actually apply them in the comparison process. In this case TPM, RCM, CBM and PM would get the full point (1) and CM and OM would get 0,5 points.

Examples of both Core and Support tables are shown to make it easier to understand how the results are listed. Down below is the first Core table that consists of the studies between the years 2000 and 2005. Red highlight on top of the “year”-cell means that the source was not available, whereas green means the source was available. In the case of studies that were not available, the score will be 1 as the methodology cannot be confirmed against the source data tables. The Core table is presented in Figure 21 below.

Year	General information			Strategy				Type			Method		
	Source	FOA	SSF	RBM	RCM	TPM	Other	PM	CM	IM	TBM	CBM	Other
2000	Bevilacqua and Braglia (2000)	Oil refine	Economic,	0,75	0,5			1	1		1	1	
2003	Al-Najjar and Alsyouf (2003)	Power ge	Economic,		1	1	1	1	1	0,75	1	1	
2003	Mechefske and Wang (2003	Power ge	Qualitativ					0,75	0,75		0,75	1	
2004	Bertolini et al. (2004)	Constructi	------------		0,5	0,5		1	1	0,75	1	1	
2004	Labib (2004)	Automati	------------		0,75	0,75		1	1	1	1	1	1
2004	Alsyouf (2004)	Pulp and p	Economic,	0,5	0,5	0,5	0,5	1	1	0,75	1	1	
2005	Carnero (2005)	Oil, gas	Economic,									1	
2005	Sharma et al. (2005)	Process	Economic,		1	1		1	1	0,75	1	1	
2005	Verma et al. (2005a)							1	1		1	1	
2005	Verma et al. (2005b)							1	1		1	1	

Figure 21. Core table, years 2000 – 2005

As can be seen from Figure 21, the last two sources cannot be confirmed therefore the scores will be taken directly from the source data tables. Every time there is a mention or application of TPM-strategy it correlates into IM type being marked with the same score as the TPM-strategy itself. Other strategies and methods are shortly introduced in their separate chapter. Below is the corresponding Support table for the years 2000 to 2005. Support table is presented in Figure 22 below.

Year	Method	TBM			CBM		IM			The rest
	Specific method	TBI	AB	OM	NPd	Pd	DOM	Auto	Other IM	
2000	Bevilacqua and Braglia (2000)	1		1	1	1				
2003	Al-Najjar and Alsyouf (2003)	1	1		1			0,75		1
2003	Mechefske and Wang (2003)	0,75			1					
2004	Bertolini et al. (2004)	1		1	1	1	0,75			
2004	Labib (2004)	1			1		1	0,75		1
2004	Alsyouf (2004)	1	1		1	0,75		0,75	0,5	0,75
2005	Carnero (2005)					1				
2005	Sharma et al. (2005)	1			1			0,75		
2005	Verma et al. (2005a)	1				1				
2005	Verma et al. (2005b)	1				1				

Figure 22. Support table, years 2000 – 2005

As was explained above, the support table has the same sources as the Core table, the difference being what data is collected from the sources. The support table includes the core methods TBM, CBM and IM which are distributed in their respective sub-methods as was explained earlier in this chapter. After completing the research and having all four core and support tables filled, three different equations are applied to analyze the results.

The points are converted into relative percentages to minimize the error that occurs when the data pools are of different sizes. For example, the years 2000 – 2005 have 10 sources whereas 2011 – 2015 has 36 sources. Without converting the points would be out of proportion when compared against each other.

$$RP_{Period\ start\ year-period\ end\ year} = \frac{Met_{Period\ start\ year-period\ end\ year}}{Number\ of\ sources} \tag{11}$$

Where *RP* is the relative percentage of certain methodology in a specific period. *Met* is the sum of points for certain methodology in a specific period. This equation is applied for each methodology. In addition, the same equation is applied for SSF even though there is no numerical data listed in the tables. FOA is excluded from the calculations.

The second analysis method compares the maintenance methodologies against each other in their respective groups. It results in the application rate of a methodology during the whole research period. This is acquired with the following equation:

$$CRP_M = \frac{\sum Met_{Period\ start\ year-period\ end\ year}}{S} \tag{12}$$

Where CRP_M is the combined relative percentage of all periods of a certain methodology. *S* is the number of periods, in this thesis it’s four (4) in all cases.

The ratio between maintenance strategy, type and method will be inspected as well. This is accomplished with the following equation:

$$CRP_{STM} = \frac{\sum CRP_M}{X} \tag{13}$$

Where CRP_{STM} is the resulting combined relative percentage per period for either strategy, type, or method. *X* is the number of methodologies in one of the three categories: strategy, type, and method, depending on which one is being calculated. This equation is implemented for all strategies, types, and methods in every 5-year period.

The results are collected from a total of 96 sources which means that there are 24 sources on average per period. However, the first period (2000 – 2005) includes only ten sources, which is by far the lowest number and should be considered when analyzing the trends. Even a couple sources can have an unwanted impact on the results even though all the results are converted into relative percentages. All the core tables, support tables and their results can be found in Appendices 3, 4, 5, and 6 in corresponding order.

6 Results of trends and visions in process engineering maintenance

This chapter presents the results of the core and support table analyses. The numerical results can be found in the appendices.

6.1 Recognized trends of field of applications and strategy selection factors

This chapter introduces the most common FOA that were found during the research of this thesis. The SSF distribution between sources is also presented. The FOA was not the main topic under research in this thesis which is why only a short list is made to give some insight on what the applications in the source data were. Not all FOA are included in this table, the accurate results can be found in Appendix 3. The table introducing FOA: s can be seen below in Table 7 on the next page.

Table 7. FOA in source data

2000 – 2005	• Power generation • Automotive • Oil industry
2006 - 2010	• Process • Oil industry • Chemical • Textile • Power generation
2011 – 2015	• Mining • Automotive and transportation • Oil industry
2016 – 2020	• Process • Transportation • Power generation

The distribution in the FOA is on a wide enough spectrum which eliminates the polarization of results in the analyses. If the FOA were chosen from too little number of FOAs the resulting trends probably would not represent the field of maintenance as a whole. Power generation, transportation and process industry were found to be the most common industries in the source data.

To keep the analysis simple and uniform with the literature review, the SSF were distributed in the six main factors that were introduced. These factors are economic, technical, feasibility, safety, environmental and social. Some interpretations had to be made but for the most part the selection criteria were addressed in the source studies. The SSF distribution over the years can be seen below in Figure 23. The numerical data that the graph is formed from can be found in Appendix 7.

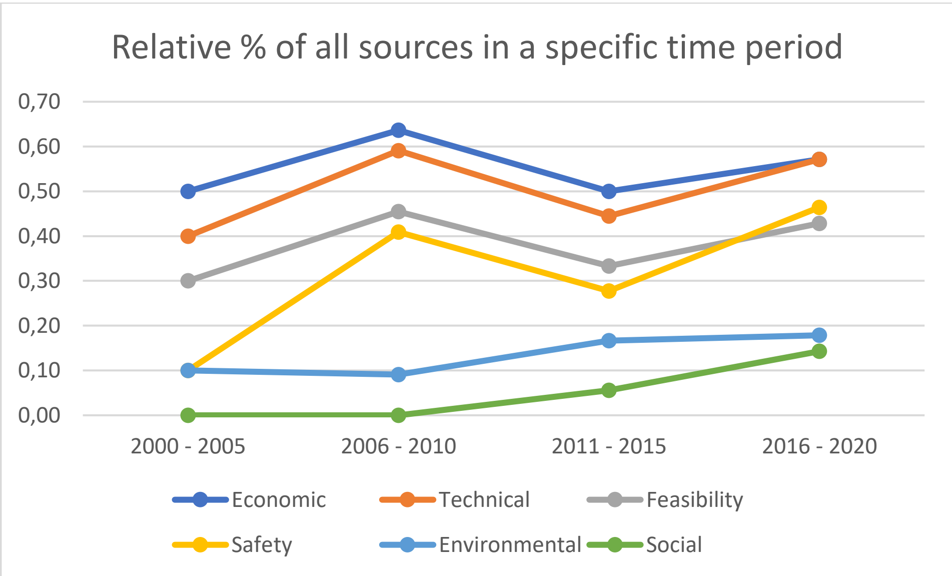

Figure 23. SSF results, calculated with Equation (11)

From the results it’s evident that social and environmental factors are not as common as the others, though both seem to have an increasing trend. Environmental factor going from 10% to almost 20% of application rate and social from 0% to 14%. As the shape of economic, technical, feasibility and safety seem to follow the same pattern, it can be argued that the pattern is directly in correlation with the number of sources. Specifically, those sources that consider the criteria in a clear manner, there were studies where the SSF were not as clear as one would hope. In total all the factors are on a slowly rising trend, safety making the biggest increase from 10% to around 45%. It seems that if a study takes the criteria into consideration, it will probably at least apply to the economic, technical, feasibility and safety factors. For the most part these four factors follow the same pattern in all periods.

6.2 Recognized trends between strategy, type, and methods

The point in this chapter is to recognize if the ratios of strategy, type and method differ throughout the years. All three methodologies' results are calculated separately. For example, the relative percentage of strategies, types and methods are summed individually, resulting in three values per period. The resulting values are the average percentage per period. The results for each period are shown in Figure 24 below.

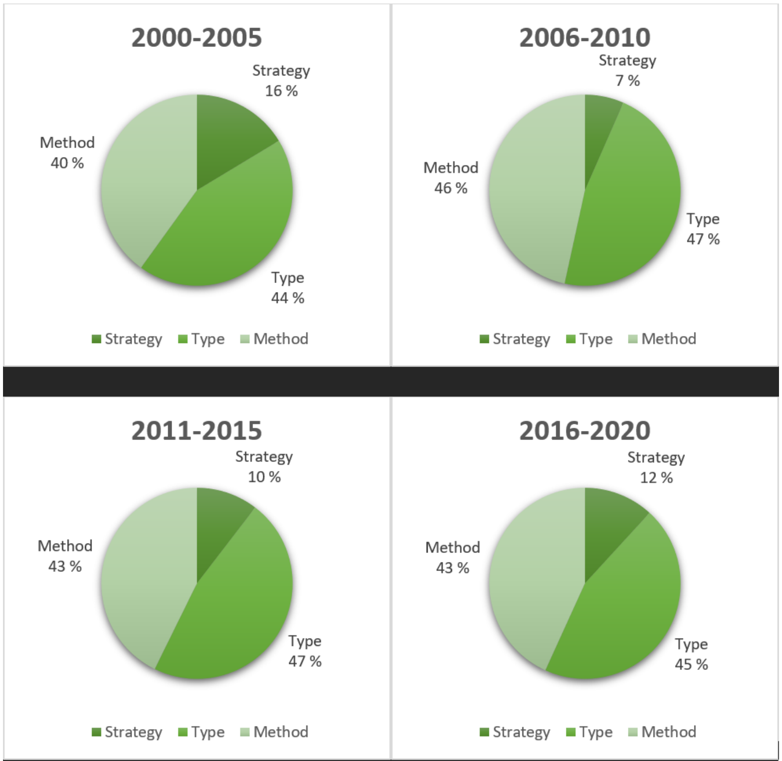

Figure 24. Results of SSF, calculated with Equation (13)

The ratios seem to be almost constant, strategy having the largest variance of 12%. However, as 2000 – 2005 had the smallest sample size it must be considered as it has the highest points for strategy of all the periods. The most important note here is that strategies seem to not be in high popularity, only around 10-15% compared to the average of 45% of types and methods. It might be that the AHP models or similar mathematical models do not work as well for choosing strategies over the maintenance methods. And as the source material included a lot of AHP related studies, it might influence the results. Another thing is that strategies should be used as the top-level tool for choosing the maintenance methods. However, many source studies define for example RCM and TBI at the same level as comparable options. The thing is, RCM should be a tool for choosing the methods. For example, with RCM analysis one would determine TBI for theoretical Unit 1 and NPd for Unit 2. Maybe most authors do realize there is a difference and that is why the number of strategies in the source studies are low. Though there were zero studies found which were comparing purely RCM, TPM and RBM or other strategies with each other.

6.3 Recognized trends of strategies

This chapter presents the results of strategies in maintenance first independently. Then the strategies are collectively compared with each other during the different periods. The strategies were RBM, RCM, TPM and others. The results are from the Core tables.

6.3.1 Recognized trends of risk-based maintenance

RBM is not as common a strategy as was presumed. Basically, all research that applied RBM was in the field of manufacturing that included chemicals in some way. This makes sense as in those applications potential hazards can have disastrous outcomes. In one steel manufacturing related research RBM was considered as an option and one wind turbine related research applied the RBM. The wind turbine related research could not be confirmed due to its unavailability though. The results show the relative percentage of RBM of all the sources in their respective time periods. Figure 25 below shows the accurate percentage distribution.

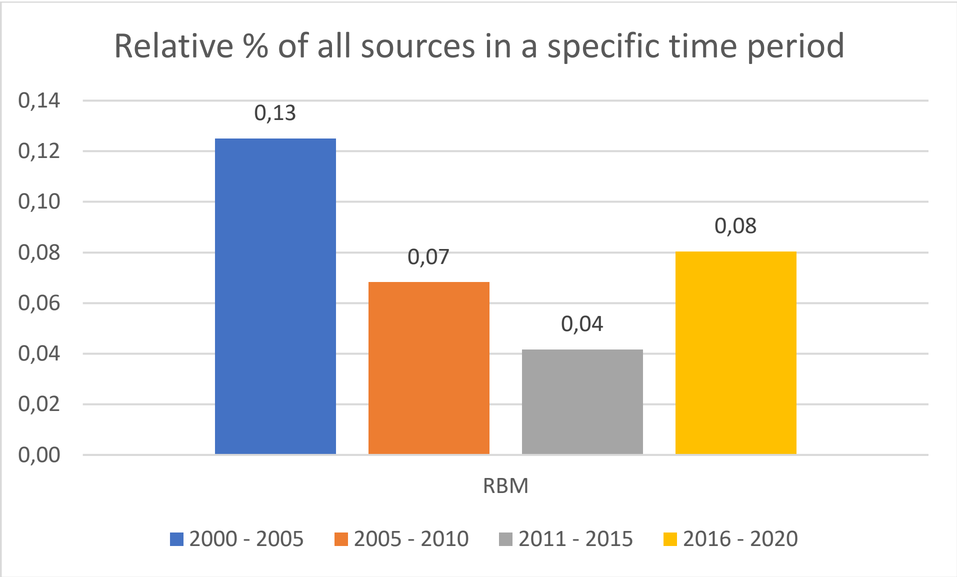

Figure 25. RBM result, calculated with Equation (11)

Based on this data RBM has no clear relation to time. At first glance its popularity would seem to slowly decrease as the years go by. However, as the strategy is highly related to the chemical industry this trend should be considered carefully. If the data source pool does not include chemical industry related sources the amount of RBM related sources drops drastically.

6.3.2 Recognized trends of reliability-centered maintenance

The trend of RCM is hard to estimate in this case. There is a linear increasing trend with the exception that its popularity starts and ends with nearly identical results. There is no clear FOA that would dominate the RCM related sources. This can be seen in Figure 26 below.

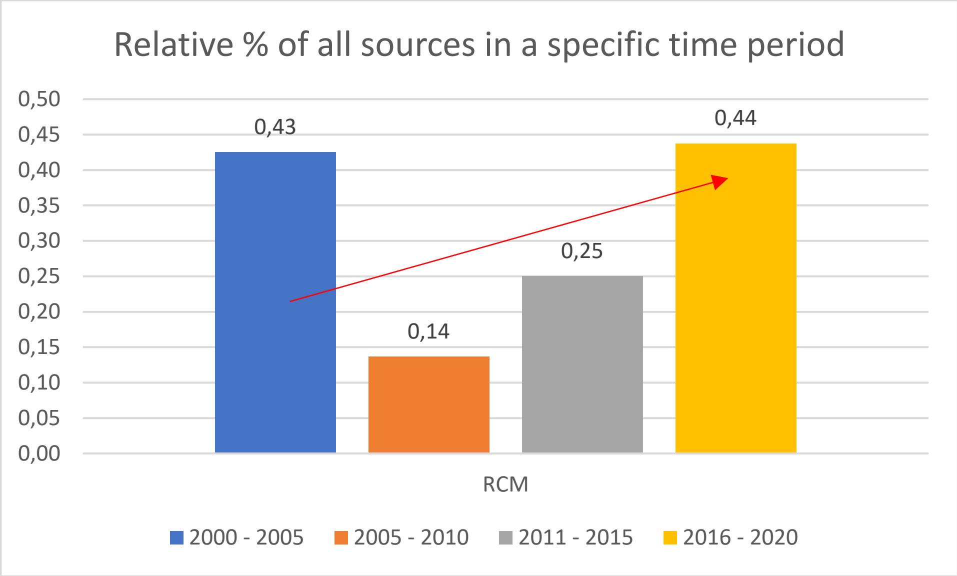

Figure 26. RCM results, calculated with Equation (11)

The popularity of RCM starts and ends at around 43-44 percent. The time 2000 – 2005 has only ten sources which means only a few sources can result in the same percentage as higher number of sources in 2016 – 2020 period. In 2000 – 2005 RCM was applied in three research out of ten, in 2016 – 2020 it was applied in 10 out of 28 research. The rest of the percentage forms from the lower points in the point system. It could be said that RCM has had an increasing linear trend during the last twenty-year period. Its field of applications is also on a relatively wide spectrum as there is research that is related to, for example: process, power generation, textile, automotive and oil industry. The fact that its popularity is closing in on 50% of all the sources in the 2016 – 2020 period is rather surprising. Considering that its popularity was only around 14 percent 5-10 years prior. This could be because it’s rather flexible as a strategy in different scenarios.

6.3.3 Recognized trends of total productive maintenance

TPM has had a decreasing trend during the years 2000 - 2020. It starts at almost 40% popularity in 2000 – 2005 and drops down almost by half by the 2016 – 2020 period. This can be seen in Figure 27 below.

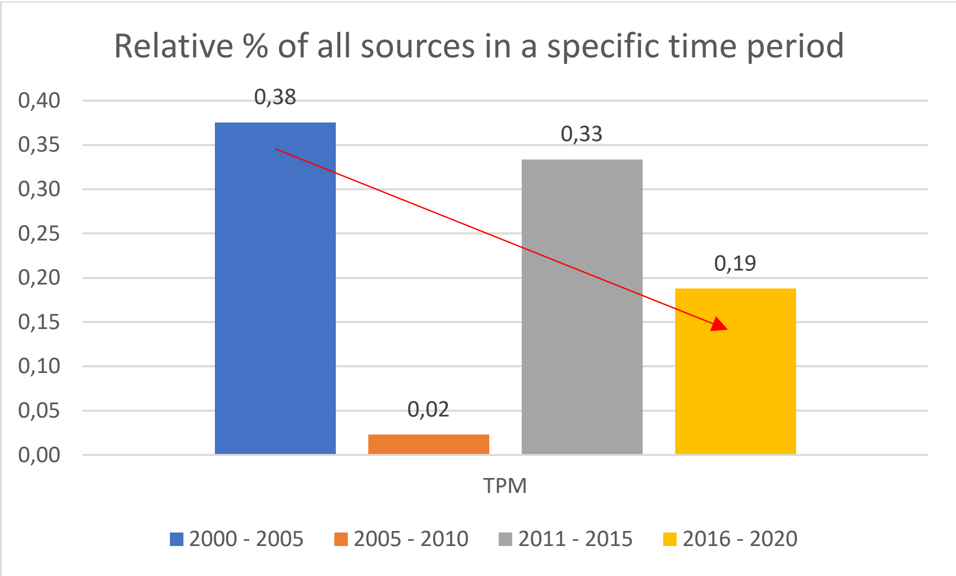

Figure 27. TPM results, calculated with Equation (11)

The downfall of TPM could stem from its outdated and clunky form in today's industry. Outsourcing of maintenance is supposedly to be on the rise and machines have become more complex. TPM might also be too heavy to implement for most companies in an efficient way due to the complexity of company structures. There is also a clear question to be asked based on these results, why in 2005 – 2010 TPM is basically not implemented at all. There were 22 sources in this period which begs the question is it just bad luck with the selection of sources or something else. It was not applied in single research during this time, only mentioned once in an oil related field of study. In 2005 – 2010 the strategy was applied in power generation, process, and automotive industries. During the time of 2011 – 2015 most of the TPM applications are related to mining and automotive. In the last period, the distribution of field of applications is wider, but the trend is still declining.

6.3.4 Recognized trends of other strategies'

Total Quality Maintenance (TQMain) is a not well-known maintenance methodology. It's not necessarily a strategy but in this case, it's defined as one. It focuses on data collection and resembles CBM, but it seems to be a broader concept of CBM. It utilizes separate relevant databases that uses Overall process Effectiveness (OPE) as a measurement tool. It seems like a combination of TPM and CBM as there is condition monitoring and a measurement system that resembles the OEE that is used in TPM.

Prognostic Health Management (PHM) came up twice, but it does have the same author which means it is not a known methodology in the field. It originates from Autonomic Logistics related study that is referred by the author of these two sources that utilize PHM. In short it seems to try to be CBM but with a more complex name. The definition resembles CBM as it's mainly based on continuing condition monitoring. The difference might be that PHM includes some automated maintenance actions depending on the application.

The final odd strategy that came up was called Technical Integrity Management (TIM). It's based on asset management and its definitions seem to change depending on the application. Some points are based on life cycle of assets while others focus more on the maintenance processes that are needed. The results of the odd strategies are shown in Figure 28 below.

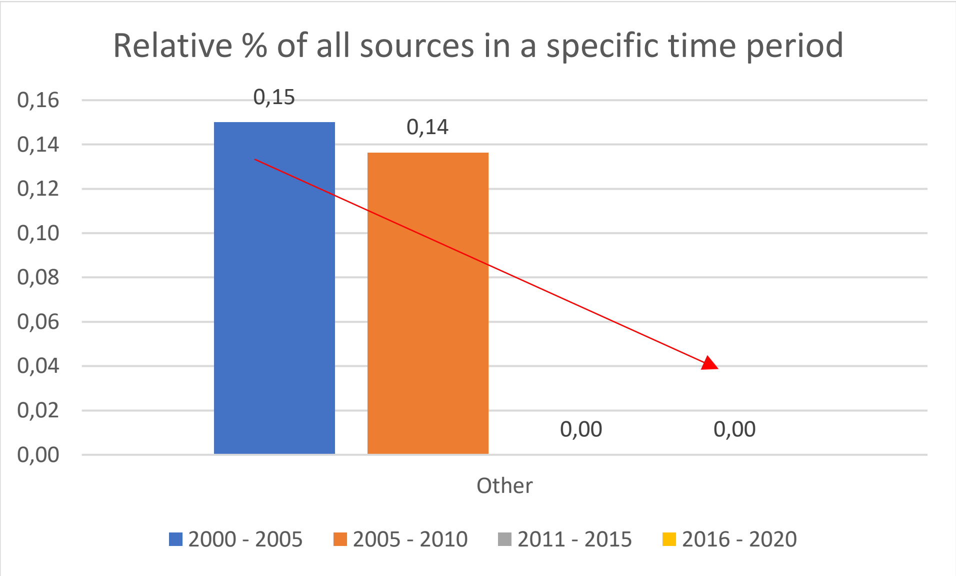

Figure 28. Results of other strategies, calculated with Equation (11)

The remaining strategies are not well-known and not even one was encountered between the years 2011 and 2020. However, the definition of strategy is so broad it can be hard to determine correctly during a study like this. On the other hand, strategies are so broad concepts they need to be explained in detail which usually would not go unnoticed. The innovation of new strategies is not trending for some reason. There can be many factors as to why this would be the case. Strategies are usually extremely heavy to implement on a company scale nowadays. The structure of companies and the continuously rising complexity of machines probably do not support the idea of complex strategy on top of these factors.

6.3.5 Collective results of strategies

Finally, all the data of the strategies are collected in this chapter. This data is represented in Figure 29 below.

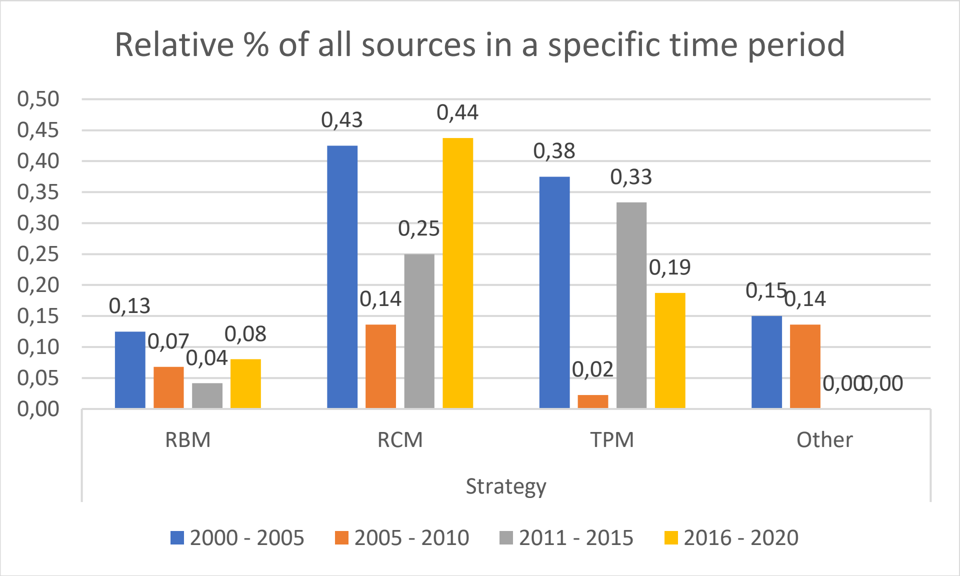

Figure 29. Collective strategy results, calculated with Equation (11)

It seems that only RCM has a clear increasing trend whereas the rest are declining. However, RBM was highly dependent on the application which means that source data selection plays a critical role in how popular it might be. RCM is probably the most flexible of all the strategies mentioned and it gives a good enough overall picture of the process. It's relatively easy to implement and it gives more information than RBM. RCM utilizes FMEA as part of the process whereas RBM focuses purely on the risks. TPM is extremely heavy to implement and in todays' industrial setting it might be too clunky in most cases nowadays. The machines are more complex than before and even though operators play an important role in keeping the equipment in good condition, more and more outsourcing is done in the field of maintenance. The mindset that everyone needs to keep their place clean and respect the company property is vital. However, many machines themselves that require actual maintenance actions require well-trained personnel. In today's company setting it seems to be a norm that every company pushes their beliefs and values from day one to every worker they employ. This is how TPM works, but it is not necessarily maintenance related. Therefore, one could argue that TPM does happen even more than before, but it is not defined as TPM anymore as it is more of a common sense that is pushed onto people.

The second way of presenting the collective results is the combined relative percentage of application between the strategies throughout the years 2000 – 2020. This is shown in Figure 30 below.

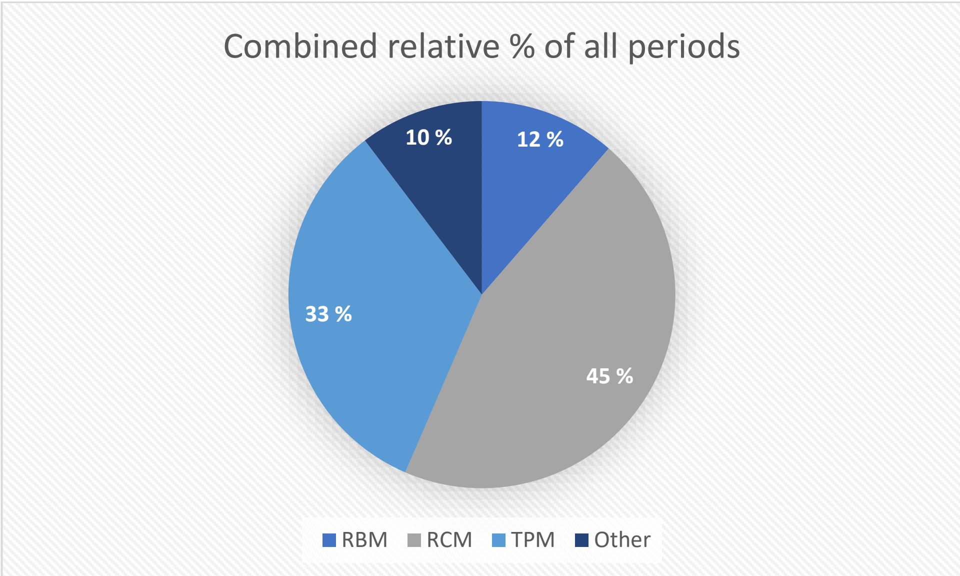

Figure 30. Relative combined popularity of each strategy between the years 2000 – 2020. Calculated with Equation (12)

When all the relative results are combined from the four periods, RCM is used almost half of the time when there is a maintenance strategy applied. TPM has a surprisingly high percentage nevertheless its decreasing trend. This is because the results are calculated with relative percentages throughout the whole 20-year period. Therefore, these collective results' pie-graphs should not be used to analyze the trends. They should be used only as support to check how reliable the actual trends are when the application percentage is known.

6.4 Recognized trends of maintenance types

This chapter presents the popularities between maintenance types separately, then in a collective manner as was done with strategies as well. The types were PM, CM and IM. The results are from the Core tables.

6.4.1 Recognized trends of preventive maintenance

It is no surprise that PM is applied nearly everywhere. It includes the most common maintenance methods such as TBI and CBM. TBI is simple to implement, that does not mean it is efficient though. The percentages can be seen in Figure 31 below.

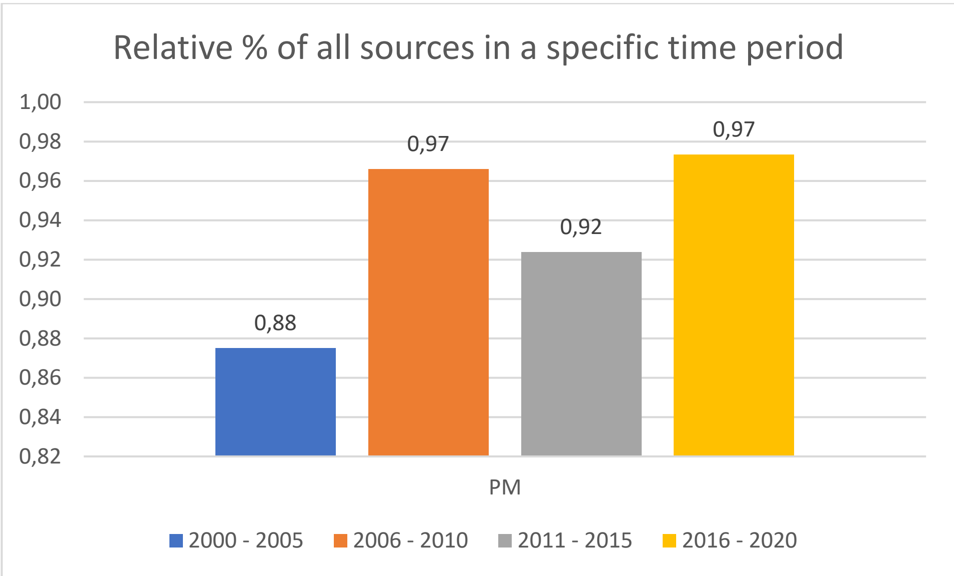

Figure 31. PM results, calculated with Equation (11)

The application of PM is closing in on 100% of all source studies in 2006 – 2010 and 2016 – 2020. Another thing is that basically all the methods listed in this thesis are related to PM, which means that if the research applies even one of the methods, it will be scoring points for PM. Therefore, the PM section itself is not too interesting itself but what is in the lower level of PM, meaning the different methods.

6.4.2 Recognized trends of corrective maintenance

Corrective maintenance is the most basic form of maintenance which is why it is no surprise that it is applied in nearly every source study. However, it is interesting that nevertheless the high application percentages, it still loses to PM. This can be seen in collective results later. The trend or CM can be seen in Figure 32 below.

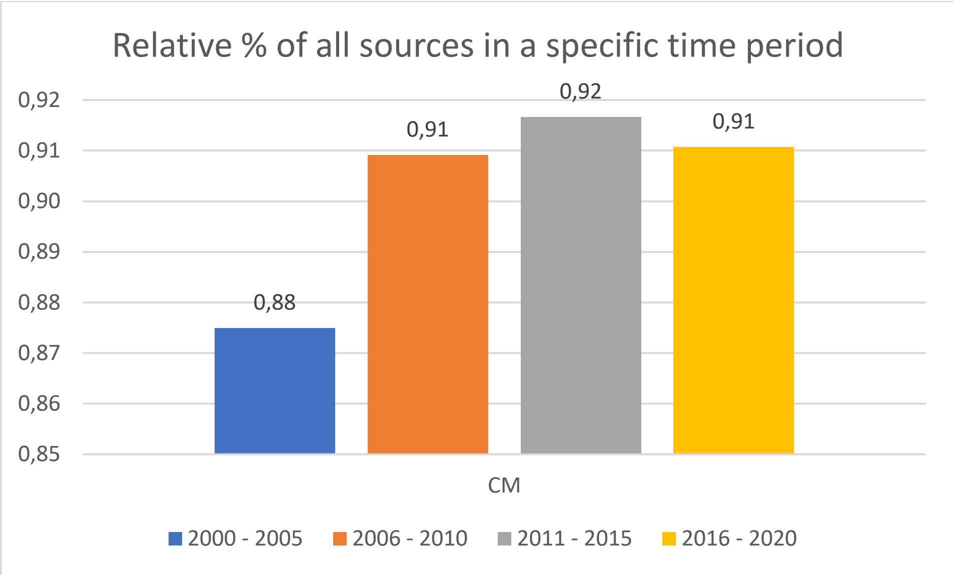

Figure 32. CM results, calculated with Equation (11)

The application percentage of CM has low variance as it’s around 90% during all periods. Maximum of 4% difference being between the 2000 – 2005 and 2011 – 2016. CM has its applications if the system under research is more complex than just a single unit type. Some units are not relevant enough that it would be worthwhile to invest resources in PM methods. These units usually do not directly affect the production of anything. These units can be the likes of air conditioning or other supporting functions in the factory. In most cases the system under research is complex enough to include at least a few of these not-too-important units.

Some units are just not allowed to break during operation or if they do, there is a backup unit taking the place of the broken one. The focus is on keeping the single unit functioning which is why CM is not considered in the study and only applied if the worst scenario happens. That is probably why there are some applications where CM is not applied.

However, CM is often used in combination with other PM and rarely as a stand-alone methodology which could also the high application rates.

6.4.3 Recognized trends of improvement

Improvement is clearly the underdog in the competition of maintenance types. It's the only type that does not exceed even 50% of the application rate during any point of time. This can be seen from Figure 33 below.

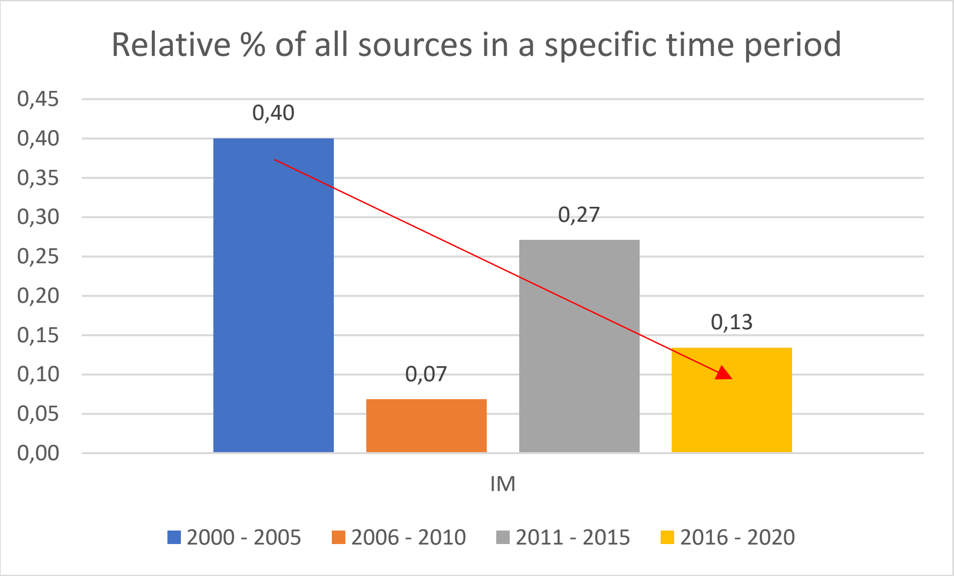

Figure 33. IM results, calculated with Equation (11)

Out of all three maintenance types, IM is the only one with a clear decreasing trend, going from 40% all the way down to 13% in the span of twenty years. This makes more sense when the analyses of methods under IM are explained in detail in the methods' results chapter. From this graph one could assume that IM is a losing trend and while it is more niche compared to PM and CM it does have its applications. The most probable reason for this trend is probably the result of two things:

Definitions of maintenance have changed: read the result chapter of DOM for details.

Because TPM strategy also has a decreasing trend: read the result chapter of Autonomous maintenance for details.

6.4.4 Collective results of maintenance types

Below is the collective graph of all maintenance types in one graph. From this the trends between can be seen more clearly, but as was said earlier the trend of IM might not be what it looks like in Figure 34 below.

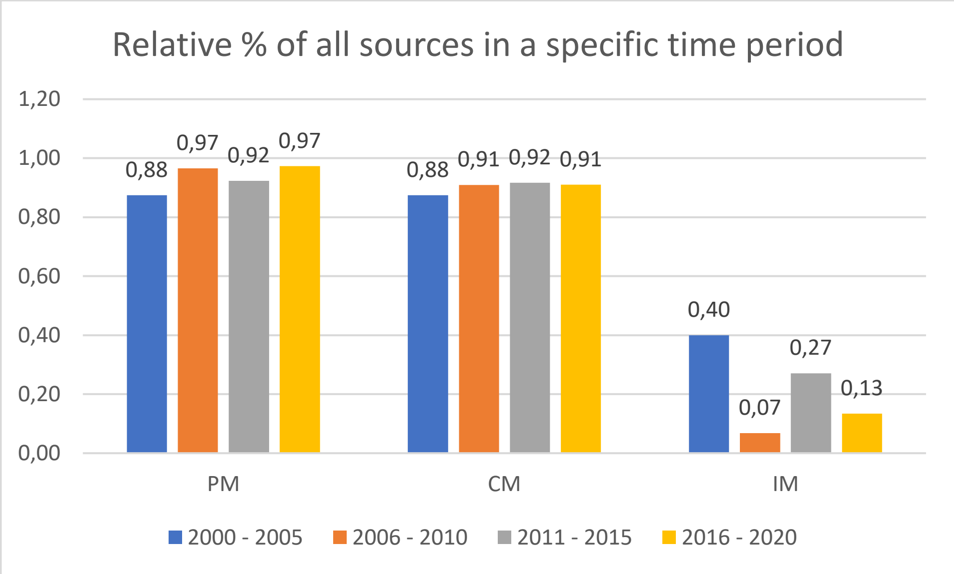

Figure 34. Collective results of maintenance types, calculated with Equation (11)

The maintenance types seem to have no relation to time except for Improvement which has a decreasing trend. PM and CM were applied on average in over 90% of the sources. It could be argued that IM shouldn’t be a maintenance type itself, but it should be part of PM. This is because the methods in IM are in fact preventive courses of actions. For example, DOM, which is included under IM, is in a way preventive action. Its goal is to eliminate the causes of certain problems which would previously cause the need for maintenance actions. They are just not the traditional preventive actions that are based on time or sensor data.

Below in Figure 35 is the combined application rate of the three maintenance types during the whole 2000 – 2020-year period.

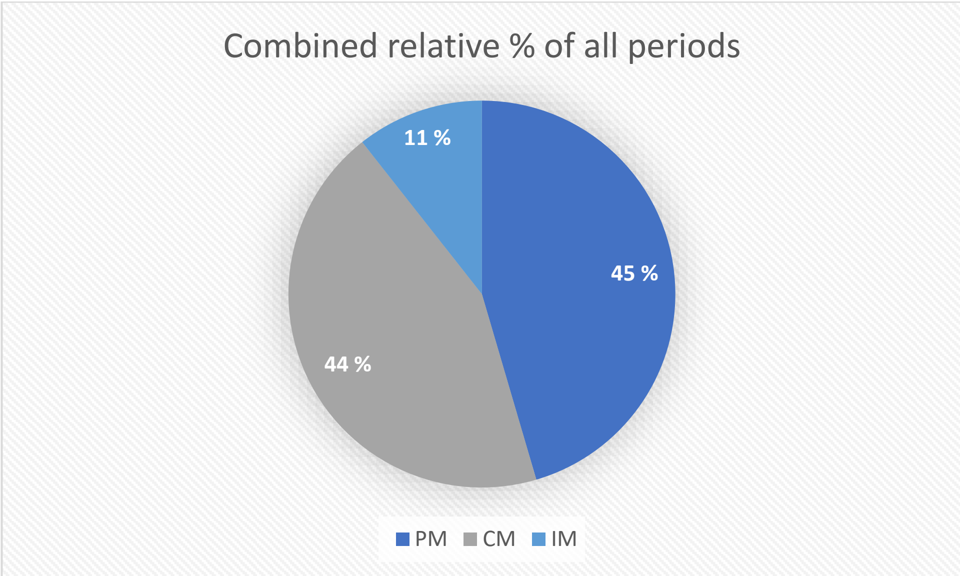

Figure 35. Relative combined popularity of each type between the years 2000 – 2020. Calculated with Equation (12)

6.5 Recognized trends of core maintenance methods

This chapter includes the results for the core maintenance methods, which are TBM, CBM and others. The results are from the Core tables. An important note here is that the core methods are not methods themselves, but act as upper-level titles for the actual maintenance methods that are applied in the sources.

6.5.1 Recognized trends of time-based maintenance

TBM is probably the easiest to implement out of all the PM related maintenance methods. This is detectable in the results as one can see below in Figure 36.

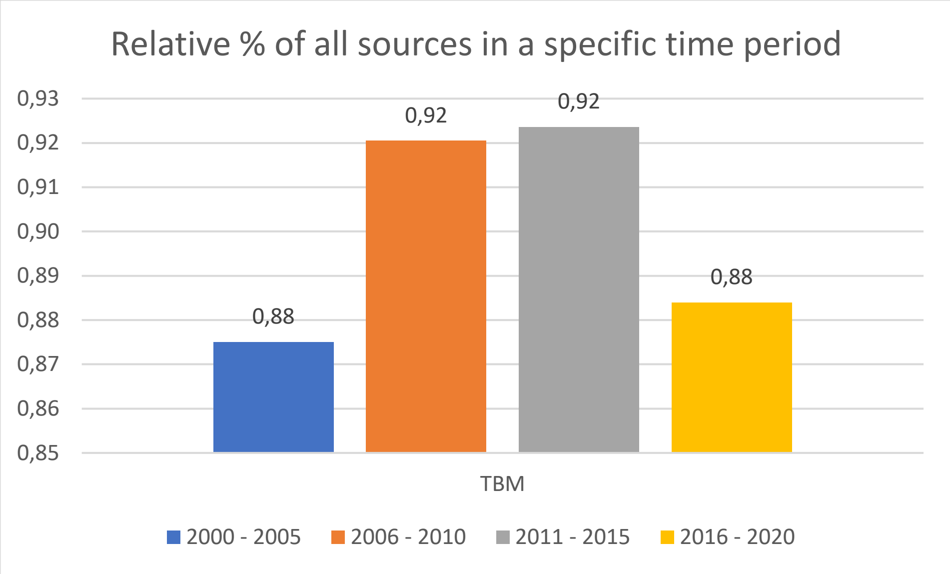

Figure 36. TBM results, calculated with Equation (11)

TBM follows closely on the percentages of PM and has low variance of 4%. There is no noticeable change during the twenty-year period. However, if one was to go back to the literature review in this thesis, there was a mention how 80% of the failure modes follow models that are not based on time. This means only 20% of failures are related to time but TBM is implemented in around 90% of the sources. The chances of every study investigating specifically time related failures are not realistic which begs the question why TBM is so widely applied in the field. It could be that the systems in most of the source studies are complex enough that they include such a variety of units where PM is a sensible option for some of them.

6.5.2 Recognized trends of condition-based maintenance

The CBM seems to be much more common than was presumed. There is no trend in relation to time in CBM except it seems to be highly used throughout the years. This can be seen in Figure 37 below.

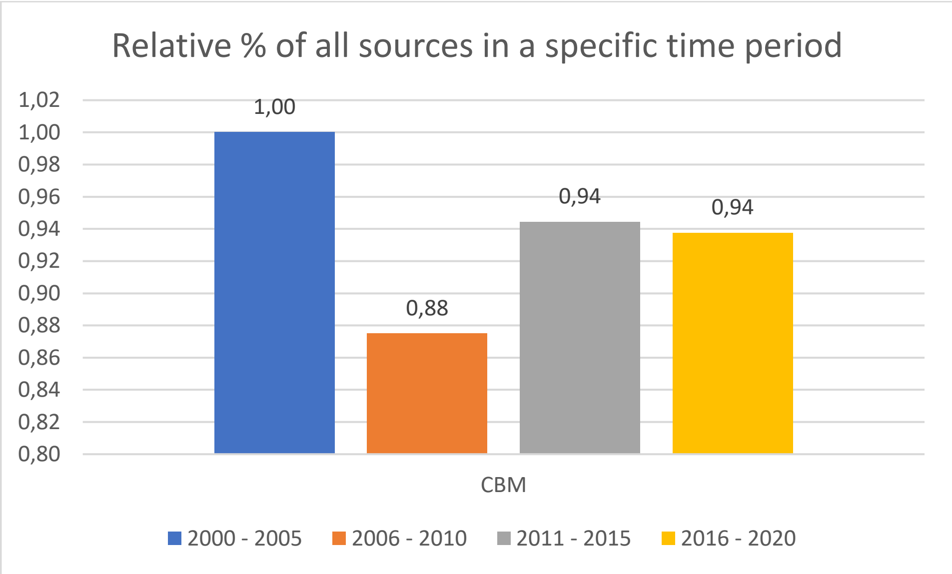

Figure 37. CBM results, calculated with Equation (11)

As one can see from Figure 37, CBM is used in nearly every source. The 100% result in the period 2000 – 2005 should be considered carefully as the period has only 10 sources, compared to the average 20+ sources in the other time periods. Otherwise, the variance seems to be like in TBM that being around 6%.

6.5.3 Recognized trends of other core methods

Adding this column in the Core table was a mistake as there were no proper other core methods. The results are from the sum of other specific methods. Graphs are shown in Figure 38 below.

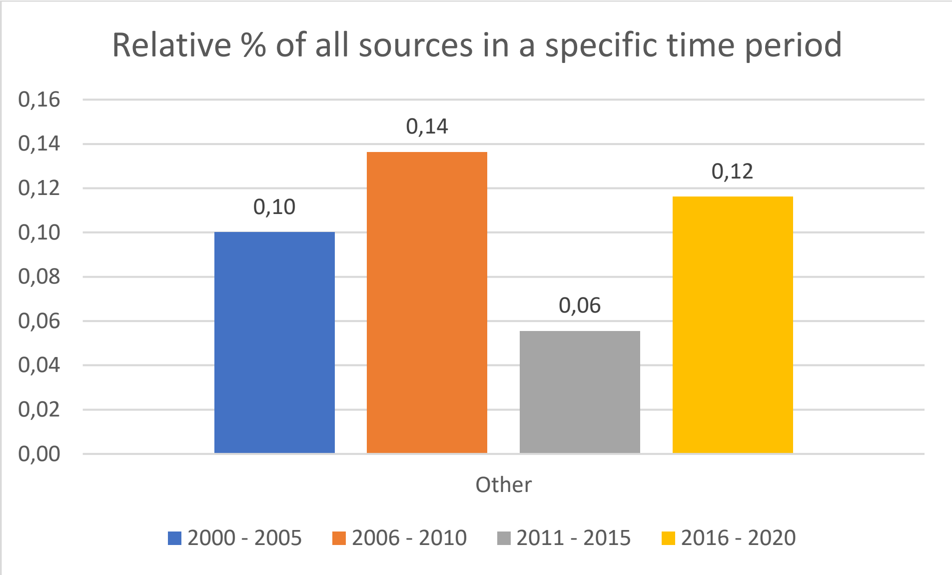

Figure 38. Other core maintenance methods, calculated with Equation (11)

The other methods are nowhere near as popular as TBM or CBM, the popularity hovering around 10-14 percent for the most part. 2011 – 2015 being an exception when the popularity dropped all the way down to 6%. The detailed methods will be explained but to sum it up here – most of the methods are either forced or they are just named differently from the commonly applied maintenance methods.

6.5.4 Collective results of maintenance core methods

There are only two core methods in the field of maintenance that were easy to determine. And it shows in Figure 39 below.

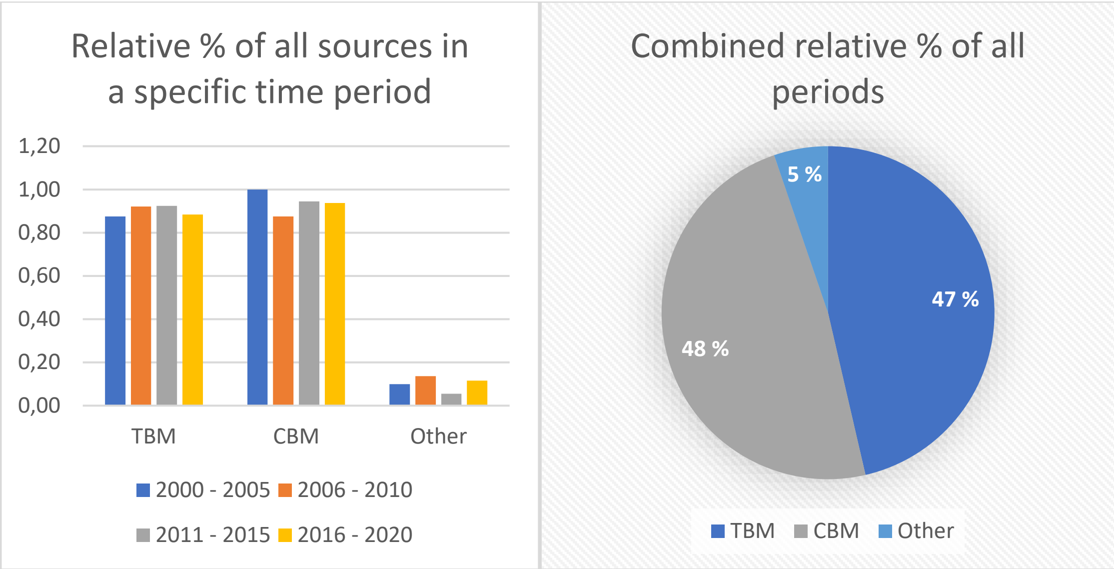

Figure 39. Collective results of core methods. Left figure calculated with Equation (11) and right with Equation (12)

The core maintenance methods have no clear relation to time, time-based, and condition-based methods were applied on average in over 90% of the sources. Basically, all the relevant maintenance sub-methods can be put under TBM or CBM as they cover around 95% of all the methods. However, there are some methods such as DOM that should not be underestimated even if it is in another category of maintenance.

6.6 Recognized trends of specific methods'

This chapter presents the results of the specific methods and their distributions between the sources. These methods are TBI, AB, OM, NPd, Pd, DOM, Auto, Other IM and the rest of the methods. The results are collected from the support tables.

6.6.1 Recognized trends of time-based interval maintenance

TBI is the baseline of TBM due to its practicality and simplicity. OEMs often include TBI in their manuals if there are time-based failure modes for some parts of the unit. However, the intervals are often quite short and seem a bit excessive in the eyes of the end-user. The end-users often have experience from the past with similar units which means they are almost as familiar with the product as the manufacturers. This experience can be fused with the OEM recommendations to convert the intervals into more sensible periods.

The TBI has the exact same percentages as TBM which means that every study that implemented a TBM method included at least TBI and in some cases some other TBM method. This is not too surprising because the other TBM methods are usually supportive methods in addition to the regular intervals that TBI has to offer. If the unit has TBM related failure modes, it has TBI method for certain and sometimes the additional support from AB and OM.

6.6.2 Recognized trends of age-based and opportunity maintenance

Both methods act as supportive methods for TBI which is why they do not have separate result chapters. It also makes more sense to analyze them at the same time because both are based on irregular or long-time intervals such as years. However, TBI can also include intervals of one or multiple years. The percentages of applications can be seen in the Figure below.

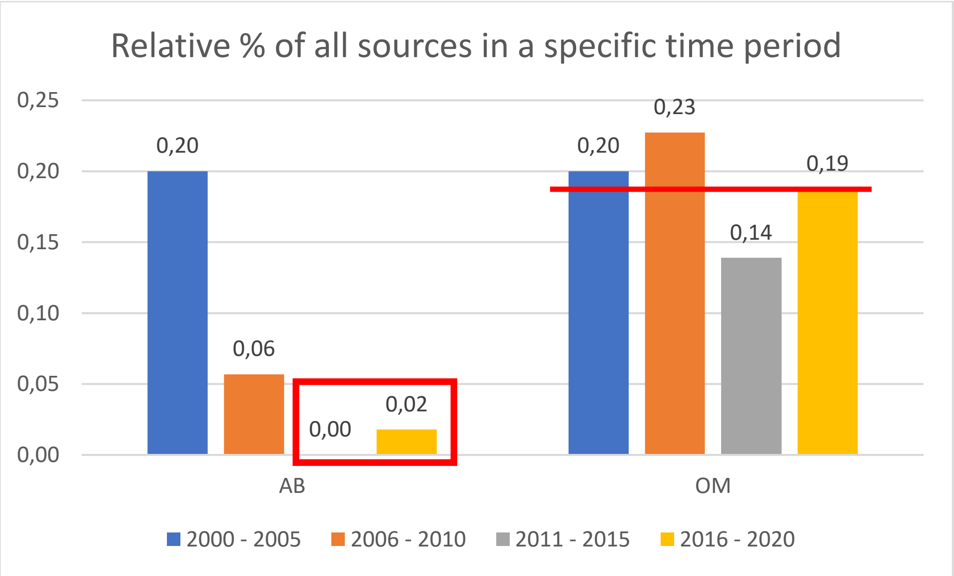

Figure 40. AB and OM results, calculated with Equation (11)

AB drops from 20% all the way down to nearly 0% of use during the period of 2000 – 2020. The reason for this is probably the result of two things, the definition of AB is not sensible and the continuously improving products in today’s industries. AB is used as a supportive method for units that have very long maintenance intervals such as 2 – 5 years or even longer. Usually, it does not make sense to implement AB as one can implement the same intervals inside TBI even though TBI is usually connected with shorter intervals. The definition of AB is just not ideal in the first place and just confuses the end-users with their options. This is an interpretation, but AB is probably just an idea that was born from TBI which should never have happened. The second reason is the continuous development of units. As AB is based on extreme intervals, those intervals should be based on past data. Therefore, collecting the data for AB is not sensible in most cases. Even if the data collected during a 5 – 10-year period is accurate, the unit has probably developed a lot during that time. This means that the data which was collected is not even applicable to the newer revision of the unit that is the flagship of the OEM at that point in time.

OM has had a steady application rate over the years. It hovers around 19% on average which is almost one fifth of TBM related studies every period. OM is implemented in cases where there are unpredictable shutdowns in the processes. OM is mostly used in the oil industry, manufacturing, and process industries such as power generation or mining according to the source list used in this thesis. Without further knowledge of the industries’ specifications, it seems logical that these types of industries can have unpredictable shutdowns or breaks from time to time. According to the popularity results in this thesis OM is highly related to the FOA, and its popularity cannot be evaluated properly through the data available in the used source lists. If only these forementioned industries were to be studied, the popularity percentage could be much higher than the 19% average shown here.

6.6.3 Recognized trends of non-predictive and predictive condition-based maintenance

The CBM related methods, NPd and Pd have quite clear differences in their application rates. The percentages can be seen in Figure 41 below.

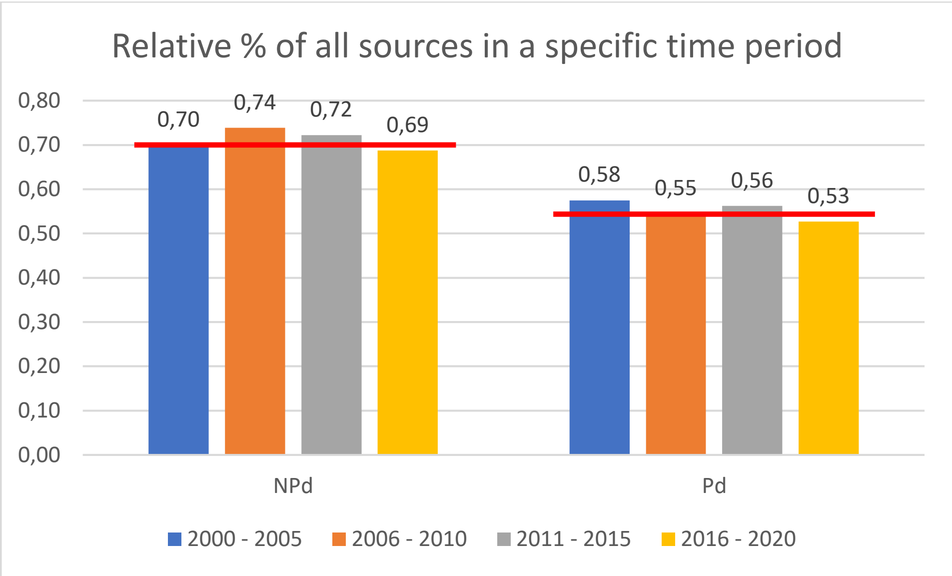

Figure 41. NPd and Pd results, calculated with Equation (11)

As one can see from the graphs, for every CBM related study usually almost three out of four studies utilized the NPd-method. Whereas only a bit more than half of the studies implemented Pd. Both seem to have no trend in relation to time. NPd is relatively useful due to data collection and it's easy to implement, which makes it attractive.

There is no clear reason as to why Pd does not have an increasing trend as one could assume. This could maybe be related to the FOA in the sense that if the unit is extremely complex the prediction models might be too hard to implement. Some FOAs can have simpler units which allow for the predictive models to be accurate and created in the first place.

The combined percentages don't form 100% in total during their respective periods as one study could utilize either one of the methods or both. There are no clear indicators which would give information on the FOAs and their relationship with these methods. The reason for the popularity difference can be simple though. As CBM is usually based on sensor data, it is simpler to just follow the sensor data and make maintenance actions according to the live data at hand. Pd requires complex models for which there are probably often not enough resources or knowledge to make those. Pd usually also utilizes other related databases which adds to the complexity of the method.

6.6.4 Recognized trends of design-out maintenance

DOM is what one could call a supportive maintenance method, in fact it probably should not even be categorized as a maintenance method which would explain its decreasing trend over the years. This can be seen in Figure 42 below.

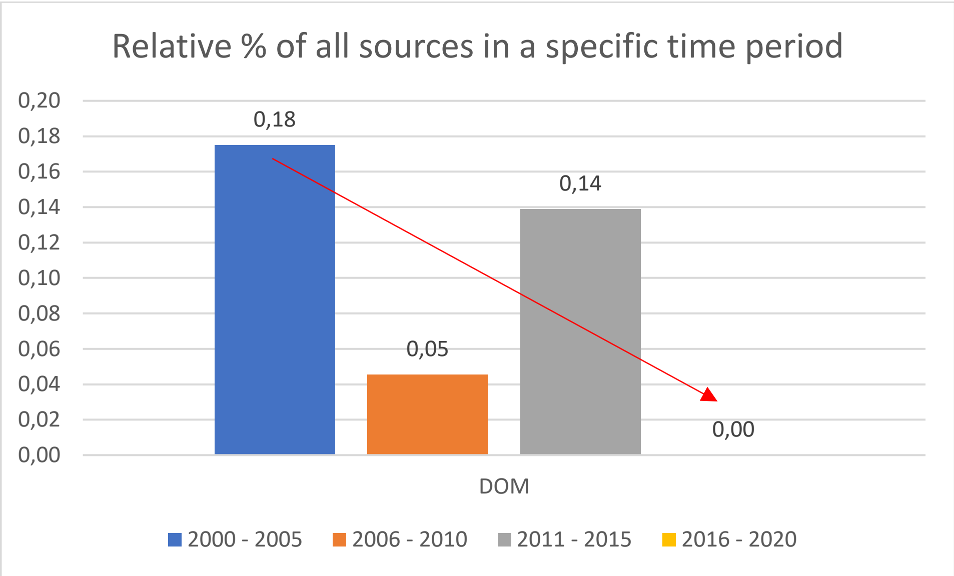

Figure 42. DOM results, calculated with Equation (11)

The popularity of DOM has dropped from 18% all the way down to 0%. DOM was utilized mainly in mining, with exceptions of automotive, aviation and construction. All mining related studies were conducted in 2011 – 2015 which explains the spike during that period. Therefore, DOM could be more popular in the mining industry. The problem is the definition of DOM. It focuses on developing a unit or product in a way that tackles the needs for some specific maintenance actions. This is a very non-direct way to maintain a unit as other methods focus on the actual maintenance actions that will be done for the unit to keep it functioning. Thing is that product development is happening all the time in every sector, but it just probably is not defined as DOM. Even if the development work is made from the standpoint of maintenance.

6.6.5 Recognized trends of autonomous maintenance

Autonomous maintenance is one of the pillars of TPM which is why the results resemble the percentages of TPM closely. The difference in the percentages comes from the point system and how they were applied in different studies. This can be seen in Figure 43 below.

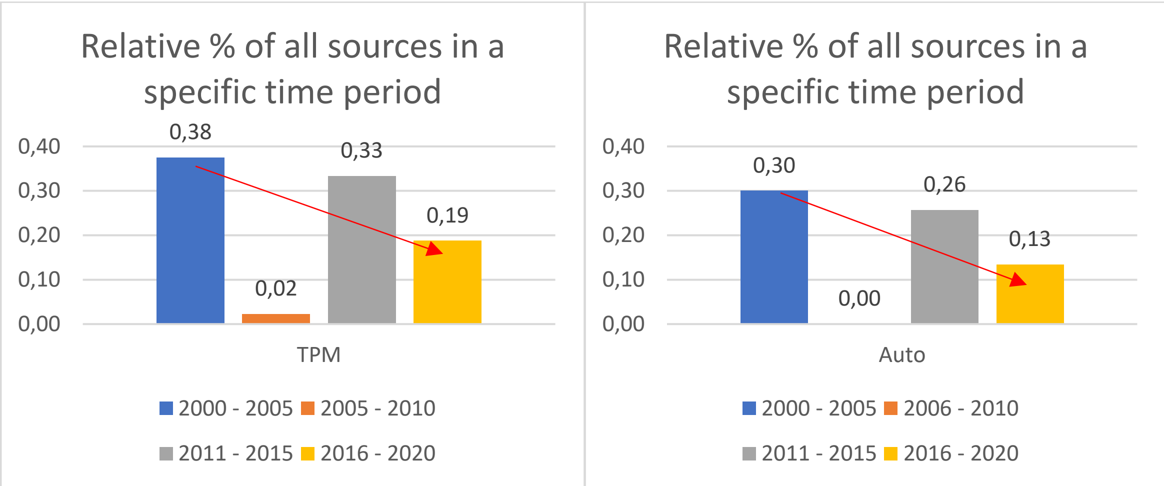

Figure 43. Results Auto, TPM to see correlation. Calculated with Equation (11)

The pattern is similar in both, a decreasing trend over the years due to the same reasons as was explained for TPM in the collective results of strategies. As companies push their beliefs and values to the workers from day one, the reasoning for Autonomous maintenance disappears. Therefore, one could assume that Autonomous maintenance does still happen much more than what the graphs make it seem like.

6.6.6 Recognized trends of other improvement methods and the rest of methods

The “Other IM”-methods section was concluded just in case there were more IM related methods in the sources. This was not the case and can be seen from Figure 44 below.

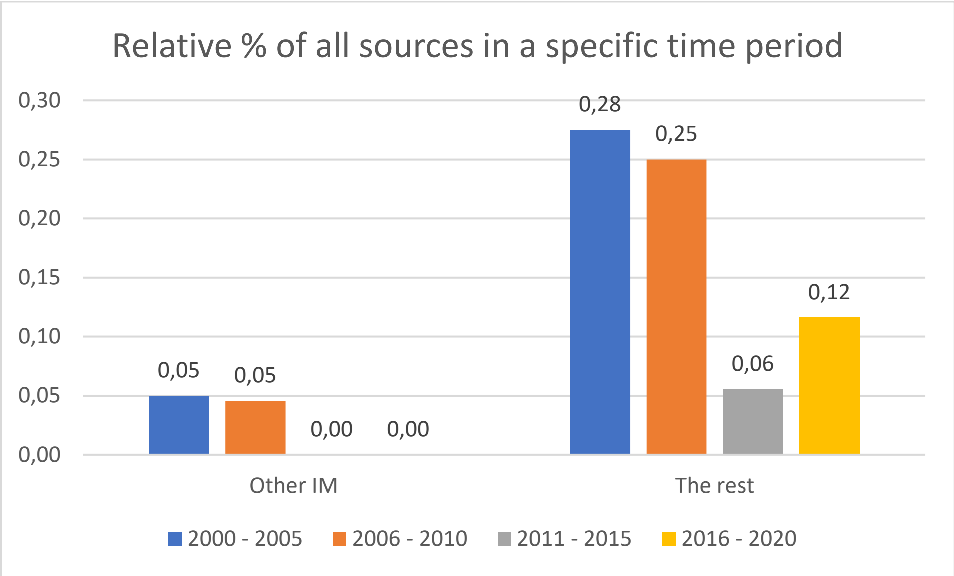

Figure 44. Other IM and the rest of maintenance methods' results. Calculated with Equation (11)

Other IM and the rest of the methods can be basically excluded from the analysis, they serve no purpose as there is not enough data. Even the couple sources that were interpreted as IM could be interpreted under some other maintenance type.

The rest of the methods could not be classified easily under any core method. Examples of these are: Skill level upgrade (SLU), imperfect maintenance, shutdown maintenance, discard, restoration, and condition prognosis. If one has made deep literature review into the topic, the names already reveal that the authors of these methods have not done it deep enough. Skill level upgrade is basically just a fancy name for better personnel training, it's not a method. Imperfect maintenance was also mentioned as a method in the literature review of this thesis. Now it can be concluded that imperfected maintenance is indeed not a known method. It's basically a sub-method of any PM related method, but it should not be defined as a method. The imperfect state of a unit is considered for example in predictive CBM or maybe even in non-predictive CBM methods. That's why imperfect maintenance should not be considered as its own method. Shutdown maintenance is a sub-method or action under OM but with a different name. Discard and restoration were not explained in the source research which makes the research rather unreliable. Condition prognosis seemed to be a method of CBM but could not be put into NPd or Pd easily. In short summary, all the other methods seem to be from authors who have not delved deep enough into the topic. Another possibility is that they have tried to make something innovative by just changing the definition and names of the methods just a bit.

6.6.7 Collective results of all methods

As the “Other IM” and the rest of the unclassified maintenance methods were deemed as unnecessary in the previous result chapter, they will not be included in the collective results-chapter. The collective graphs can be seen below in Figure 45.

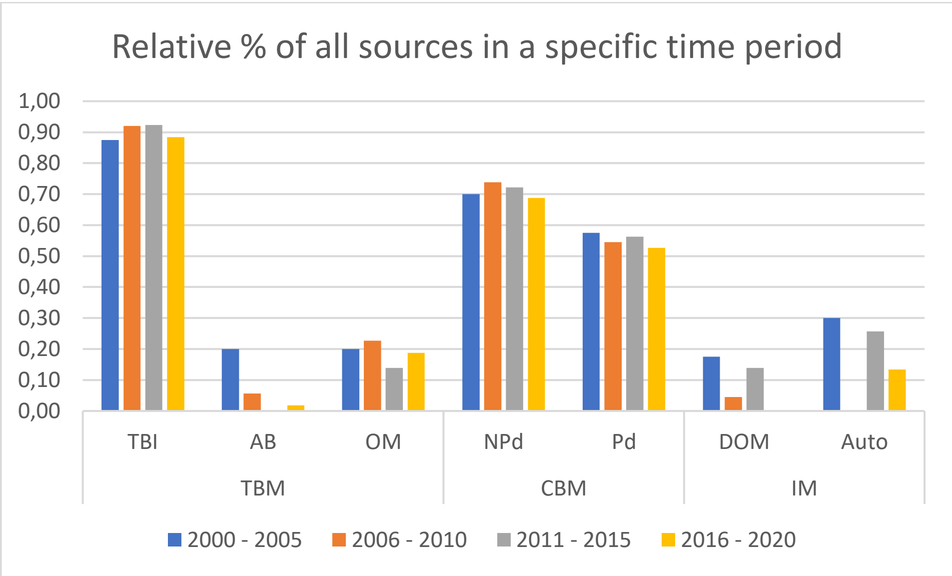

Figure 45. Collective results of all methods, calculated with Equation (11)

TBI is the clear leader in TBM methods, but as was mentioned earlier it is no surprise. AB and OM act as supportive methods for TBI. In most cases only TBI can be applied on its own whereas AB and OM won’t work well as the only maintenance method.

The difference between TBM and CBM based methods is probably since CBM methods require more from the unit. The unit must have a measurable parameter and it must have a known correlation with a known failure mode. TBI on the other hand in the simplest case only requires data from previous breakdowns. This data can be used to determine the intervals for specific maintenance actions. The DOM and Auto act more as supportive methods as was explained in their respective result chapter. Another way of showing the popularity of methods is shown in Figure 46 below.

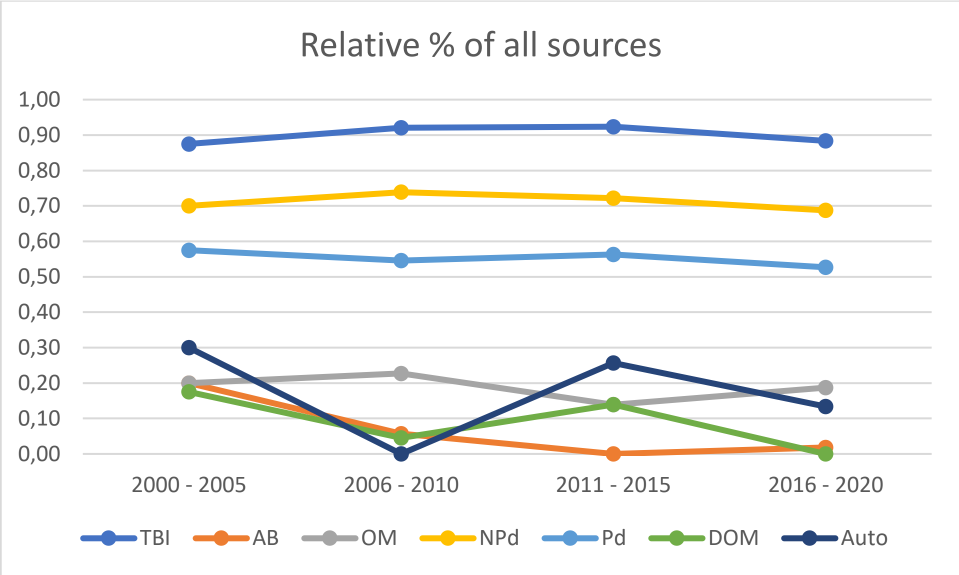

Figure 46. Methods' popularities throughout 2000 – 2020. Calculated with Equation (11)

This is the same data presented in different forms. There is the stable top three that include TBI, NPd and Pd in corresponding order from top to bottom. Other methods have much larger variance in application rate. From Figure 46 one can see the methods which are not in the top three are not competing in the same level. This is most probably because the top three are the easiest to implement in terms of resource requirements and the goals being clearer in them.

The last comparison of methods is put in a way, where all the methods' relative percentages throughout the whole 20-year period are compared against each other. In other words, there is a single relative value for each method. The data can be seen in Figure 47 below.

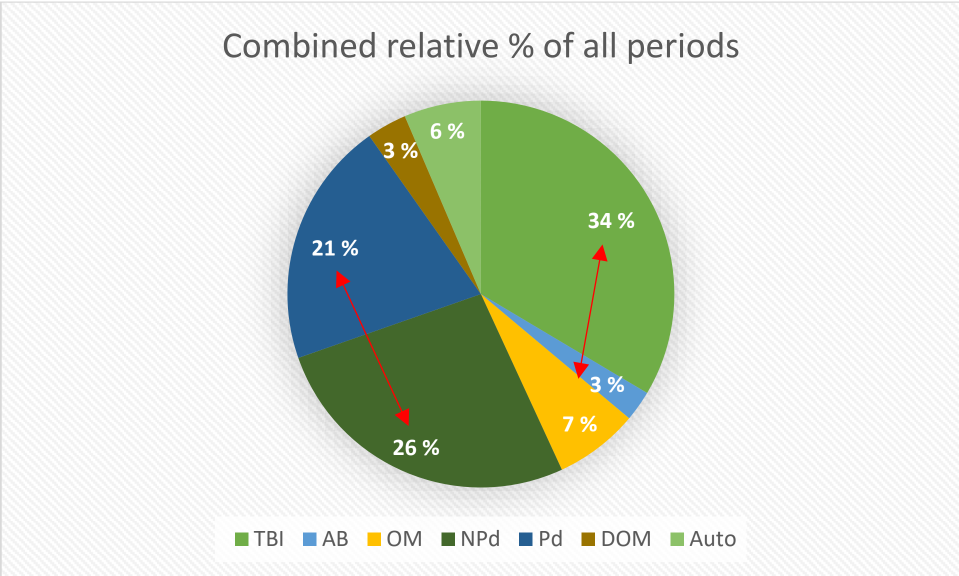

Figure 47. Relative combined popularity of each method between the years 2000 – 2020. Calculated with Equation (12)

When all the methods' popularities are combined from the four periods, these are the resulting popularities between the methods. NPd and Pd (CBM methods) combine total percentage of 47% against the combination of TBI, AB and OM (TBM methods) which form 44%. Therefore, the most popular maintenance methods are CBM based methods in the years 2000 – 2020. But the competition between the TBM and CBM based methods is close; both have their applications, but neither is clearly more popular than the other.

There is a difference in the percentages of these summed up TBM and CBM values and the collective results of core maintenance methods. This is because when calculating the results with the sub-methods, there are more datapoints. This allows for more accurate analysis which leads to slight differences in the results. In the collective results CBM had 48% and TBM 47% application rate.

6.7 Recognized trends of visions

The results of the visions must be considered with caution as a low number of sources were used for this analysis. Six sources were used for the visions. The result table for the visions can be seen in Figure 48 below.

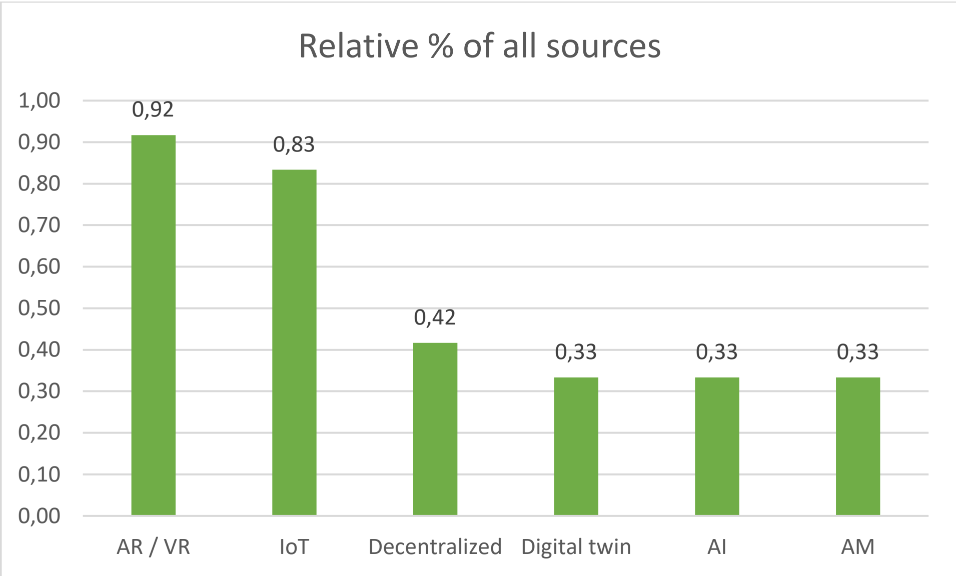

Figure 48. Relative percentage of visions discussed in internet, calculated with Equation (11)

AR/VR and IoT are the clear winners in the category of maintenance visions as far as a few sources seem to imply. IoT has potential as it can be implemented more easily than any other methodology in this list. The data for IoT applications basically exists already, for example, through CBM sensors or PM service logs. To implement IoT nothing too innovative must be done outside of handling the data in an efficient way. AR and VR applications require more innovation, and their downfall might be the resources that are needed for them. AR is more flexible because it does not require artificial environments which probably allows for easier software updates as the units change over time. With AR it's also probably possible to use AI in combination for feature recognition for certain parts of units which would allow for even more flexibility. In VR one is probably limited with the fact that the environment and the unit must be modeled virtually.

Nevertheless, the percentages of the other methodologies should not be overlooked. For example, AI due to its rapid development in general in the last few years. In fact, AI is probably the most potent methodology of all of these as it can go as far as choosing the strategies, types and methods and applying them accordingly in each scenario. Or even create new methodologies when there is enough data to allow machine learning to do its work.

Digital twin probably shouldn't be categorized as its own methodology as it's like VR, which might explain the surprisingly low application rate. The definition of digital twin and VR are different but digital twin is very likely implemented in VR. It all comes down to the definitions in all fields of research how uniform the information in a field is.

AM should probably not be implemented in these results as it cannot be defined under any category of maintenance methodologies such as type or core method mentioned in this thesis. It acts as an inventory support which in a way could be defined as maintenance method, but it would have to be categorized somehow differently.

Overall, the visions would seem to be more like supportive or sub-methods that are based on today’s top three methods, which were the TBI, NPd and Pd. The official data table and results can be found in Appendix 8.

7 Discussion

This chapter evaluates the results of the thesis from different points of view. The most notable conclusions are collected.

7.1 Comparison and connections with former research

One of the biggest issues that was known from the beginning is the fact that many researchers do not define the differences between the levels of maintenance. The levels of maintenance are sometimes there but not in sufficient accuracy. This leads to interpretation that must be made by the person or people who are creating new research of the topic. It seems that much research in the field does not make a deep enough dive into the literature to understand the differences between the levels. Many studies refer to, for example PM directly as TBI when that is not the case. PM is the type that includes the most common maintenance methodologies in today’s applications, or the ones being visioned in the future.

7.2 Objectivity and reliability aspects

Objectively observing, the goals of this thesis were achieved but not in a perfect way. There were misassumptions when creating the point system and the tables for the maintenance methodologies. The distribution of headers on the tables could have been clearer and there is room for improvement. The columns related to IM were not nearly as popular as anticipated which made them basically unnecessary. The same applies for the other methodologies as there was a surprisingly low number of them and if there were, they did not seem high quality studies. Overall, the problem with this table tool is probably the layers it has. For example, how the definition of IM had to be made into one of the core methods in addition to it already being a maintenance type. The field of maintenance has its terms so loosely defined the layers must be there to keep track of things.

Sensitivity analysis is a thing to consider when looking at the results. As was mentioned earlier, the first period, years 2000 – 2005, had only 10 sources. Even though the results are converted into relative percentages the lower number of sources have larger variance impact on every methodology when compared to the other periods. All the sources were picked from the two studies of Shafiee (2015) and Patil et al. (2022), this means that their choices of sources have an impact on this thesis as well. As these two studies were related more into the selection process of the maintenance methodologies, their source studies might have different spectrum of methodologies on average. If one were to choose the studies one by one the results could be different. However, the source studies were chosen from wide variety of fields which takes the doubt of the methodologies packing up between low number of fields. If one was to add more sources by picking them separately or finding another study that has listed information the results could be slightly different.

7.3 Novelty value of results

There was a clear gap in information as to how maintenance methodologies are defined and utilized in literature. Many researchers focus on the selection process of maintenance methodologies but basically none focus on the methodologies themselves and their application rates. This thesis offers some insight into the lack of information in this regard.

7.4 Conclusions

Some clear trends were identified in the categories of strategies and methods. The type-category was extremely stable as was expected because they just act as the distribution factors for the actual methods. There were a lot more strategies in the sources than the studies of Shafiee (2015) and Patil et al. (2022) made it to seem. This was mostly because of the point system, the forementioned studies did not consider the strategies or methodologies that were only mentioned as part of literature review.

As for the trends of methods, it is interesting how the top three methods, TBI, Pd and NPd have clearly the most stable results and don’t seem to be having any relation to time in the large scale of things. On the contrary, all the supporting methods seem to have either no relation to time or decreasing trends. However, this does make sense when one looks at the visions of maintenance.

When one looks at the visions of future maintenance methodologies, most of them are based on huge amounts of data. AI, AR, IoT, decentralized maintenance, all of these require a large pool of data to work properly. And when checked it can be seen the most common and stable trending methods are either TBI or CBM related methods. Both can offer the data required for the new visions in maintenance. When evaluating the bigger picture, it could be argued that TBM and CBM are the core of every single relevant method out there in PM. The supporting methods just seem to change over time from such as AB, autonomous or likewise methods. Nevertheless, the dominance of PM, digital twins, and its simulations or likewise methods could be defined under the type of IM.

There is a lot of research regarding different methodologies for the selection process of maintenance methodologies. However, when compared to the actual industry only a fraction use tools such as AHP or MCDM. There is also research that evaluates the different maintenance methodology selection processes, which barely anyone uses in real applications. These notes raise the question as to why there is this gap between research and the actual industry.

7.5 Topics for future research

Future research should delve even deeper into the classification of levels in maintenance. New methodologies will replace the old ones, or they'll change their form as was seen already during this thesis. With the upcoming visions there is a chance new types will be needed that cover the variety of new methods. New methods based on the visions will be created and should be investigated.

Another important topic is the failure models. Failure models are the base for the need for maintenance. Therefore, failure models should also be looked more into as some of them are maybe not applicable in today's units.

8 Summary

In this thesis the trends of maintenance methodologies were investigated. The definitions of maintenance were interpreted from the literature which were then applied in the trend analysis tool. The takeaway results from the analyses were the following.

The application rates between strategies, types and methods do not seem to have changed over the years 2000 – 2020. The most important note is that strategies seem to not be in high popularity, only around 10-15% compared to the average of 45% of types and methods. It might be that the AHP models or similar mathematical models do not work as well for choosing strategies over the maintenance methods. And most of the source studies were based on the maintenance methodology selection which were utilizing these models.

The strategy selection factors were divided into six main factors, economic, technical, feasibility, safety, environmental, and social. Four out of six, those being the economic, technical, feasibility, safety were the most utilized factors. They had a clear pattern that if one of these factors were applied, usually all four were applied. The environmental and social factors had a slightly increasing trend. Environmental factor going from 10% to almost 20% of application rate and social from 0% to 14%.

All the strategies' application ratios either had no relation time or were on a decreasing trend, except for reliability centered maintenance. RCM is simple to execute, and it is highly flexible. RBM focuses too much on risk assessment and neglects other factors. For most applications, TPM seems outdated in today's industry, which explains its decreasing trend.

The maintenance types seemed to have no relation to time except for Improvement which had a decreasing trend. Preventive and Corrective maintenance were applied on average in over 90% of the sources.

The core maintenance methods had no clear relation to time, time-based, and condition-based methods were applied on average in over 90% of the sources.

From the specific maintenance methods, time-based interval maintenance, non-predictive and predictive condition-based maintenance were the top three methods by far during the whole period of 2000 – 2020.

Judging by the principles of future visions, they were deemed as the supportive or sub-methods of today's top three methods, which were the time-based interval maintenance, non-predictive and predictive condition-based maintenance.

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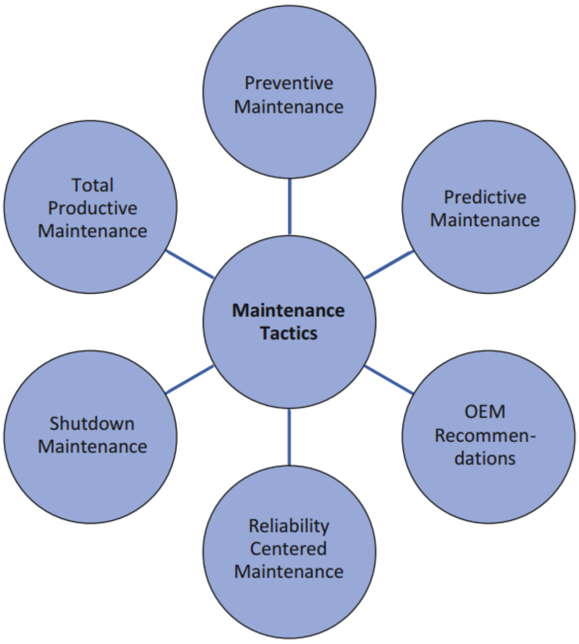
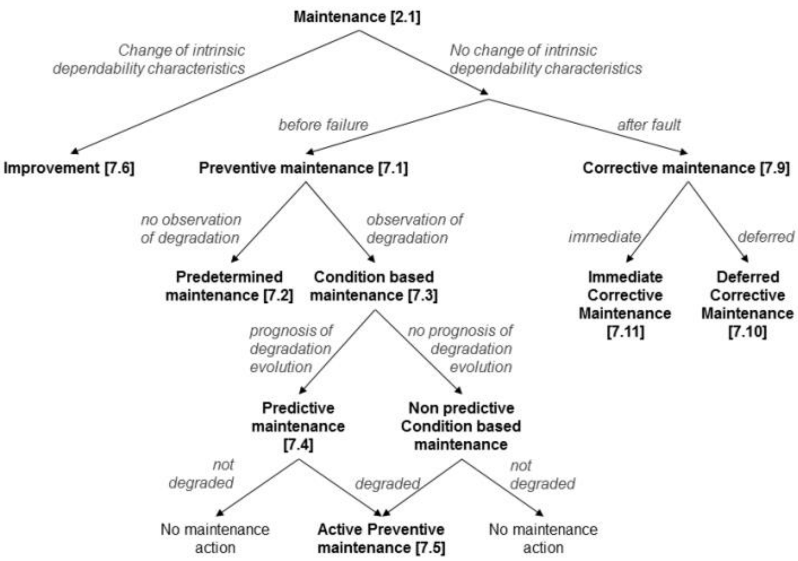


Fig. 2.6 Maintenance tactics

Maintenance tactics, Velmurugan, Dhringra, 2021, p. 38



Maintenance types (SFS-EN 13306:2017:en)

Impact of Maintenance 9

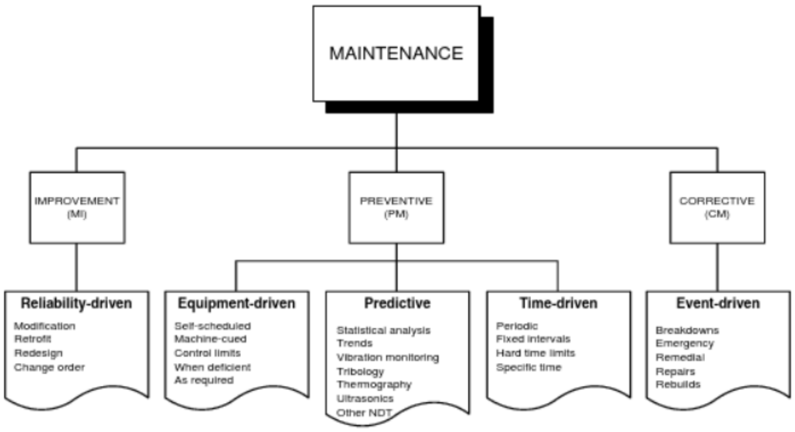


Figure 1.2 Structure of maintenance.

Mobley 2004 page 9

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39,3

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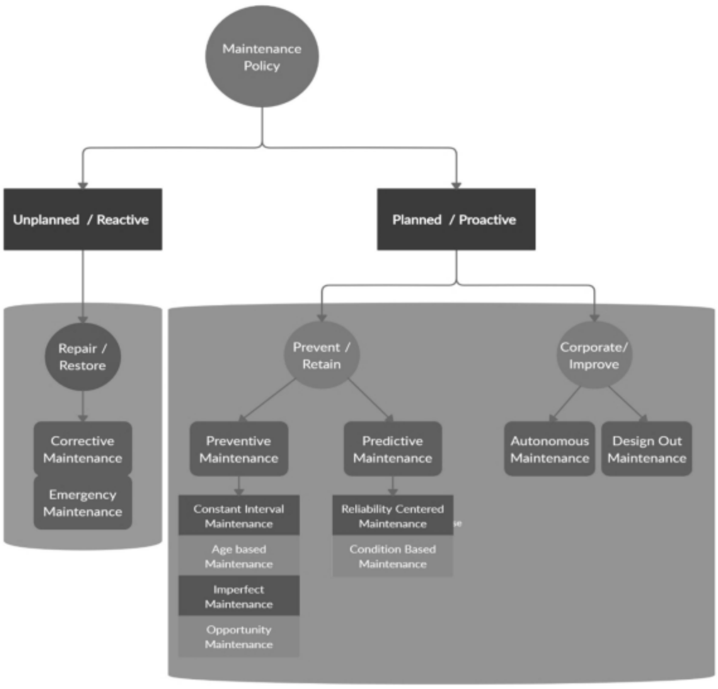

Figure 3.
Classification of maintenance strategy models

Patil et al. 2022, p. 680

Appendix 2, Criticality classification of equipment in industry

PSK Standardisointi

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Criticality Classification of Equipment in Industry

PSK 6800
Liite1
Appendix1

Unit
Object of classification
Prepared by
Version
Date

Criticality limit: 400
Weighting factor of production loss Wp: 100

Identifier of object	Name of object	Time between failures (1…8)	Safety risks (0…16)	Environ-mental risks (0…16)	Production loss (0…4)	Quality costs (0…4)	Repair costs (0…4)	Criticality index	Criticality sub-indexes				
		Weighting W -->	30	20	100	30	20	K	Ks	Ke	Kp	Kq	Kr
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
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								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0
								0	0	0	0	0	0

Core table 1, 2000-2005

	General information			Strategy				Type			Method		
Year	Source	FOA	SSF	RBM	RCM	TPM	Other	PM	CM	IM	TBM	CBM	Other
2000	Bevilacqua and Braglia (2000)	Oil refinery plant	Economic, technical, safety	0,75	0,5			1	1		1	1	
2003	Al-Najjar and Alsyouf (2003)	Power generation	Economic, technical, safety		1	1	1	1	1	0,75	1	1	
2003	Mechefske and Wang (2003	Power generation	Qualitative, unspecified					0,75	0,75		0,75	1	
2004	Bertolini et al. (2004)	Construction	-		0,5	0,5		1	1	0,75	1	1	
2004	Labib (2004)	Automative	-		0,75	0,75		1	1	1	1	1	1
2004	Alsyouf (2004)	Pulp and paper	Economic, safety, environmental, feasibility	0,5	0,5	0,5	0,5	1	1	0,75	1	1	
2005	Carnero (2005)	Oil, gas	Economic, technical									1	
2005	Sharma et al. (2005)	Process	Economic, technical		1	1		1	1	0,75	1	1	
2005	Verma et al. (2005a)	-	-					1	1		1	1	
2005	Verma et al. (2005b)	-	-					1	1		1	1	

Appendix 3, Core table 2, 2006-2010 (2)

YEAR	General information			Strategy				Type			Method		
	Source	FOA	SSF	RBM	RCM	TPM	Other	PM	CM	IM	TBM	CBM	Other
2006	Bertolini and Bevilacqua (2006)	Oil, gas	-	0,5	0,5	0,5		1	1			1	
2007	Li et al. (2007)	Process	Economic, technical, feasibility, safety					1	1		1	1	
2007	Verma et al. (2007)	-	-					1	1		1	1	
2007	Wang et al. (2007)	Power generation	Economic, technical, feasibility, safety					1	1		1	1	
2007	Zaeri et al. (2007)	Manufacturing	Economic, technical, feasibility, safety					1	1		1	1	
2008	Gaonkar et al. (2008	-	Economic, technical, feasibility, safety					1	1		1	1	
2008	Dong et al. (2008)	Power generation	-		0,5			1	1		1	1	
2008	Fazlollahtabar and Yousefpoor (2008)	Education	-					1	1		1	1	
2008	Jafari et al. (2008)	-	Economic, technical, feasibility, safety					1	1		1	1	
2008	Pariazar et al. (2008)	Manufacturing	Economic, technical, feasibility, safety					1	1		1	1	
2008	Reichelt et al. (2008)	Construction	-					1	1		1		
2008	Shyjith et al. (2008)	Textile	Environmental, feasibility, technical, (cost as sub-criteria)		1			1			1	1	
2009	Ahmadi et al. (2009)	Aviation	Economic, technical				1	1	1	0,75	1	1	
2009	Ilangkumaran and Kumanan (2009)	Textile	Environmental, feasibility, technical, social (cost as sub-criteria)		1			1			1	1	
2009	Mousavi et al. (2009)	-	-					1	1		1	1	
2010	Ahmadi et al. (2010)	Aviation	-				1	0,25	1	0,75	0,25	0,25	1
2010	Arunraj and Maiti (2010)	Chemical	Risk, cost	1				1	1		1	1	1
2010	Bashiri et al. (2010)	-	Technical, economic					1	1		1	1	
2010	Cheng and Tsao (2010)	Transportation	Risk, cost, safety, feasibility					1	1		1		
2010	Ghosh and Roy (2010)	Process	-					1	1		1	1	
2010	Ratnayaka and Markeset (2010)	Oil, gas	Economic, technical, feasibility, safety, environmental				1	1	1		1	1	1
2010	Vahdani et al. (2010)	-	Economic, technical, feasibility					1	1		1	1	

Appendix 3, Core table 3, 2011-2015 (3)

YEAR	General information			Strategy				Type			Method		
	Source	FOA	SSF	RBM	RCM	TPM	Other	PM	CM	IM	TBM	CBM	Other
2011	Momeni et al.	Oil, gas	Economic, technical, feasibility, safety					1	1		1	1	
2011	Nagar	Electronics	-					1	1		1	1	
2011	Nezami and Yildirim	Automotive	Economic, technical, feasibility, safety, env., soc.		1	1		1	1	0,75	1	1	
2011	Peng and Wang	Power generation	-					1	1		1	1	
2011	Peng and Wang	Power generation	-					1	1		1	1	
2011	Gaonkar et al	-	-									1	
2011	Sarkar et al	Power generation	Economic, technical, feasibility, safety					1	1		1	1	
2011	Tajadod et al	-	-					1	1		1	1	
2011	Tan et al	Oil, gas	Economic, technical, feasibility, safety	0,5	1			1	1		1	1	
2011	Vahdani and Hadipour	-	-					1	1		1	1	
2012	Aghaee and Fazli	Automotive	-		0,75	1		1	1	0,75	1	1	
2012	Chan and Prakash	Manufacturing	Economic, technical			1	1, TQMain	1	1	0,75	1	1	
2012	Ding and Kamaruddin	-	-			0,75		1	1	0,75	1	1	
2012	Kumar and Maiti	Chemical	Economic	1	0,75			1	1		1	1	1
2012	Kushwash	-	-					1	1		1	1	
2012	Sadeghi and Alborzi-Manesh	Steel manufacturing	Economic, feasibility			1		0,25	1	0,75	0,25	0,75	1
2012	Sarkar and Behera	-	-		1	1		1	1	0,75	1		
2012a	Shahin et al.	Mining	Economic, technical		0,5	1		1	1	0,75	1	1	
2012b	Shahin et al.	Mining	Economic, technical		0,5	1		1	1	0,75	1	1	
2012	Zaim et al	Pulp and paper	Economic, feasibility, safety					1	1		1	1	
2012	Fouladgar et al.	Mining	Economic, technical, safety			1		1	1	0,75	1	1	
2012	Ilangkumaran and Kumanan	-	-		1			1			1	1	
2013	Ierace and Cavalieri	-	Technical, feasibility					1	1		1	1	
2013	Xie et al	Mining	Economic, technical, feasibility, safety					1	1		1	1	
2013	Nezami and Yildirim	Automotive	Economic, technical, feasibility, safety, env., soc.		1	1		1	1	0,75	1	1	
2013	Braglia et al.	-	Economic, technical		0,75	0,5		0,75	1	0,75	0,75	1	
2013	Ioannis and Nikitas	Transportation	-					1	1		1	1	
2013	Jayaswal et al	-	-					1	1		1	1	
2013	Odeyale et al	-	-					1	1		1	1	
2013	Pourjavad et al	Mining	Economic, technical		0,5	1		1	1	0,75	1	1	
2013	Rashidpour	-	Economic, technical, feasibility, safety, env.					1	1		1	1	
2013	Sagar et al	Transportation	Economic, technical, feasibility, safety, env.					1	1		1	1	
2013	Thor et al.	-	-			0,75		1	0,75	0,75	1	1	
2014	Lazakis and Ölçer	Industry	-					1	1		1	1	
2014	Velmurugan and Dhingra	Petrochemical	-		0,25			0,25	0,25		0,25	0,25	

2015	Kirubakaran and Ilangkumaran	-	Economic, technical, feasibility, safety, env.					1	1		1	1	

Appendix 3, Core table 4, 2016-2020 (4)

	General information			Strategy				Type			Method		
YEAR	Source	FOA	SSF	RBM	RCM	TPM	Other	PM	CM	IM	TBM	CBM	Other
2016	Azadeh and Abdolhossein Zadeh	-	-		0,5			1	1		1	1	0,5
2016	Xia et al.	Network	Economic, technical, feasibility, safety, environmental, social					1	1		1	1	1
2017	Carnero and Gomez	Electronics	-		0,5			1	1			1	
2017	Panchal et al.	-	-		1			1	1		1	1	
2017	Ge et al.	-	-	0,25				0,25			0,25	0,25	
2017	Zarei and Ghaedi-Kajuei	-	-		1			1	1		1	1	
2017	Özcan et al	-	Economic, echnical					1	1		1	1	0,75
2018	Shagluf et al.	Manufacturing	Economic, technical, feasibility					1	1		1	1	
2018	Emovon et al.	-	Economic, technical, feasibility, safety, environmental		0,5			1	1		1	1	
2018	Ivanov et al.	-	Economic, technical, safety					1	1		1	1	
2018	Hemmati et al	Process	Economic, technical, safety		0,5	0,5		1	1		0,75	1	1
2018	Borjalilu and Ghambari	-	Economic, technical, feasibility, safety		1			1	1		1	1	
2018	Dachyar et al.	-	Economic, technical, social, environment, safety, feasibility		0,75			1	0,5		1	1	
2018	Srivastava et al	-	Economic, technical, feasibility, safety					1	1		1	1	
2018	Ohta et al	Railway	-					1	1		1	1	
2018	Fecarotti and Andrews	-	Economic, technical		0,5			1	1		1	1	
2018	Seiti et al	Steel fabrication	Economic, technical, feasibility, safety, environmental, social	0,5	0,5	1		1	1	0,75	1	1	
2019	Teng et al.	-						1					
2019	Asuquo et al.	Maritime	Economic, technical, feasibility, safety		1			1	1		1	1	
2019	Animah and Shafiee	-	Economic, technical, feasibility, safety, environmental, social					1	1		1	1	
2019	Srivastava et al	-			1			1	1		1	1	
2019	Martin et al.	-	Economic, technical, feasibility, safety		0,75	1		1	1	0,75	1	1	
2019	Shafiee et al	Wind turbine	-	1				1	1		1	1	
2020	Galankashi et al.	Cement	Economic, technical, feasibility, safety		1	1		1	1	0,75	1	1	
2020	Kurian et al.	Industry	Economic, technical, feasibility, safety	0,5				1	1		1	1	
2020	Gedikli et al.	Food industry			1	0,75		1	1	0,75	1	1	
2020	Mostafa and Fahmy	-						1	1		1	1	
2020	Aghaee et al.	-	Economic, technical, feasibility, safety		0,75	1		1	1	0,75	0,75	1	

Appendix 4, Support tables (1)

Support table 1, 2000-2005

Year	Method	TBM			CBM		IM			The rest
	Specific method	TBI	AB	OM	NPd	Pd	DOM	Auto	Other IM	
2000	Bevilacqua and Braglia (2000)	1		1	1	1				
2003	Al-Najjar and Alsyouf (2003)	1	1		1			0,75		1
2003	Mechefske and Wang (2003)	0,75			1					
2004	Bertolini et al. (2004)	1		1	1	1	0,75			
2004	Labib (2004)	1			1		1	0,75		1
2004	Alsyouf (2004)	1	1		1	0,75		0,75	0,5	0,75
2005	Carnero (2005)					1				
2005	Sharma et al. (2005)	1			1			0,75		
2005	Verma et al. (2005a)	1				1				
2005	Verma et al. (2005b)	1				1				

Support table 2, 2006-2010

YEAR	Core method	TBM			CBM		IM			The rest
	Specific method	TBI	AB	OM	NPd	Pd	DOM	Auto	Other IM	
2006	Bertolini and Bevilacqua (2006)	1				1				
2007	Li et al. (2007)		1		1	1				
2007	Verma et al. (2007)	1				1				0,5
2007	Wang et al. (2007)	1			1	1				
2007	Zaeri et al. (2007)	1		1	1	1				
2008	Gaonkar et al. (2008	1				1				
2008	Dong et al. (2008)	1			1					
2008	Fazlollahtabar and Yousefpoor (2008)	1			1	1				
2008	Jafari et al. (2008)	1			1					
2008	Pariazar et al. (2008)	1		1	1	1				
2008	Reichelt et al. (2008)	1								
2008	Shyjith et al. (2008)	1			1	1				
2009	Ahmadi et al. (2009)	1		1	1		1			
2009	Ilangkumaran and Kumanan (2009)	1			1	1				
2009	Mousavi et al. (2009)	1		1	1	1				
2010	Ahmadi et al. (2010)	0,25			0,25				1	3
2010	Arunraj and Maiti (2010)	1			1					1
2010	Bashiri et al. (2010)	1	0,25		1	1				
2010	Cheng and Tsao (2010)	1								
2010	Ghosh and Roy (2010)	1			1					
2010	Ratnayaka and Markeset (2010)	1		1	1					1
2010	Vahdani et al. (2010)	1			1					

Appendix 4, Support table 3, 2011-2015 (2)

	Core method	TBM			CBM		IM			The rest	
YEAR	Specific method	TBI	AB	OM	NPd	Pd	DOM	Auto	Other IM		
2011	Momeni et al.	1		1	1	1					
2011	Nagar	1				1					
2011	Nezami and Yildirim	1			1			0,75			
2011	Peng and Wang	1			1	1					
2011	Peng and Wang	1			1	1					
2011	Gaonkar et al										
2011	Sarkar et al	1		1	1	1					
2011	Tajadod et al	1			1	1					
2011	Tan et al	1			1						
2011	Vahdani and Hadipour	1			1						
2012	Aghaee and Fazli	1			1	1		0,75			
2012	Chan and Prakash	1			1			0,75			
2012	Ding and Kamaruddin	1				1		1			
2012	Kumar and Maiti	1			1					1	
2012	Kushwash	1				1					
2012	Sadeghi and Alborzi-Manesh	0,25			0,75	0,75		0,75		1	
2012	Sarkar and Behera	1						0,75			
2012a	Shahin et al.	1			1		1	0,75			
2012b	Shahin et al.	1			1		1	0,75			
2012	Zaim et al	1				1					
2012	Fouladgar et al.	1		1	1			0,75			
2012	Ilangkumaran and Kumanan	1				1					
2013	Ierace and Cavalieri	1			1						
2013	Xie et al	1			1	1					
2013	Nezami and Yildirim	1			1			0,75			
2013	Braglia et al.	0,75			1	0,5	1				
2013	Ioannis and Nikitas	1			1	0,75					
2013	Jayaswal et al	1		1	1	1					
2013	Odeyale et al	1				1					
2013	Pourjavad et al	1			1		1	0,75			
2013	Rashidpour	1			1						
2013	Sagar et al	1		1	1	1					
2013	Thor et al.	1			1	1	1	0,75			
2014	Lazakis and Ölçer	1				1					
2014	Velmurugan and Dhingra	0,25			0,25	0,25					
2015	Kirubakaran and Ilangkumaran	1			1	1					

Appendix 4, Support table 4, 2016-2020 (3)

	Core method	TBM			CBM		IM			The rest
YEAR	Specific method	TBI	AB	OM	NPd	Pd	DOM	Auto	Other IM	
2016	Azadeh and Abdolhossein Zadeh	1	0,5	1	1					0,5
2016	Xia et al.	1			1					1
2017	Carnero and Gomez					1				
2017	Panchal et al.	1			1	1				
2017	Ge et al.	0,25			0,25	0,25				
2017	Zarei and Ghaedi-Kajuei	1		1	1	1				
2017	Özcan et al	1				1				0,75
2018	Shagluf et al.	1				1				
2018	Emovon et al.	1			1					
2018	Ivanov et al.	1			1	0,75				
2018	Hemmati et al	0,75			1					1
2018	Borjalilu and Ghambari	1			1	1				
2018	Dachyar et al.	1				1				
2018	Srivastava et al	1			1					
2018	Ohta et al	1				1				
2018	Fecarotti and Andrews	1		0,75		1				
2018	Seiti et al	1			1			0,75		
2019	Teng et al.									
2019	Asuquo et al.	1			1					
2019	Animah and Shafiee	1			1					
2019	Srivastava et al	1			1	1				
2019	Martin et al.	1			1	0,75		0,75		
2019	Shafiee et al	1			1					
2020	Galankashi et al.	1			1	1		0,75		
2020	Kurian et al.	1		0,5	1					
2020	Gedikli et al.	1		1				0,75		
2020	Mostafa and Fahmy	1		1	1	1				
2020	Aghaee et al.	0,75			1	1		0,75		

Core table 1, 2000 – 2005

Level / Methodology	Methodology	Total number of methodologies	Relative % of all sources
Strategy	RBM	1,25	0,13
	RCM	4,25	0,43
	TPM	3,75	0,38
	Other	1,50	0,15
Type	PM	8,75	0,88
	CM	8,75	0,88
	IM	4,00	0,40
Method	TBM	8,75	0,88
	CBM	10,00	1,00
	Other	1,00	0,10

Core table 2, 2006 - 2010

Level / Methodology	Methodology	Total number of methodologies	Relative % of all sources
Strategy	RBM	1,50	0,07
	RCM	3,00	0,14
	TPM	0,50	0,02
	Other	3,00	0,14
Type	PM	21,25	0,97
	CM	20,00	0,91
	IM	1,50	0,07
Method	TBM	20,25	0,92
	CBM	19,25	0,88
	Other	3,00	0,14

Core table 3, 2011 - 2015

Level / Methodology	Methodology	Total number of methodologies	Relative % of all sources
Strategy	RBM	1,50	0,04
	RCM	9,00	0,25
	TPM	12,00	0,33
	Other	0,00	0,00
Type	PM	33,25	0,92
	CM	33,00	0,92
	IM	9,75	0,27
Method	TBM	33,25	0,92
	CBM	34,00	0,94
	Other	2,00	0,06

Core table 4, 2016 - 2020

Level / Methodology	Methodology	Total number of methodologies	Relative % of all sources
Strategy	RBM	2,25	0,08
	RCM	12,25	0,44
	TPM	5,25	0,19
	Other	0,00	0,00
Type	PM	27,25	0,97
	CM	25,50	0,91
	IM	3,75	0,13
Method	TBM	24,75	0,88
	CBM	26,25	0,94
	Other	3,25	0,12

Support table 1, 2000-2005

Methodology	Method	Total number of methods	Relative % of all sources
TBM	TBI	8,75	0,88
	AB	2,00	0,20
	OM	2,00	0,20
CBM	NPd	7,00	0,70
	Pd	5,75	0,58
IM	DOM	1,75	0,18
	Auto	3,00	0,30
	Other IM	0,50	0,05
The rest	The rest	2,75	0,28

Support table 2, 2006-2010

Methodology	Method	Total number of methods	Relative % of all sources
TBM	TBI	20,25	0,92
	AB	1,25	0,06
	OM	5,00	0,23
CBM	NPd	16,25	0,74
	Pd	12,00	0,55
IM	DOM	1,00	0,05
	Auto	0,00	0,00
	Other IM	1,00	0,05
The rest	The rest	5,50	0,25

Support table 3, 2011-2015

Methodology	Method	Total number of methods	Relative % of all sources
TBM	TBI	33,25	0,92
	AB	0,00	0,00
	OM	5,00	0,14
CBM	NPd	26,00	0,72
	Pd	20,25	0,56
IM	DOM	5,00	0,14
	Auto	9,25	0,26
	Other IM	0,00	0,00
The rest	The rest	2,00	0,06

Support table 4, 2016-2020

Methodology	Method	Total number of methods	Relative % of all sources
TBM	TBI	24,75	0,88
	AB	0,50	0,02
	OM	5,25	0,19
CBM	NPd	19,25	0,69
	Pd	14,75	0,53
IM	DOM	0,00	0,00
	Auto	3,75	0,13
	Other IM	0,00	0,00
The rest	The rest	3,25	0,12

Appendix 7, SSF values and results

SSF values

Factor	2000 - 2005	2006 - 2010	2011 - 2015	2016 - 2020
Economic	5,00	14,00	18,00	16,00
Technical	4,00	13,00	16,00	16,00
Feasibility	3,00	10,00	12,00	12,00
Safety	1,00	9,00	10,00	13,00
Environmental	1,00	2,00	6,00	5,00
Social	0,00	0,00	2,00	4,00

SSF relative percentages

Factor	2000 - 2005	2006 - 2010	2011 - 2015	2016 - 2020
Economic	0,50	0,64	0,50	0,57
Technical	0,40	0,59	0,44	0,57
Feasibility	0,30	0,45	0,33	0,43
Safety	0,10	0,41	0,28	0,46
Environmental	0,10	0,09	0,17	0,18
Social	0,00	0,00	0,06	0,14

Appendix 8. Visions table and results

Date	Author	AR / VR	IoT	Decentralized	Digital twin	Artificial intelligence	AM
26/10/2022	Infraspeak team	1	1	1			
08/09/2018	Global electronic services inc.	1	1	1			1
06/01/2022	MaintenanceCare	0,5		0,5	1		
10/10/2022	StartUs-insights	1	1		1	1	
16/12/2022	Artesis	1	1			1	
12/07/2022	Prometheusgroup	1	1				1

Methodology	Total number of methods	Relative % of all sources
AR / VR	5,5	0,92
IoT	5	0,83
Decentralized	2,5	0,42
Digital twin	2	0,33
Artificial intelligence	2	0,33
AM	2	0,33