Meta-analysis of Knowledge Assets for Continuous Improvement of Maintenance Cost Controlling

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Abstract

Maintenance is a combination of multilateral and cross-functional activities and processes. Maintenance processes are identified in both strategic management and operation systems. Managers, engineers, technicians and operators collaboratively contribute in conducting and performing preventive or corrective maintenance activities. Maintenance management is to provide the long-term business strategy that ensures capacity of the production, quality of the product, and the best life cycle cost. It is a decision-making activity which has been highly correlated with expertise of maintenance staff and their own practical experience. Maintenance management intends not only to keep the desired performance of machinery, but to continuously improve quality and cost effectiveness of the pertained processes. Maintenance cost management (MCM), consisting of cost planning, monitoring and controlling, thereby is an essential part of the sustainable and efficient maintenance management system. MCM is determined as a knowledge-centered and experience-driven process where exploiting existing knowledge and generating new knowledge strongly influences every instance of cost planning. Taking into account the dynamics of knowledge assets, an interdisciplinary research raises practical implications in the domain of maintenance.

The key aspect of the present work is *learning from past experiences* for continuous improvement of the maintenance cost planning and controlling. Learning in MCM is an evolutionary and iterative process through which a chief maintenance officer (CMO) compounds and deepens his/her knowledge. CMO analyzes former experiences gained in the past maintenance planning periods, identifies facts or artifacts (i.e. evidence for improving the planning process), and finally enhances planning of the upcoming events by applying the lessons learned.

This work principally constitutes a model, *Costprove*, for meta-analysis of maintenance knowledge assets. The knowledge assets are articulated, represented, and stored in repositories (i.e. explicit knowledge), or remain with (a group of) individuals and need to be extracted, documented, and validated (i.e. implicit knowledge). Meta-analysis is a set of methods for discovering the strength of the relation between certain predefined entities. It provides evidence for decision-makers (e.g. CMO) to discover hidden improvement potentials in cost planning, and incrementally attain desired company objectives. The main focus of this work is to establish a mathematical meta-analysis for (i) identifying the relation between cost figures (planned, unplanned and total cost), and operation parameter (number of maintenance activities), and (ii) trading-off between planned and unplanned cost. Hence, the model deploys an economic approach for identifying desired cost figures in every planning period, and ultimately defining operation-related parameters.

Anticipating the trend of the fourth industrial revolution, the foremost result of this thesis is the development of an integrated and practice-oriented knowledge-based approach to maintenance cost planning and controlling.

Zusammenfassung

Instandhaltung ist eine Kombination aus multilateralen und bereichsübergreifenden Aktivitäten und Prozessen. Instandhaltungsprozesse bestehen sowohl aus strategischem Management als auch aus operativen Systemen. Manager, Ingenieure, Techniker und Anwender leisten gemeinsam Beiträge zur Administration und Durchführung präventiver oder wiederherstellender Instandhaltungsaktivitäten. Das Instandhaltungsmanagement dient dazu, für die langfristige Unternehmensstrategie zu sorgen, die die Produktionskapazitäten, die Produktqualität und die niedrigsten Lebenszykluskosten gewährleistet. Es handelt sich um eine Funktion der Entscheidungsfindung, die hochgradig mit der Expertise der Instandhaltungsmitarbeiter und ihren eigenen praktischen Erfahrungen verbunden ist. Das Instandhaltungsmanagement sorgt nicht nur dafür, die gewünschte Leistungsfähigkeit des Maschinenparks zu gewährleisten, sondern verbessert kontinuierlich die Qualität und Kosteneffektivität der betreffenden Prozesse. Das Instandhaltungskosten-management (MCM), bestehend aus Kostenplanung, -überwachung und -steuerung, ist somit ein wesentlicher Bestandteil eines nachhaltigen und effizienten Instandhaltungsmanagementsystems. MCM ist als wissenszentrierter und erfahrungsgetriebener Prozess zu verstehen, bei dem die Nutzung vorhandenen und die Generierung neuen Wissens jedes Element der Kostenplanung maßgeblich beeinflusst. Unter Einbeziehung der Dynamik der Wissensbestände erhöht ein interdisziplinärer Forschungsansatz die praktische Relevanz im Bereich der Instandhaltung.

Der Schlüsselaspekt der vorliegenden Arbeit ist „aus Erfahrungen lernen“ mit dem Ziel einer kontinuierlichen Verbesserung der Instandhaltungskostenplanung und -kontrolle. Lernen im Instandhaltungskostenmanagement ist ein evolutionärer und iterativer Prozess, durch den der „Chief Maintenance Officer“ (CMO) sein Wissen verknüpft und vertieft. Der CMO analysiert bisherige Erkenntnisse, die in den vergangenen Planungsperioden erworben wurden, identifiziert Fakten oder Hypothesen (z.B. Bestätigungen für die Verbesserung des Planungsprozesses) und verbessert schließlich die Planung des zukünftigen Geschehens durch die Umsetzung des Erlernten.

In dieser Arbeit wird insbesondere ein Modell, *Costprove*, für die Meta-Analyse von Instandhaltungswissen entwickelt. Die Wissensbestände sind artikuliert, dargestellt und abgespeichert (explizites Wissen) oder befinden sich bei Personen und müssen extrahiert, dokumentiert und validiert werden (impliziertes Wissen). Meta-Analyse ist ein Methodenpaket zur Entdeckung der Stärke der Beziehung zwischen bestimmten vordefinierten Objekten. Es liefert den Entscheidern (z.B. CMO) Hinweise, verdeckte Verbesserungspotentiale bei der Kostenplanung zu finden und schrittweise die gesteckten Unternehmensziele zu erreichen. Der Hauptfokus dieser Arbeit liegt darauf, eine mathematische Meta-Analyse zu erzeugen, die 1. das Verhältnis zwischen den Kostenarten (geplante, ungeplante, gesamte Kosten) und den Handlungsparametern (Zahl der Instandhaltungsaktivitäten) identifiziert und 2. geplante und ungeplante Kosten optimiert. So stellt das Modell einen wirtschaftlichen Ansatz zur Identifizierung der gewünschten Kostengrößen in jeder Planungsperiode bereit und definiert abschließend die damit zusammenhängenden operativen Parameter.

Den Trend der vierten industriellen Revolution vorwegnehmend, besteht das Hauptergebnis dieser Dissertation in der Entwicklung eines integrierten und anwendbaren wissensbasierten Ansatzes zur Instandhaltungskostenplanung und -kontrolle.

Declaration of Honor

I hereby confirm on my honor that I personally prepared this dissertation entitled Meta-analysis of Knowledge Assets for Continuous Improvement of Maintenance Cost Controlling, and carried out myself the activities directly involved with it. I also certify that I have used no resources other than those cited according to the rules for academic work, and which I have identified by means of precise indications of source or footnote.

This work has successfully passed a plagiarism review using the plagiarism finding tool Docoloc.

This academic work has not been submitted to any other examination authority and is submitted in both printed and electronic form. I confirm that the content of the digital version is completely identical to that of the printed version.

I am aware that any false declaration will have legal consequences.

Signature: Fazel Ansari Siegen, 28.07.2014

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List of Abbreviations

BCM	Business-centered maintenance
CAO	Chief accounting officer
CEO	Chief executive officer
CM	Corrective maintenance
CME	Chief maintenance engineer
CMMIS	Computerized maintenance management information system
CMO	Chief maintenance officer
Costprove	Two-level maintenance cost controlling system for continuous learning and improvement in MCM
ERP	Enterprise resource planning
KIBP	Knowledge-intensive business process
KM	Knowledge management
KPI	Key performance indicator
MaE	Maintenance engineering
MaM	Maintenance management
MBM	Maintenance budget management
MCM	Maintenance cost management
PM	Preventive maintenance
RCM	Reliability centered maintenance
TLC	Total life cycle cost strategy
TPM	Total productive maintenance
VDM	Value-driven maintenance

Introduction

In today's industry, maintenance is an integral part of the production strategy subject to periodic, predictive, and corrective maintenance (CM) of the machineries, equipment and physical assets. The German Machine Tool Builders' Association (VDW)[1] reported the annual cost of more than €12 billion for installation, repair and maintenance of machine tools (VDW, 2012). In typical manufacturing companies, maintenance costs are between 15% and 40% of the total cost of production (Wireman, 2014). The potential to reduce or optimize maintenance cost is about 10-20%; including the material and labor cost (Pawellek, 2013). Effective cost saving and controlling ultimately influences economy of production and profit. The studies confirmed that reducing maintenance cost by between 3.5-16%, while keeping production costs the same, leads to an increase in pre-tax profits of between 2.8-14% (Wireman, 2014). So management (i.e. planning, monitoring and controlling) of budget and expenditures is essential for the overall success of companies. According to (DIN, 2010-12), maintenance cost management (MCM) should be seen from both operational and strategic perspectives. The participants of the cost management program are not only limited to labor and engineers, but also senior managers and chief engineers (i.e. chief maintenance officer (CMO), chief maintenance engineer (CME), plant manager) and top management of the company are responsible.

To respond to the demand on improving cost effectiveness and efficiency of maintenance, management concepts and systems such as total productive maintenance (TPM), reliability centered maintenance (RCM), total life cycle cost strategy (TLC) and lean maintenance have been established. Such efforts intend to develop, implement and utilize comprehensive maintenance programs in both operational and strategic level as well as maintenance management information systems.

Despite the advantages, maintenance management concepts mainly deal with conducting work orders, planning, and monitoring associated cost and required budget using classic methods of accounting. Literature of maintenance includes several sophisticated models formulated by the researchers for improving cost management process. Surely the impact and importance of such models should be acknowledged. However, continuous improvement of MCM is tailored to the use of knowledge assets of the maintenance. In particular, maintenance management systems and processes are knowledge-driven. They use, produce, and store knowledge. Explicit knowledge is stored in repositories as documented entities. Maintenance practitioners hold implicit knowledge as hard/soft competencies, skills, and experiences which are in a different quality level based on intelligence and creativity of (group of) individuals. These explicit or implicit types of knowledge are the main intellectual capital of organizations.

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[1] Verein Deutscher Werkzeugmaschinenfabriken (VDW).

The goal of this dissertation is to integrate knowledge-based approaches for continu-continuous improvement of maintenance cost controlling. Specifically, the key aspect is to learn from the experiences of the past cost planning period (t) and accordingly improve the forthcoming maintenance event ($t+1$). The meta-analysis is used to identify the strength of the relation between cost and operation parameters for planning maintenance activities. The cost parameters are defined as planned, unplanned and total cost and the operation parameter is the number of maintenance activities. Planning starts with defining the cost parameters based on analysis of past experiences (i.e. historical records and reports of former planning periods) and consideration of a company's goal (i.e. budget). It follows by calculating the minimum of total cost, and finally defining optimum number of maintenance activities. In the controlling phase, attainment of the predefined goals is examined through an analysis of deviation between actual and desired values. This leads to the identification of facts or artifacts that should be further explored for improving the upcoming planning period ($t+1$). Therefore the entire planning-monitoring and controlling activities should be seen as a learning process. To reach this goal, a novel model, *Costprove*[2] is constituted through an interdisciplinary research. The results are reflected in four chapters.

Chapter 1 surveys the state of the art in MCM. It discusses definitions and basics such as maintenance management concepts, and maintenance cost planning and controlling, including budget management, maintenance organization and knowledge assets. The extensive literature review and morphological analysis examine cost models which appeared in the literature of maintenance, especially in the domain of production systems and physical assets. The findings of the literature survey establish the characteristics of *Costprove* model.

Chapter 2 discusses the development of *Costprove,* first the mathematical reference model and second the quantitative model, including guidelines and algorithm for applying *Costprove*. The model is studied in a use-case application.

Chapter 3 presents the results for the implementation and realization of the *Costprove* Toolbox. First, a review on features, functionalities and constraints of a computerized maintenance management information system (CMMIS) is given. It includes study of commercial software packages. Second, the *Costprove* is verified through needs analysis with maintenance professionals. Third, the *Costprove* Toolbox is designed and finally the prototypes are presented.

Chapter 4 summarizes the key findings of the dissertation, examines open issues and foresees potentials for future research.

Figure 1 visualizes the structure of the dissertation and relations between chapters and sections.

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[2] Two-level maintenance cost controlling system for continuous learning and improvement in MCM.

Fig.1. Structure of the thesis and content of the chapters.

1 State of the Art in Maintenance Cost Management (MCM)

1.1 Maintenance Management Concepts: Definitions and Basics

Maintenance is a combination of technical, administrative and management activities including supervision actions for keeping a desired functional status of an observation unit during its life cycle (DIN, 2010-12). Maintenance actions are therefore intended to retain an observation unit (entity) in, or restore it to a required functional state (Rausand, et al., 2003), (IEC, 1990). An observation unit may refer to any component, equipment, subsystem or in a broader perspective any functional unit, resource or system (Strunz, 2012), (DIN, 2010-12).

The desired functional status is defined using standard measures, especially *Availability*[3] (Rausand, et al., 2003), (Dhillon, 2002). **Availability** is "the ability of an item […] to perform its required function at a stated instant of time or over a stated period of time" (BS, 1991 (Confirmed on 2012)), (Rausand, et al., 2003). It is a function of (a) inherent reliability, (b) maintainability, and (c) maintenance support (Rausand, et al., 2003).

Reliability is "the probability that an item will perform its stated mission satisfactorily for the given time period when used under the specified conditions" (Dhillon, 2002). To comply with desired reliability, engineering expertise should be applied to identify and manage risk factors (Mobley, 2008).

Maintainability is "the ability of the item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources" (BS, 1991 (Confirmed on 2012)), (Rausand, et al., 2003). Maintainability of an item is a design parameter. It is aimed to "reduce repair time, as opposed to maintenance, which is the act of repairing or servicing an item or equipment" (Rausand, et al., 2003), (Dhillon, 2002), (Smith, et al., 1973).

Maintenance support depends on availability as well as quality of several influential factors such as tools, spare parts, skill and expertise of maintenance personnel, and technology support, including information technology (Pawellek, 2013), (Strunz, 2012), (Mobley, 2008).

The fundamental background and mathematical representation corresponding to availability, reliability and maintainability is discussed by several authors like (Pfeifer, 2002), (Dhillon, 2002), (Rausand, et al., 2003), (Jardine, et al., 2005), (Mitchell, 2006), (Wang, et al., 2006), (Mobley, 2008), (Ben-Daya, et al., 2009).

Maintenance activities/tasks are classified in different ways in the literature. The most common classifications are based on occurrence of failure. As shown in Figure 2, the

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[3] It is also addressed as "Dependability" by some authors and standards (Rausand, et al., 2003).

major types of maintenance are **Preventive Maintenance (PM)** and **Corrective Maintenance (CM)**[4].

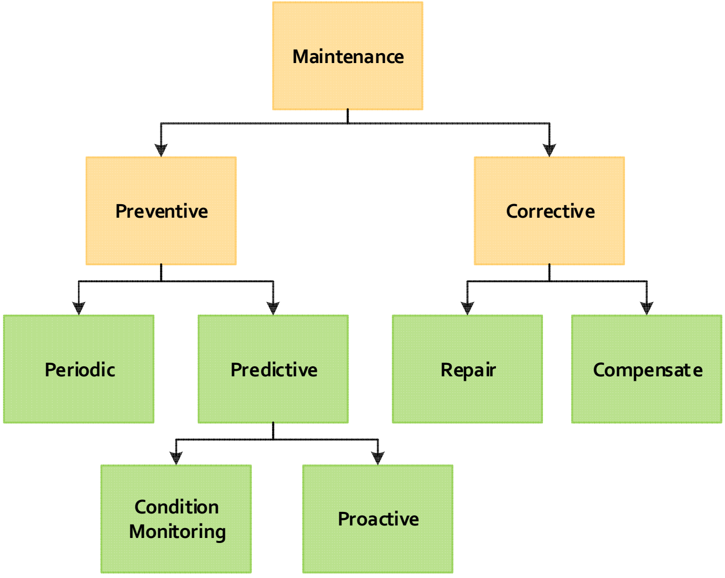

Fig.2. Types of maintenance – Adopted by the author from the content of (Rausand, et al., 2003).

PM is all maintenance actions carried out on a basis of planned, periodic, specific schedule, proactive or predictive to keep an item/equipment in stated/desired working condition through the process of checking, monitoring and reconditioning. Particularly the sub-tasks of PM can be categorized as periodic or predictive (Gross, 2006), (Ben-Daya, et al., 2009).

Periodic maintenance is related to ***Age-based*** or ***Clock-based maintenance*** activities (Rausand, et al., 2003). The former refers to "the tasks that are carried out at a specific age of the item" (Rausand, et al., 2003). In this case, age is measured, for example, on the basis of time in operation (Rausand, et al., 2003).The latter concerns with the tasks carried out on the basis of schedules at predefined calendar times (Rausand, et al., 2003).

Predictive maintenance deals with "measurement of one or more condition variables of the item" (Rausand, et al., 2003). Therefore, it is also called as ***Condition-based***

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[4] This is a mutual classification pointed out by several authors such as, but not limited to, (Dhillon, 2002), (Rausand, et al., 2003), (Jardine, et al., 2005), (Gross, 2006), (Mobley, 2008), (Ben-Daya, et al., 2009).

maintenance by several authors such as (Rausand, et al., 2003), (Mobley, 2008), (Veldman, et al., 2011a), (Veldman, et al., 2011b), and (Prajapati, et al., 2012).

Predictive maintenance "uses regular evaluation of the actual operating condition of plant equipment, production systems, and plant management functions to optimize total plant operation" (Mobley, 2008). It takes a life cycle perspective with regards to maintenance. In this context, "maintenance is initiated when a condition variable approaches or passes a threshold value" (Rausand, et al., 2003). Examples of condition variables are vibration, temperature, etc. The monitoring is applied through using sensors and condition-monitoring systems (Marwala, 2012), inspection, test/analysis on the basis of continuous or regular intervals (DIN, 2010-12), (Rausand, et al., 2003).

Besides, ***Proactive maintenance*** enhances PM deploying failure root-cause analysis. It is intended to gather feedback and accordingly improve design, workmanship, installation, scheduling, and maintenance procedures, i.e. continuous improvement of maintenance programs. In addition, it applies periodical and regular "evaluation of the technical content and performance interval of maintenance tasks" (Dhillon, 2002).

In sum, PM is employed to:

(a) Forestall and reduce the probability of the failure (Rausand, et al., 2003).

(b) Regulate unacceptable degradation level of the observation unit in the forthcoming service (Dhillon, 2002).

(c) Optimize planned maintenance actions, i.e. time and cost-effective maintenance (Mobley, 2008).

(d) Eliminate unplanned maintenance actions, i.e. the requirement for unplanned repairs of an observation unit, and associated costs (Mobley, 2008).

Hence PM processes collect data, especially corresponding equipment effectiveness, reliability, maintainability, and operating costs (Mobley, 2008).

CM is carried out after the occurrence of a failure or recognizing the deficiency of an item/equipment (Dhillon, 2002), (Rausand, et al., 2003), (Mobley, 2008). The target is to shortly bring the observation unit (item/equipment) back into functioning/defined state (Dhillon, 2002), (Rausand, et al., 2003). It is also called ***Breakdown maintenance*** or ***Run-to-failure maintenance*** (Rausand, et al., 2003). CM tasks can be classified into two major categories as repair and compensating (cf. Figure 2).

Repair refers to set of activities which are selectively carried out, depending on suitability, to restore a failed item to its operational/defined state. These activities can be demarcated as (Dhillon, 2002):

(a) Replacement of a redundant item

(b) Salvage i.e. disposal of non-repairable materials

(c) Rebuild i.e. complete disassembly, checking, repair and re-assembly of defected item

(d) Overhaul i.e. inspect and repair only as appropriate

(e) Servicing e.g. refilling of a repaired crankcase

Compensating is to switch the failed item in a redundant item or standby unit with a viable replacement or working alternative, and consequently adjust the effect of the failure for a limited time (Rausand, et al., 2003).

Quality of PM or CM tasks/activities is evaluated as *perfect*, *minimal*, *imperfect*, *worse* or *worst*, based on the restoration degree of the failed item (Wang, et al., 2006). The aforementioned expressions are defined as (Wang, et al., 2006):

(1) **Perfect repair/maintenance** → Restore a system to operating condition *'as good as new' (*system).

(2) **(Physical) Minimal repair** → Restore a system to the state before the occurrence of failure (same failure rate).

(3) **Imperfect repair/maintenance** → Restore a system *'not as good as new but younger'* (system).

(4) **Worse repair/maintenance** →Restore a system which inadvertently (accidentally) causes higher failure rate or decreases the life span.

(5) **Worst repair/maintenance**→ Attempts to restore a system which inadvertently (accidentally) makes the system fail or break down.

In the hierarchical perspective of maintenance organization, activities/tasks are classified as first operational, and second strategic. The former refers to *Maintenance Engineering* (MaE), and the latter to *Maintenance Management* (MaM). MaE is defined as "a staff function whose prime responsibility is to ensure that maintenance techniques are effective, equipment is designed and modified to improve maintainability, ongoing maintenance's technical problems are investigated, and appropriate corrective and improvement actions are taken" (Mobley, 2008). So the objectives of MaE include:

(1) "Improve maintenance operation,

(2) Reduce the amount and frequency of maintenance,

(3) Reduce the effect of complexity,

(4) Reduce the maintenance skills required,

(5) Reduce the amount of supply support, and

(6) Improve and ensure maximum utilization of maintenance facilities" (Dhillon, 2002), (Wang, et al., 2006).

Maintenance engineers are basically trained as physical scientists, and thus they need to be further trained to empirically analyze the problems and apply decision-making procedures (Fei, 2008). The quality of decisions is directly influenced by:

(1) "Clear definition of alternatives,

(2) Identification of aspects common to all alternatives (which then become irrelevant),

(3) Establishing appropriate viewpoint and decision criteria, and

(4) Considering consequences and their measurability" (Fei, 2008).

MaM is to provide the long-term business strategy that "ensures production capacity, product quality, and [the] best life cycle cost" (Mobley, 2008). It is a decision-making activity which has been highly correlated with expertise of maintenance staff and their own practical experience. Taking into account a large number of decision criteria and preferences, it is vital to choose the "best" strategy at the "best" possible time and "optimum" cost. Hence, the main objectives of MaM are provision of:

(1) Leadership and management

(2) Single point accountability, i.e. clear definition of the responsibilities of maintenance workers and related interactions

(3) Knowledge asset management, i.e. required technical expertise, know-how and related technologies as well as skills and competency of maintenance personnel

(4) Risk management

(5) Life cycle asset management

(6) Life cycle cost and budget management

The ultimate goal is to "achieve and sustain optimum reliability, maintainability, useful life, and life cycle cost for a facility's asset, as well as its processes" (Mobley, 2008).

In this dissertation, the main focus is on MaM and bilateral implications of MaM and MaE. In particular the concentration is on managing and controlling of the maintenance cost of production machines/equipment, using maintenance knowledge assets. The goal is to provide evidence for consistent decision-making on effective costing and allocation of budget. In the text, the strategic body of maintenance is referred to MaM and the operational to MaE.

In the literature of MaM several management concepts can be detected, particularly TPM, RCM, TLC, lean maintenance, and knowledge-based maintenance (Pawellek, 2013).

TPM[5] is "a comprehensive, life cycle approach, to equipment management that minimizes equipment failures, production defects, and accidents. It involves everyone in the organization, from top level management to production mechanics, and production support groups to outside suppliers" (Mobley, 2008). The main objective of TPM is to "continuously improve the availability and prevent the degradation of equipment to achieve maximum effectiveness" (Mobley, 2008). In this way, the strong engagement and support of management and maintenance workers is required, especially to guarantee the attainment of the incremental improvement (Mobley,

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[5] The concept of TPM and its barriers are discussed by several authors such as (Nakajima, 1988), (Suzuki, 1992a), (Suzuki, 1992b), (Dhillon, 2002), (Rausand, et al., 2003), (Wireman, 2004), (Kelly, 2006), (Ahuja, et al., 2008), (Mobley, 2008), (Ben-Daya, et al., 2009), (Attri, et al., 2012) and (Pawellek, 2013).

2008). TPM involves all departments associated with or benefitted from, namely maintenance, operations, plant/site management, design, engineering, project management, construction engineering, inventory and stores, purchasing, accounting and finance (Wireman, 2004). Considering different organizational structure (work breakdown), the aforementioned associated departments and beneficiaries may differ. Proper implementation of TPM results in improvement of equipment and maintenance effectiveness, early stage PM, training knowledgeable maintenance workers, and involving operators in routine maintenance (Wireman, 2004), (Pawellek, 2013).

TPM was created in the early 1970s in Japanese manufacturing companies, primarily Toyota-based companies (Nakajima, 1988), (Kelly, 2006), (Pawellek, 2013). It was established in response to the needs of total quality management (TQM) and just-in-time manufacturing (JIT) (Kelly, 2006). The first concept of TPM was given by Suzuki (Suzuki, 1992a), (Suzuki, 1992b). Later TPM was developed and implemented in England, United States and the European states (Kelly, 2006), (Pawellek, 2013). In Germany, it took until the 1990s, when single companies implemented productivity-based maintenance (Röben, 1997), (Barlage, 2005), (Pawellek, 2013). Since 2000, the sustainability requirements/goals have raised new demands for maintenance, particularly in the area of asset management. The life cycle perspective to maintenance is highly recognized, for example, in terms of selection of maintenance/repair-friendly machines (Martens, et al., 2005), (Pawellek, 2013).

RCM[6] is “a systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective PM tasks” (Crellin, et al., 1988), (Rausand, et al., 2003). Its objective is “to ensure that any physical facility is able to continuously meet its designed functions in its current operating context” (McKenna, et al., 1997), (Dhillon, 2002). RCM includes PM (i.e. periodic, proactive and predictive maintenance) and CM (i.e. run-to-failure maintenance and fix-when-fail) (Dhillon, 2002), (Mobley, 2008).

The concept was developed and implemented in the 1970s, mainly in the aircraft industry, the military forces, the offshore oil and gas industry, and later in many other industries (Rausand, et al., 2003), (Dhillon, 2002). In comparison with TPM, RCM has better shaped and structured, i.e. “the literature presents TPM as more of an amorphous concept than RCM” (Hipkina, et al., 2000). Coexistence of RCM and TPM is advantageous, i.e. implementing RCM within the framework of TPM (Ben-Daya, 2000), (Ahuja, et al., 2008). The reason is underlying considerable effect of RCM on overall efficiency and enhancement of PM. “RCM offers a sound framework for optimizing the maintenance effort and getting the maximum out of the resources committed to the PM program” (Ben-Daya, 2000).

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[6] The fundamental aspects of RCM concept and its constraints are described and elaborated by several authors such as (Nowlan, et al., 1978), (Crellin, et al., 1988), (McKenna, et al., 1997), (Dhillon, 2002), (Rausand, et al., 2003), (Mobley, 2008), (Ben-Daya, et al., 2009), and (Pawellek, 2013).

TLC is a comprehensive concept to MaM particularly for planning and monitoring maintenance cost of the plant (Pawellek, 2013). It takes into account the maintenance/service cost associated with the asset life cycle (Pawellek, 2013). The objective is to eliminate the gap between determination/estimation of ownership cost and actual expenditures through the asset life cycle (Röben, 1998), (Pawellek, 2013). Thus, it considers all associated life cycle costs such as cost of engineering/construction, operation, maintenance, production, and disposal.

In this context, **business-centered maintenance (BCM)** approach is noticeable. BCM is " a framework of guidelines for deciding maintenance objectives, formulating equipment life plans and plant maintenance schedules (Maintenance Planning), designing the maintenance organization (Maintenance Doing) and setting up appropriate systems of documentation and control (Maintenance Control)" (Kelly, 2006). As shown in Figure 3, BCM consists of the basic steps of the management process. It is concerned with (1) managerial endeavors for understanding each function of maintenance (e.g. cost management), (2) determination of objectives, (3) establishment of plans to achieve the objectives, (4) building an organization to carry out the plan, and (5) analysis of feedback (Kelly, 2006). The steps are applied iteratively to comply with desired objectives. In particular, the process is initiated and developed in steps 1-4. Afterwards, feedback should be gathered to check whether the plan and organization are meeting the objectives and to detect improvement potential (Kelly, 2006).

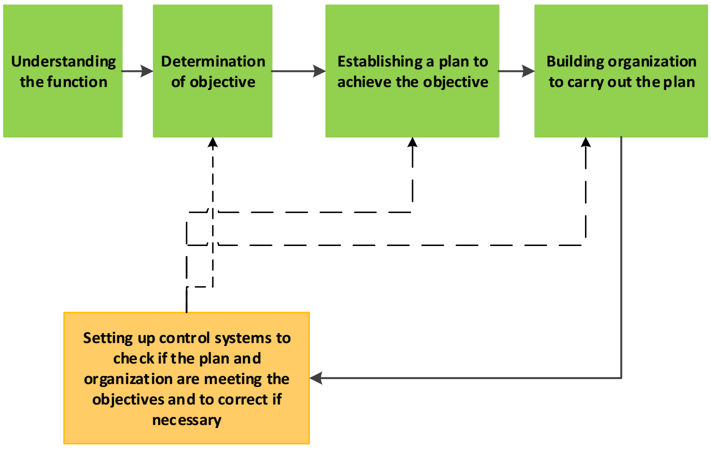

Fig.3. Basic steps of the management process in BCM- sketched by the author from the original source (Kelly, 2006).

Lean maintenance is a part of the lean management philosophy (Nicholas, 2011), (Pawellek, 2013). The characteristics of lean management are reflected in the concept of "Lean Maintenance" (Pawellek, 2013). Lean management is based on a premise that the survival and the success of a company/organization depend on "its ability to continuously improve its product and services to meet and exceed customer demands" (Nicholas, 2011). Otherwise the company is limited in its flexibility and cannot react quickly enough to a rising of product variety and market change conditions requested by the customer (Pawellek, 2013). The lean management is derived from the concept of continuous improvement (Nicholas, 2011), and the Kaizen theory of incremental improvement (Imai, 2002). The measure to achieve continuous improvement is to produce and manage things better, faster, cheaper and with more agility (Nicholas, 2011). This implies the need for flattening hierarchies and a process-oriented alignment of all business activities (Pawellek, 2013). Maintenance, as a business-centered activity, is highly concerned and influenced by lean management philosophy. In particular, lean maintenance reallocates work orders and breaks down the maintenance activities (Pawellek, 2013). For example, integrating maintenance activities in the area of production can eliminate maintenance cost, especially when the operators can handle routine maintenance and take the responsibility of their machines (Pawellek, 2013). This can be applied to asset management as well. The alignment to lean maintenance should be sustained through appropriate training and organization of the staff (Pawellek, 2013).

Knowledge-based maintenance assumes that competitive advantages for reducing maintenance cost is achieved through holistic consideration, rather than atomistic, of all influential components and gaining knowledge of maintenance (Sturm, 2001), (Reiner, et al., 2005), (Pawellek, 2013). It takes into account long-term effects of maintenance policies and decisions on economic terms (Pawellek, 2013). So the major focus is on analyzing maintenance as a non-isolated sub-domain which influences on organizational value creation (Pawellek, 2013). The further objective is to develop a rough (generic) concept for the optimization of maintenance (Pawellek, 2013). In this model, maintenance knowledge is created through comprehensive consideration of maintenance consequences, system condition, and organization / processes (Sturm, et al., 2001), (Pawellek, 2013). These processes distinctively gather operational knowledge (i.e. the combination of data and information such as reports in databases). The acquired knowledge is then transmitted to three areas that provide overall strategies of maintenance (i.e. risk-based maintenance, condition/time-based maintenance, and TPM and lean maintenance). All the outcomes are considered in a unified way (Pawellek, 2013).

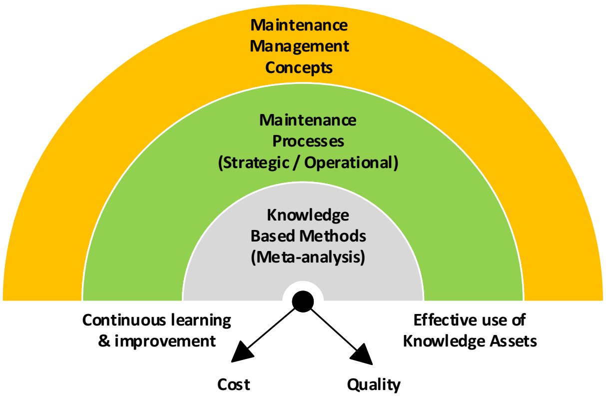

Fig.4. Knowledge-based approach to maintenance for continuous improvement.

Although the aforementioned approach to knowledge-based maintenance is comprehensive, it only reveals the relation between several management approaches without indicating the logics of the relation, and the extent of deploying or producing knowledge. Moreover, no mechanism for acquisition, modeling, and representation of the knowledge is proposed. The types and homogeneities of knowledge assets have not been discussed. Hence, one cannot justify using or employing the model for improving MaM. It is only valuable in the context of conception of maintenance and defining required components.

In the perspective of computer science, knowledge-based maintenance should necessarily hold principles of knowledge-based systems (KBS) and pertained approaches (Russell, et al., 2010), (Beierle, et al., 2008). In this dissertation, knowledge-based maintenance is defined as an integrated framework for meta-analyzing knowledge assets (cf. sub-section 1.2.3) through learning from the past events and experiences, and improving forthcoming events (Ansari, et al., 2012b), (Ansari, et al., 2014a). This especially addresses the provision of proper evidence for maintenance managers to improve quality of decisions (Ansari, et al., 2014a). The purpose of this work is to employ meta-analysis of knowledge assets for improving maintenance cost controlling, and ultimate quality of maintenance processes (cf. Figure 4). Therefore, there is a certain difference between premises of this work and existing approaches in the literature named as knowledge-based maintenance. The foundations of this approach are further discussed in the following sub-sections, and later elaborated in Chapter 2 and 3.

1.2 Maintenance Cost Planning and Controlling

Planning, monitoring and controlling are equally important to manage business processes such as maintenance. These are associated with efficient use of physical resources and personnel, continuous performance improvement of practitioners and processes, and finally sustaining organizational goals. Notably "the cost of maintaining equipment often varies from two to 20 times the acquisition cost" (Dhillon, 2002). So effective planning and efficient controlling is required to increase the accuracy of planning, and detect improvement potentials for the forthcoming planning period. MCM is a function of MaM with a focus on plan, administer, monitor and control of the maintenance cost life cycle, i.e. the entire process encompasses costs and budget, and their impact and implications on production profit (Lamb, 2009), (Levitt, 2009), (Mirghani, 2009), (Dhillon, 2002).

Planning, monitoring and controlling processes "require identifying specific activities, responsibilities, and indicators for testing **efficiency** and **effectiveness**" (Franceschini, et al., 2007). Efficiency is basically defined as doing things right, whereas effectiveness is concerned with doing the right things (Franceschini, et al., 2007). "Efficiency means getting the most (output) from resources (input), whether they are people or products" (Franceschini, et al., 2007). On the other hand, "effectiveness means setting the right goals and objectives, and making sure they are properly accomplished" (Franceschini, et al., 2007). Effectiveness is mainly result-oriented; thereby it is measured by comparing the achieved results with target objectives (Franceschini, et al., 2007). Efficiency is process-oriented whereby it is concerned with links between process performances and the employed resources (Franceschini, et al., 2007). In order to plan, monitor and control MCM activities, the focus is on two principal objectives. Firstly, ***process quality*** deals with the efficiency of MCM processes. Secondly, ***product quality*** subject to the effectiveness of the MCM processes. Efficiency and effectiveness are validated by using *metrics* and *indicators*. Some authors distinguish between these two terms. In general, metrics are quantitative information that is processed for the specific needs of the business analysis and control (Hilgers, 2008). They are characterized by being able to represent a situation in a concentrated form (Hilgers, 2008). In contrast, indicators imply an indirect measurement approach and do not map facts which could be measured directly (Hilgers, 2008).[7] Considering various accounts, in this dissertation the term measure is used to refer to metrics or indicator.

In order to define MCM measures, the cost attributes of maintenance should be identified. There are various accounts on defining and classifying maintenance cost attributes which are studied in this section.

According to maintenance literature, cost attributes are generally listed as:

(1) Direct costs

(2) Lost production/opportunity costs

(3) Degradation costs

(4) Standby costs

Maintenance cost attributes are classified into two major categories; *Direct* and *Indirect cost.* In this paradigm, direct costs are associated with “keeping the equipment operable and include costs of periodic inspection and PM, repair cost, overhaul cost, and servicing cost” (Dhillon, 2002). Direct costs also cover the labor and material expenses needed to implement maintenance actions.

Indirect costs are related to:

- Loss of production due to primary equipment breakdown and unavailability of standby equipment, and lost opportunities in uptime, rate, yield, and quality due to non-operating or unsatisfactorily operating equipment.
- Deterioration in the equipment life due to unsatisfactory/inferior maintenance, which raises costs to the safety of people, property, and the environment.
- Operating and maintaining standby equipment.[8]

Besides, Hahn and Laßmann defined, **planned** and **unplanned** cost as the major cost attributes (Hahn, et al., 1993). In this paradigm, the total maintenance cost is

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[7] This paragraph is adopted from the contribution of the author in (Nasiri, et al., 2013)

[8] The cost attributes are extracted and categorized by the author, based on reviewing of MCM literature such as: (Hastings, 2010), (Levitt, 2009), (Mirghani, 2009), (Dhillon, 2002), (McKenna, et al., 1997), (Niebel, 1994) and (Cavalier, et al., 1996).

calculated as the summation of planned and unplanned maintenance cost (Hahn, et al., 1993). It comprises the planned cost of downtime, inspection, or repair, and unpredicted downtime, including failure and repair costs, and loss of contribution margin in case of a bottleneck (Hahn, et al., 1993). Figure 5 depicts the concept of the cost model (cost/benefit ratio), where the total maintenance cost (K_I) is interpreted through indication of planned (K_{VI}) and unplanned maintenance costs (K_S) for a single production machine as: $K_I = K_{VI} + K_S$. The argument (n) implies the intensity of maintenance activities in a certain period, that on the one hand influences the planned maintenance operations cost, and on the other, the unplanned maintenance operations cost in that period. In other words, (n) indicates proceeding of PM activities to optimize planned and unplanned maintenance cost. Since the unplanned cost function is non-linear and planned cost function is linear, the summation curve is expected to have a single (global) minimum that reveals the optimum number of maintenance activities (n_{opt}) for a single production machine in the certain planning period (e.g. per month). This optimum is directly associated with the minimum of total maintenance cost $(K_{I_{min}})$ of a single production machine in the corresponding maintenance costing period. Similar approaches to the cost model of Hahn and Laßmann (1993) are detected in earlier references, e.g. (Tempest, 1976) and (Newbrough, 1967). Later, the trade-off curve (cf. Figure 5) is discussed underlying the framework of TPM, e.g. by (Wireman, 2004), (Mobley, 2008), (Stevenson, 2012). The model is a prevailing theory, arguing that "as the planned maintenance goes up, the unplanned maintenance (breakdown) goes down, and [consequently] the total maintenance costs goes down as a result [before reaching the minimum]" (Mobley, 2008). This cost model is also examined as a basis for estimating total cost of reliability (Fei, 2008).

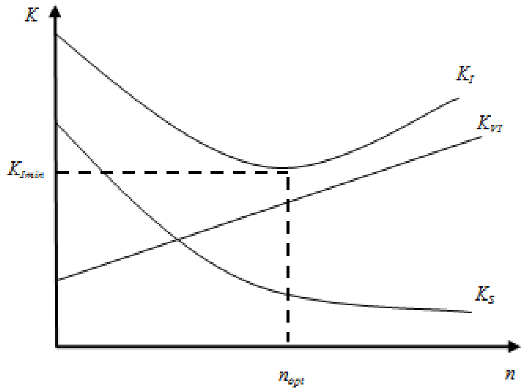

Fig.5. The trade-off curve of Hahn and Laßmann for MCM based on the indication of planned and unplanned cost (Hahn, et al., 1993).

The paradigm constituted by Hahn and Laßmann (1993) emphasizes the desired goal of MCM. It coherently puts the ***"planning-monitoring-controlling"*** challenge or gap of MCM into the foreground. The reason is the synoptic (ideal) characteristics of the model to direct the optimal relation between n_{opt} and $K_{I_{min}}$. It in turn is used as a basis of comparison for the current and desired state of MCM. The need to cover this gap is also the core objective of the BCM methodology (Kelly, 2006). In fact, planned and unplanned costs cover both aforementioned categories of direct and indirect cost. In contrast to the paradigm of Hahn and Laßmann (1993), classifying and analyzing cost attributes as direct and indirect only addresses the *causes* of maintenance expenses. It could not be clearly interpreted in terms of *expected* or *predicted effects* on maintenance actions and associated expenditures. In this dissertation, therefore, the model of Hahn and Laßmann (1993) is used as a basis for identification of cost attributes and development of MCM measures for bridging the gap of planning-monitoring-controlling.

As discussed earlier, monitoring is to determine whether all planned or pre-assigned objectives or goals are fulfilled or not. So it is to examine the current situation based on the captured data from the past event. In controlling, both planning and monitoring are integrated, and effective use of the intellectual capital of maintenance (i.e. data, information, and explicit/implicit knowledge) is vital. In other words, planning requires knowing what is happening, while controlling is to seek improvement potentials, i.e. knowing what has happened and what the deficiencies are. There are several factors influencing planning-monitoring-controlling such as (but not limited to) "asset condition (i.e. age, type, and condition), operational expertise and experience, company policy, type of service, skills of maintenance personnel, operational environment, equipment specification, and regulatory controls" (Levitt, 2009). Since the aim of planning is to estimate and shape future events based on the currently derived knowledge, the mentioned factors and several more, depending on each use-case scenario, should be extensively considered.

In summary, classifying cost of maintenance into planned and unplanned provides a basis for bridging the gap of 'planning-monitoring-controlling'. The gap can be compensated through developing a continuous learning and improvement system. Such a system should firstly gather relevant knowledge assets (i.e. internal or external), secondly analyze those using meta-analytical methods, thirdly provide reference measures for deepening the insight of maintenance managers into the current situation, and ultimately lead to continuous improvement of MCM. The improvement potentials can be recognized, for instance, via detection of strategic/operational drift from the optimal factors of the model of Hahn and Laßmann (1993). These issues are discussed in the scope of this dissertation (cf. Chapter 2 and 3).

1.2.1 Maintenance Budget Management

Maintenance Budget Management (MBM) is a function of MCM to control financial resources for running and measuring effectiveness of maintenance operations (Hastings, 2010) , (Lamb, 2009). Budget is allocated either in terms of operation (i.e. operating budget) or project (i.e. project budget) (Dhillon, 2002), (Westerkamp, 1997). In the operating budget, each category of planned (predicted) expenditures (cost) is itemized to control normal operating labor, material, and overhead costs for the coming financial year (Dhillon, 2002). The budget, therefore, includes all foreseeable MaE activities such as clock-based, age-based, condition-based, and opportunity-based maintenance (Rausand, et al., 2003). The project budget is concerned with non-operating budget e.g. major construction, equipment purchase or on-the-job training of human resources (Lamb, 2009), (Dhillon, 2002). This leads to estimate cost of resources and overhead expenses to complete a project.

Any type of budget can be prepared, either based on historical data (i.e. historical approach) or without (i.e. zero-based approach) (Hastings, 2010), (Lamb, 2009). Historical approach uses "the experiences of earlier financial years to determine cost estimates for the coming year" (Dhillon, 2002). In contrast, zero-based approach develops budget from "justification of current requirements or priority versus the availability of funds" (Dhillon, 2002). Thus, it is associated with the risk that may cause a positive or negative effect (i.e. opportunity or lost). The negative side is, for instance, reallocation of the budget due to inaccurate budgeting. The risk, however, can raise opportunities for managers, knowledgeable persons and new producers to compete in the market and improve their capabilities. Table 1 summarizes the main advantages and drawbacks of these two approaches. Advantages and drawbacks of budget preparation approaches indicate that both do not accurately use related intellectual capital of MCM. The reason is underlying the gap of "planning-monitoring-controlling". While relying on the earlier experiences is invaluable, it is also vital to prioritize the distribution of funds and generate new knowledge through the preparation of the budget for the upcoming financial year. In other words, the drawbacks of both approaches can be compensated by developing a new approach as a mixture of *zero-based* and *history-based* budget preparation.

Table 1. Advantages and drawbacks of history- and zero-based budget preparation approaches – Adopted by the author form (Levitt, 2009), (Lamb, 2009), (Dhillon, 2002)

Type of budget	Advantages	Drawbacks
Historical approach	is efficient and rational	perpetuates past errors (error forwarding)
	requires less paperwork	
	can use/integrate documented/stored knowledge in repositories and expertise of domain experts	proportions funding of ineffective operations to effective ones
	compensates risks of budget reallocation	
Zero-based approach	is accurate, based on classification of expenditures (i.e. required by law, not required by law and first-time budget item)	is time-intensive
	thorough and comprehensive process	
	effectively uses and distributes available funds	requires more documentation and paperwork
	provides clear understanding of organizational objectives and goals in all management levels and between practitioners	includes risk of budget reallocation
	generates relatively new documented knowledge	

1.2.2 Organization and Assignment of Responsibilities in MCM

It is possible to group activities and responsibilities of MCM into two general classes[9]:

(1) **Basic or operational functions** for planning, monitoring and reporting the status to the top management.

(2) **Advanced or meta-functions** that demand adequate controlling and planning knowledge, authority to (re)establish policies, and make decision on MCM and its chain effects on production economy.

The advanced functions are assigned to chief executive officer (CEO), and CMO as well as chief accounting officer (CAO). Their responsibility includes:

(1) Establishment of MCM policies based on production economy and organization objectives.

(2) Establishment of strategies to control cost flow of maintenance, including expenditures and budget.

(3) Control maintenance costs in certain intervals.

(4) Extract improvement potentials.

(5) Redefine strategies for operational level.

(6) Supervise secondary functions (basic functions).

(7) Make a decision and plan budget for new interval.

Staff of the basic functions is mainly the CME as well as engineers, operators and administrative personnel. In this level, planning and monitoring of cost flow should be done that includes:

(1) Planning of maintenance costing for the new interval (based on the assigned budget).

(2) Monitoring of expenditures and resources.

(3) Documentation of MCM data using maintenance databases and information systems by means of desktop computer, laptops, mobile phone or tablet.

(4) Reporting to top management about overhaul and the expenditures ratio of the planned budget.

(5) Extract and report improvement potentials in maintenance costing i.e. text-based report addressing a specific problem or forthcoming obstacle.

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[9] The classifications and elaboration of the activities and responsibilities is done by the author based on review of (Lamb, 2009), (Levitt, 2009), (Mirghani, 2009), (Mobley, 2008), and (Dhillon, 2002).

In fact, the aforementioned staff classification and the assignment of the duties are ideal and their suitability is a matter of each single case. Organizational structure, culture and centralization/decentralization of MaM and MaE activities (particularly MCM) are thereby among influential factors to relatively shape the type of task breakdown and definition of duties. The gap of 'planning-monitoring-controlling' is specifically engaged with performance of maintenance practitioners, and therefore MCM essentially needs a structured organization with proper definitions of roles and duties.

1.2.3 Management of Knowledge Assets in MCM

MCM processes create and incorporate knowledge assets. "Knowledge assets are the inputs, outputs and moderating factors of the organization's knowledge-creating activities and hence they are constantly evolving" (Nonaka, et al., 2000), (Schiuma, et al., 2010). There are three groups of knowledge assets, which are human, structural and relationship capital (Dawson, 2000), (Dawson, 2005), (Schiuma, et al., 2010). Human capital is the knowledge, expertise, skills, competence and creativities of the people/group of people who are working and creating value in the organization (Dawson, 2000), (Dawson, 2005), (Schiuma, et al., 2010). Structural capital is technological infrastructure such as hardware, software or data warehouse, and processes which do not necessarily depend on key staff (Dawson, 2000), (Dawson, 2005), (Schiuma, et al., 2010). Relational capital is "relationships with clients, suppliers, distributors, partners, alliance members, academics, regulators and others, as well as organizational image and brands" (Dawson, 2000), (Dawson, 2005).

In this way, it is significantly important to define 'knowledge', especially because it is a vague and ambiguous term in relation to data and information. The literature on knowledge management (KM) does not present consensus and unanimity to define the term of knowledge. It is a very popular way to define knowledge through identifying the distinction between knowledge, information and data (Wijnhoven, 2006). However, the definitions are sometimes diverged, or at least not converged, especially comparing different disciplines (e.g. philosophy, sociology, natural sciences, information management, and computer science) (Maier, 2007).[10] In the field of information management and computer science, the mutual agreement seemingly is to define them in an hierarchical relationship (Maier, 2007). "Whereas data designates 'raw', unconnected, quantitative or qualitative items, the term information relates to answers to questions, statements about situations or facts" (Eppler, 2006). In other

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[10] Several definitions of KM are reviewed by the author. The difference in the KM account and perspective can be detected through comparing the following sources (but not limited to): (Polanyi, 1964), (Polanyi, 1967), (Ackoff, 1989), (Nonaka, 1994), (Nonaka, et al., 1995), (Davenport, et al., 1998), (Montana, 2000), (Alavi, et al., 2001), (Davenport, et al., 2002), (Watson, 2003), (Leavitt, 2003), (Mentzas, et al., 2003), (Gottschalk, 2004), (Baets, 2005), (Dalkir, 2005), (Jennex, et al., 2005), (Wijnhoven, 2006), (Coakes, et al., 2006), (Schwartz, 2006), (Eppler, 2006), (Jennex, 2007), (Maier, 2007), (Leistner, 2010), (Schiuma, et al., 2010), and (Fathi, 2013).

words information is "contextualized, categorized, calculated, corrected and condensed data" (Davenport, et al., 1998), (Eppler, 2006). Hence information is created when various sets of data are linked to form one coherent statement (Eppler, 2006). "The resulting entity can be called a piece of information: a coherent set of statements that forms a message" (Eppler, 2006). Finally information can become knowledge "when it is correctly interpreted and connected with prior knowledge" (Eppler, 2006).

Knowledge is classified according to a certain typology for distinction between tacit, explicit and latent knowledge (Wijnhoven, 2006). **Tacit knowledge** is a person-dependent knowledge (personal knowledge). This type of knowledge *is not and cannot be expressed* (Wijnhoven, 2006). Tacit knowledge is non-representational, whereas explicit and latent knowledge. **Explicit knowledge** "*is or could be expressed without attenuation*" (Wijnhoven, 2006). **Latent knowledge** "*could be expressed but it is difficult to express it without attenuation*" (Wijnhoven, 2006). In the field of computer science, knowledge is mostly seen as **explicit** or **implicit** (tacit or latent). This classification categorizes knowledge by examining whether it is represented and documented. Thus the knowledge which is not documented is considered as implicit that might need to be discovered, extracted, represented, documented or validated.

Knowledge is employed or produced within knowledge-intensive business processes (KIBP) (Gronau, et al., 2004), (Eppler, 2006). KIBP encompass and derive knowledge assets. A process is knowledge-intensive "if its value can only be created through the fulfillment of the knowledge requirements of the process participants" (Gronau, et al., 2004). Process participants are organizations or (group of) individuals involved in the process and sub-process(es) either as internal or external stakeholders. Hence, KIBP is defined "as a productive series of activities that involves information transformation and requires specialized professional knowledge" (Eppler, 2006). The objective of KM, therefore, is to make information actionable and reusable. KM is generally defined as an iterative, life cyclic, dynamic and systematic process which encompass the creation, acquisition, extraction, storage, retrieval, discovery, application, review, sharing and transfer of the knowledge captured from/within KIBP[11]. This definition only addresses the KM life cycle and, in turn, employing KM needs feasibility and technical requirement analysis of each application domain e.g. maintenance.

In the perspective of MaM, KM is to integrate KIBPs and manage knowledge life cycle, especially to utilize knowledge assets for operational and strategic endeavors such as decision-making. MaM is a kind of KIBP which encompass all three types of knowledge assets (i.e. human, structural and relationship capital). MaM activities and

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[11] This is a cumulative definition adopted by the author by reviewing and combining the definitions or statements given by (Alavi, et al., 2001), (Watson, 2003), (Leavitt, 2003), (Mentzas, et al., 2003), (Gottschalk, 2004), (Baets, 2005), (Dalkir, 2005), (Jennex, et al., 2005), (Wijnhoven, 2006), (Eppler, 2006), (Jennex, 2007), (Maier, 2007), (Leistner, 2010), (Fathi, 2013).

processes produce and use knowledge assets, particularly in planning, monitoring and controlling of the maintenance cost life cycle (cf. Figure 6).

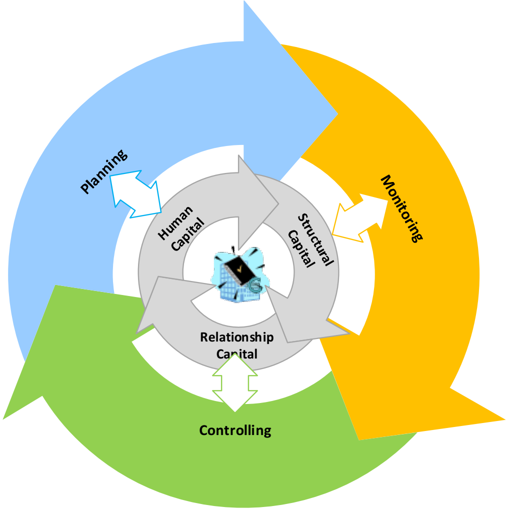

Fig.6. Dynamics of knowledge assets in MCM.

In the context of MCM, existing knowledge should be exploited and new knowledge will be explored for handling maintenance costing and related decision-making activities. Existing knowledge is associated with entities which are identified, extracted, documented and stored in structured databases and organizational memories. CMMIS regularly and systematically identifies, acquires, accumulates and stores explicit types of maintenance knowledge assets. In addition to the CMMIS, enterprise resource planning (ERP) systems, as an integrated platform, are used to support the CMO and CME in planning and monitoring of maintenance cost flow (Lamb, 2009). Basically, the CMMIS records statistics, numeric and text entities, which are composed of three types. These types are (1) structured (e.g. budget sheet and failure monitoring report), (2) unstructured (e.g. text report), or (3) semi-structured (e.g. email, voice mail, videos, graphics, and text message). The first type of records can be directly processed with subsystems of the CMMIS. It is subject to maintenance schedules, resources/inventory management, budget management and cost controlling, failure diagnoses, and condition monitoring (Bagadia, 2006), (Mobley, 2008). The second type consists of text-based documents like manuals, guidelines, regulations, standards, and reports which requires preprocessing, and thus cannot be directly used by the CMMIS. Other information sources include semi-structured records. Examples are emails exchanged between maintenance staff, research paper repositories dedicated to the field of maintenance, webpages or internet sources providing information on maintenance. The CMO needs to utilize all three types of record to manage planning-monitoring-controlling activities. An ideal CMMIS provides a structured database to store all types of records (Bagadia, 2006), (Mobley, 2008). In addition, the CMMIS supplies maintenance personnel with certain functionalities to analyze the acquired values for condition monitoring (i.e. monitoring and analyzing sensor data), and PM/CM's indicators and measures (Bagadia, 2006).

Despite the advantages, there are barriers to the CMMIS. Notably, it does not effectively use, maintenance knowledge assets, particularly in maintenance costing and budget management. For instance, in maintenance cost administration, the CMO and CME are required to summarize, aggregate and analyze large numbers of maintenance records (e.g. historical data, reports) of the past planning period. He/she needs to meta-analyze knowledge assets of MCM, i.e. identify the strength of the relationship between two or more (limited) (cost and operational) variables for making proposals and estimating budget of the next planning (forthcoming) period (cf. Figure 5). In this context, the CMO is able to validate the outcomes (estimations), based on his/her domain expertise. This example is, similarly, extendable to the top level of management, CEO and CAO, for tactical and strategic decision-making on budget and expenditures, as well as production economy. Remarkably, the main *black hole* of the commercial CMMIS is the lack of decision analysis modules, especially for cost and budget controlling. A detailed discussion on the CMMIS including analysis of subsystems, features and constraints is presented in Chapter 3.

Moreover, knowledge gaps are identified through controlling past events. This leads to exploring new knowledge to resolve existing problems. Human capital is a priceless source of knowledge. New knowledge is derived from the soft/hard competencies and skills, abilities, creativities and experiences of maintenance personnel. New knowledge should be systematically extracted, documented and stored in the CMMIS databases. In order to share and transfer new extracted knowledge, it should be validated by domain experts such as the CMO. Creating new knowledge is a learning process in which the CMO first detects the gaps and deficiencies in the past planning period and then strives to handle them in the forthcoming planning period. This ultimately leads to continuous improvement of MCM.

In this dissertation, cost- and text-based records (feedback of maintenance personnel) of MCM are analyzed using mathematical and textual meta-analysis (cf. Chapter 3). The analysis supports the CMO in identification of knowledge gaps and upgrading MCM activities. This provides opportunities for generating new knowledge from past experiences in cost controlling. This issue is elaborated in Chapter 3.

1.3 Literature Survey of MCM Models

This section provides an introduction to the chronological literature survey of mathematical and non-mathematical models (approaches) to MCM (cf. Appendix 7.1 – Table 24). At first, the characteristics of the literature survey are discussed, and later the modeling approaches in MCM.

In fact, the literature of MaM and MaE includes a large number of economic and business models. The diversity of subjects in the context of maintenance also leads to a variety of models. In this dissertation, the scope of the selection procedure is limited to the models that consider economic impacts of maintenance. In particular, cost-based maintenance models are considered, i.e. the models applied in the domains of mechanical and civil engineering, production (i.e. total product life cycle), and operations management. The relevancy and quality of the selected models are highly important. So certain databases, especially the journals with significant research impact in the domains of operational research, maintenance engineering, engineering management, business management, and production management, are selected. Investigating the scientific databases and journals, in the first step, brings up approximately 95 relevant articles. In the second stage, all papers have been reviewed and non-relevant, out-of-date, or poor quality works have been excluded (i.e. approximately 15 articles). Following this, the related and interconnected works have been searched out. This has decreased the number of models and clarified the path dependencies between some of the models (cf. Appendix 7.1 – Table 24). Finally, the research results in the qualification of 68 models[12]. The literature survey is not only intended to extend and deepen the insight into existing models in the literature of maintenance, it coherently provides a basis for classification and morphological analysis of the reviewed models (cf. Section 1.4). The results of the survey appear in Table 24 (cf. Appendix 7.1). Notably, it includes a summary of approximately 68 models selected by the investigation of several scientific databases and maintenance journals and publications. In Appendix 7.1, all the models are sorted in a temporal manner, from the earliest to latest. In the case of a model having a continual approach or dependency to other models, the references have also been cited. This shows no contradiction with the chronological study, and in turn considers path dependency of the reviewed models.

There are two types of models for MCM, mathematical (quantitative), and non-mathematical (qualitative). Mathematical modeling in maintenance is a vast field. It includes the majority of existing models aimed at improving the quality of maintenance systems and processes, as well as those assisting maintenance managers in decision-making activities. Rausand and Høyland emphasized that “it is often recommended to establish mathematical models that can be used to assess the impacts of maintenance decisions” (Rausand, et al., 2003). They added that using mathematical models supports the simulation of maintenance strategies and reveals the associated effect, maintenance cost, and operational performance (Rausand, et al., 2003). The simulation can facilitate the selection of the best [most effective] decision, and it can provide promising results in an industrial context (Rausand, et al., 2003).

In addition to mathematical models, economic measures and indicators of MCM should be considered, particularly **key performance indicators (KPIs)**. KPIs are managerial and business-oriented tools for monitoring and controlling the performance of maintenance in both operational and managerial levels. In general, indicators or measures are used for providing information for specific requirements of busi-

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[12] Of the selected models, 31% are from the articles published by the IEEE Transactions, namely articles which appeared in IEEE Transactions on (1) Reliability, (2) Engineering Management, and (3) Energy Conversion. The survey showed 16% to be from journals of operational research, 10% from maintenance engineering journals especially the articles appearing in the *Journal of Quality in Maintenance Engineering* (JQME), and also 10% came from production management journals published by Springer and Elsevier. Maintenance handbooks and books and well-known IEEE conferences on reliability and maintainability make up 10% of the articles. Additionally, 9% of the articles belong to the conference publications (proceedings) of the European Operations Management Association (EurOMA), and other related peer-reviewed conferences on production and operations management. Last but not least, 4% of models come from articles published by *IIE Transactions* (IIE stands for Institute of Industrial Engineers).

ness controlling and analysis (Hilgers, 2008). Paramenter defined KPIs as “a set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization” (Paramenter, 2010). Cray declared that KPIs are “crucial inputs for senior managers to perform effectively” (Cray, 2008). In the context of MCM, Dhillon reviewed a series of KPIs deployed in operational layers, particularly for labor, material, equipment, and preventive or corrective activities (Dhillon, 2002). He also examined the indices developed to measure effectiveness of maintenance activities with respect to cost e.g. maintenance cost ratio where total maintenance cost is divided by total cost of sales (Dhillon, 2002). The other examples of maintenance costing indices are: Maintenance labor cost to material cost ratio, maintenance cost to total manufacturing cost ratio, maintenance cost to value of facility ratio, maintenance cost to total man-hours workers ratio, and PM cost to total breakdown cost ratio (Dhillon, 2002). KPIs are useful to monitor the performance of maintenance and to collect data for the forthcoming planning phase (Mitchell, 2006). In combination of the mathematical models reviewed earlier, KPIs reinforce the supporting of MCM managers to examine the current state of the maintenance performance versus desired state (i.e. objectives of organization and production economy). This issue is further discussed by several authors such as (Cray, 2008), (Fei, 2008), (Mitchell, 2006), and (Dhillon, 2002). Five selected approaches using KPIs in MCM are cited in Appendix 7.1, namely, (Rommens, 2012), (Salonen, et al., 2011), (Kister, 2008), (Kelly, 2006) and (Dhillon, 2002).

In contrast, non-mathematical models are comparatively few. Such models are used to conceptually reveal the association between strategic and operational layers of maintenance. They are mainly established based on, but not limited to, the principles of MaM concepts (cf. Section 1.1 – Discussion on TPM, RCM, TLC, lean maintenance, and knowledge-based maintenance).

The mathematical and non-mathematical models, cited in Appendix 7.1 (cf. Table 24), are analyzed in the following section (cf. Section 1.4 – Table 6).

1.4 Morphological Analysis of MCM Models

In order to demarcate the boundaries and overlaps between all reviewed models in Section 1.3, selection of a consistent methodology is crucially important. Especially, when the aim of the analysis is to coherently identify the types of modeling and determine approaches to problem-solving for bridging the gap of planning-monitoring-controlling in MCM. In this context, *morphological analysis* is desirable[13]. Typically a “box” (table) is developed, in which each line represents a criterion, and each column is associated with its expression. Table 2 depicts such a box for analyzing the models of MCM. It deploys distinctive criteria and their different expressions for consistent classification. Therefore, for example, one model can simultaneously encompass any combination of the criteria, but only with one associated expression for

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[13] Fritz Zwicky (1898-1974) proposed the idea of morphological analysis (Zwicky, 1969), (Zwicky, 1989).

each criterion. Table 2 includes eight criteria which are marked with a number, and every associated expression has a distinctive index. For instance criterion 1 is "type of modeling" which is associated with "1.1 Mathematical, 1.2 Non-mathematical and 1.3 Combined". The other criteria are similarly represented.

Table 2. The criteria and associated expressions for morphological analysis of MCM models

Criteria	**Expressions**		
1. Type of modeling	Mathematical (Quantitative) (**1.1**)	Non-mathematical (Qualitative) (**1.2**)	Combined (**1.3**)
2. Type of problem-solving	Incremental (**2.1**)	Synoptic (**2.2**)	Combined (**2.3**)
3. Focus of purpose	Description (**3.1**)	Explanation (**3.2**)	Decision-making (**3.3**)
4. Extent of the model (with regard to the object)	Partial (**4.1**)	Total (**4.2**)	
5. Reaction of parameters	Deterministic (**5.1**)	Stochastic (**5.2**)	Fuzzy (**5.3**)
6. Consideration of time	Static (**6.1**)	Semi-dynamic (**6.2**)	Dynamic (**6.3**)
7. Scope of application	Situationally applicable (**7.1**)	Universally applicable (Reference models) **(7.2)**	
8. Remarks: Heuristic	Yes	No	N.A.

Interpretation of each expression might be different or misleading. In some cases, abstract terms like "incremental" and "synoptic" approaches to problem-solving, should be identified. This ultimately influences indication of the type and clarifies the border for combined approaches. Providing exact explanation is a prerequisite for successful execution of the morphological analysis. It is in turn a key for methodological study. Table 3 identifies the characteristics of every criterion, and reveals the extent of the definition for every associated expression.

Table 3. The identifiers for the criteria and associated expressions

Criteria	**Characteristics of the associated expressions**
Type of modeling	• **Mathematical models** are (quantitative) systems of equations and numbers of economic/non-economic variables. In some cases, the mathematical models are **incomplete**. This refers to the visual models which only picture an abstract relation between certain variables using graphs (i.e. lines and curves). • **Non-mathematical models** are the visualization of the concepts; flow charts, including sequential relation and types of association between different components, or descriptive models in natural languages. They provide a conceptual and qualitative picture of a system. Such models are used to depict either an existing or ideal situation in the context of the problem domain. • **Combined models** use a combination of quantitative and qualitative approaches for modeling a system (i.e. the model consists of mathematical and non-mathematical elements).
Type of problem-solving[14]	Incremental and synoptic problem-solving refers to a group of characteristics which do not necessarily happen simultaneously in a system. Due to the importance and complexity of these approaches, a detailed discussion is given in sub-section 1.4.1. Here the main keywords only are addressed. • **Incremental** characteristics are detectable in a system with (but not limited to) “feedback loop”, “considering historical data”, “focusing on continuous improvement or solving a problem over an infinite time span”, “monitoring over an infinite time span”, and “targeting the average value of a variable over an infinite time span”. • **Synoptic** characteristics are determined through analyzing a system with (but not limited to) “open loop”, “inconsideration of historical data”, “focusing on solving a problem as it is modeled”, and “targeting the optimum, maximum or minimum value of a certain variable(s)”. • **Combined** characteristics are difficult to detect. They are case-dependent, for example, the combination of optimizing cost using feedback loop or embedding synoptic models in an incremental environment.
Focus of purpose	This criterion refers to which end a model is designed and what it can be used for. In this context the focus of purpose can be ***description***, ***explanation*** or ***decision-making*** (Berens, et al., 2004), (Klein, et al., 2004), (Frankel, 2008). • **Description models** refer only to the purpose of reporting or drawing the picture of an event, function or system. For instance, a piece list of a machine only describes its elements, but is not able to show anything in the manner of a scientific explanation. • **Explanation models** provide hypothesis (or what-if relationship) to scientifically define a scope or structure of a system using the *deductive-nomological*

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[14] Detailed information for comparing incremental and synoptic approaches is presented in Table 4 and 5 in sub-section 1.4.1. The results of the morphological analysis are presented in sub-section 1.4.2.

Criteria	Characteristics of the associated expressions
	model (Hempel–Oppenheim model) for defining conditions and associated consequences. Such models can be used for prognosis. • **Decision-making models** are used for selection of the most desirable (optimal) alternative. The alternatives are developed based on explanatory models. Those, in turn, are developed in the ascending stage based on descriptive models. Examples are decision-making models used for trading-off between economic parameters and selection of the most desirable policy in MCM.
Extent of the model	• **Partial models** do not deal with the whole problem. For example, they only deal with maintenance cost, but not with the benefits or value of maintenance. • **Total models,** in contrast, deal with the problem holistically i.e. considering all (organic or functional) relations and interdependencies between cost and benefits.
Reaction of parameters	In the context of the mathematical models, the reaction of parameters/variables can be classified into three categories as follows: • **Deterministic behavior** refers to non-random evolution of parameters (i.e. only in one way). • **Stochastic behavior**, in contrast, emphasizes the random evolution of parameters (i.e. different ways over time). Such a behavior is developed based on the probability theory. • **Fuzzy behavior** refers to a group of models which deploy the concept of fuzzy logic in which truth can assume a continuum of values between 0 and 1. Therefore the parameter is not completely true or false, whereas it expresses a probable range of values.
Consideration of time	• **Static models** represent the equations without considering the time variable. • **Semi-static models**, however, considers the behavior of a system over time instances (discontinuous), but they do not include a time-dependent variable explicitly. • **Dynamic models** directly represent the equations including time variable.
Scope of application	• **Situationally applicable models** refer to customized models for solving a unique problem. Such models normally consider a singular use-case scenario with radically distinctive borders (barriers) and constraints from other related problems. • **Universally applicable models**, in contrast, provide a generic reference model for solving a group of problems in one or different domain(s).
Heuristic	In addition to incremental and synoptic approaches, the problem-solving can also be developed using experiences or even trial-and-error for solving a problem. Such heuristic approaches do not guarantee the solving of a problem. Meta-heuristic approaches, in contrast, provide a pattern for solving a wide range of problems. These issues are discussed in sub-section 1.4.1. In the morphological analysis, three expressions are considered for identifying the heuristic or meta-heuristic nature of the problem-solving as: • **Yes (Y)** which indicates that the author(s) of reviewed papers report(s) or recommend(s) solving a problem (by means of the presented model) in heuristic procedure. In addition, the study is extended for meta-heuristic approaches by indicating the well-known meta-heuristic methods which are used in the context of problem-solving like genetic algorithms. • **No (N)** which indicates that author(s) has (have) explicitly refused to use any heuristic or meta-heuristic method. • **Not available (N.A.)** which emphasizes the fact that the author(s) has (have) either not reported or recommended using any heuristic or meta-heuristic approaches, but not explicitly refused them.

1.4.1 Types of Problem-Detection and Solving

Literature of strategic planning and management deals with two major schools of thought (general approaches) for strategy formulation and process modeling; synoptic and incremental. The former is based on “principles of rational decision-making and assume that purpose and integration are essential for a firm’s long-term success” (Fredrickson, 1983). In contrast, the latter is based on how organizations really make strategic decisions (Fredrickson, 1983).

Toft defined ***Synoptic formalism (Rationalism)*** “as a wide range of problem-solving approaches that can be characterized as being ideal, rational, sequential and comprehensive” (Toft, 2000). This school of thought is originated by (Andrews, 1971), (Ansoff, 1977), (Steiner, 1979), and (Lorange, 1980). They mainly discussed long range planning and traditional strategic planning (Toft, 2000).

Methe et al. pointed out that an incremental approach to strategic management argues that strategic problems are too complex and ever changing (Methe, et al., 2000). Therefore, the strategic decision-making cannot be accomplished in a rational and straightforward manner, and it is coherently incremental and adaptive (Methe, et al., 2000). This school of thought is known as ***Incrementalism***. Furthermore, incremental approaches break through the barriers of synoptic formalism by stating that the latter is not applicable in some cases, and therefore cannot be used, and even should not try to be used in such cases (trying it regardless is not rational) (Seidenberg, 2012). The well-known incremental approaches are “bounded rationality”, “muddling through”, “disjointed incrementalism”, “logical incrementalism”, “piecemeal engineering”, and “Kaizen”. These approaches are respectively discussed by (Simon, 1997 (1957:1st)), (Lindblom, 1959), (Braybrooke, et al., 1963), (Quinn, 1980), (Popper, 2003), and (Imai, 2002). The term “incremental approach” or “continuous improvement” - (Nicholas, 2011) - is considered and examined in the management literature, especially in contributions or partial overlapping to the thematic areas such as *organizational change* (Beck, 2001), (Nicolai, 2010), *optimization of business process* (Becker, 2008), (Schmelzer, et al., 2010), *corporate planning*, *account planning* (Picot, et al., 1978), (Bresser, 2010), *product innovation* (especially the discussion of radical and incremental methods to innovation management) (Beck, 2001), (Leavitt, 2003), (Becker, 2008), (Goffin, et al., 2010), (Nicholas, 2011), and *quality management* (Pfeifer, 2002), (Evans, et al., 2011).

As a consequence, synoptic models are to maximize the organizational goals which are defined in economic or financial terms, based on a rational and comprehensive procedure (Methe, et al., 2000). Incremental models are to decentralize the selection of alternatives through adapting to environmental changes and, therefore, “organization is constrained to multiple goals composed of an admixture of economic, political and social considerations” (Methe, et al., 2000). The major characteristics of synoptic and incremental approaches to (strategic) management discussed in the literature are presented and compared in Table 4.

Table 4. Comparison of major characteristics of synoptic and incremental approaches to strategic management (Adopted by the author from multiple sources: (Lindblom, 1959), (Picot, et al., 1978), (Fredrickson, 1983), (Mintzberg, 1990), (Ansoff, 1991), (Seidenberg, 2012))

Characteristics	**Synoptic**	**Incremental**
Initiation/trigger mechanism	Continuous environmental scanning generates opportunities/problems for strategic action.	Problem/performance gaps initiate a search for solution.
Relationship between means (alternatives) and ends (goals)	First, identify the ends of action and the means to achieve them (i.e. **ends-means** process).	Means and ends are not easily distinguishable. The remedial change outcome is considered at the same time that the means for achieving it is analyzed (i.e. **means-ends** process).
Concept of choice	The best choice is the one that most closely approximates the desired end.	The choice of an alternative is made by combining the considered alternatives (means) and their possible consequences (ends), and simultaneously selecting the one that yields the most desired outcome (i.e. agreement achieved by choosing an alternative or the means to an end).
Analytic comprehensiveness	All important factors are considered.	All possible factors are not considered. Analysis is based on a few alternatives only marginally different from the existing state of affairs.
Integrative comprehensiveness	Efforts are made to integrate decisions into a unified strategy.	Little attempt to integrate, consciously, the individual decisions that could possibly affect one another (i.e. not integrated but loosely coupled).
Decision-making and planning behavior	Anticipative and goal-oriented.	Reactive to urgent problems.
Goal-orientation	Specific.	Indeterminate.
Temporal and factual horizon of problem	Long-term and comprehensive.	Short-term and limited to the current sub-problems.
Evaluation process of alternatives	Analytical and comprehensive.	Piecemeal (in stages).
Continuity of planning	Integrated and unique.	Stepwise and sequential.
Flexibility of planning	Limited.	Adaptive.

Synoptic and incremental approaches have been examined, criticized and/or comparatively studied by numerous authors of (strategic) management, particularly Lindblom (Lindblom, 1959), Dror (Dror, 1964), Picot and Lange (Picot, et al., 1978), Fredrickson (Fredrickson, 1983), Johnson (Johnson, 1988), Mintzberg (Mintzberg, 1990), Ansoff (Ansoff, 1991), Toft (Toft, 2000), Methe et al. (Methe, et al., 2000), Miller (Miller, 2011), and Seidenberg (Seidenberg, 2012). Hard critiques and debates can be detected concerning “Incrementalism” and/or “Rationalism” (Synoptic formalism). For example, Johnson argued that “consciously managed incremental change does not necessarily succeed in keeping pace with environmental change” (Johnson, 1988). This is a so-called phenomenon of “strategic drift” when the “incrementally adjusted strategic change and environmental change, particularly market changes, moved apart” (Johnson, 1988). This phenomenon is rooted in the characteristics of incremental approaches especially *mean-end relationship* (i.e. prioritization of the alternatives to goals), and concept of choice (i.e. selection of the approximate choice rather than the best choice, or the one that most closely approximates the desired end) (cf. Table 3). Seidenberg reviewed and compared four incremental models “disjointed incrementalism”, “logical incrementalism”, “piecemeal engineering” and “Kaizen”, and concluded that these models differ in several ways, so one cannot speak about one single kind of “Incrementalism” (Seidenberg, 2012). In addition, Methe et al. skeptically indicated that synoptic approaches to strategic management should be tried with caution (Methe, et al., 2000).

During the evolution of synoptic and incremental models over the past 45 years, they have been extensively discussed from both a practical and theoretical perspective. However, which one is “**the best way of problem-solving**”?

Fredrickson suggested “not only organizations that employ both synoptic and incremental approaches, but the strategic process may be synoptic on some characteristics (e.g. the process is proactively initiated) and **simultaneously** incremental on others (e.g. strategic decision is not the result of conscious choice)” (Fredrickson, 1983). This hypothesis was reconsidered through an empirical investigation by (Methe, et al., 2000). They pointed out the question of selecting either incremental or synoptic as not precise, and it should be reformulated to **“when and how”** the two approaches could be used (Methe, et al., 2000). Hence the question of selecting "one best way" to solve problems (either synoptic or incremental) is the wrong one. Instead, **coexistence** and **combination** of the two basic approaches to strategic management is recommended (Fredrickson, 1983), (Toft, 2000), (Methe, et al., 2000), (Bresser, 2010) and (Seidenberg, 2012). Table 5 presents the findings based on the literature study and needs analysis regarding the major features of synoptic and incremental approaches to problem-solving (decision-making) activities (Seidenberg, 2012) and (Ansari, et al., 2013). It advances the characteristics presented in Table 4, and provides recommendations to decide “when and how” synoptic and incremental approaches can be used.

Table 5. Major features for the selection of synoptic and incremental approaches (Adopted by the author from (Seidenberg, 2012) and (Ansari, et al., 2013))

	Synoptic approach	**Incremental approach**
Underlying principle of cybernetics/Control	Open loop.	Closed loop.
Involved management phases	Planning and decision-making.	All, especially including monitoring.
Type of complexity reduction	Trivialization of source of problems by structuring.	Tentativeness by the solution of the problem.
Type of problem shifting	Degenerative.	Progressive.
Cause of the phenomenon, to solve the "wrong" problem	Unsuitable modeling, especially by highly reduced complexity.	Unsuitable problem selection /prioritization.
Time sequence of the problem-solving process	Defined initial and defined end (project).	Without a defined end (ongoing task).
Status of problem-solving	Definitively (elimination of the problem).	Tentatively (Dealing with or handling the problem).
Expected quality level of problem-solving	High.	Low.
Possibility of wrong decision (Risk of decisions)	Not included in the basic model of decision theory.	Considered in this approach.
Modeling of risk	Explicit modeling or abstracted from risk (risk-free).	Probability-based analysis of alternatives, stepwise and piecemeal problem-solving.
Direction of evaluation of problem-solving	Forward (based on the goal) What is left to do?	Backward (based on previous state/literal review). What has been reached?
Benchmark to assess the problem-solving	Absolute, based on optimum.	Relative, comparative.
Innovation driven characteristic	Radical.	Learning from experiences and evaluations of prototypes.

Besides discussion of synoptic and incremental approaches to problem discovery and solving, heuristic models need to be taken into account. **Heuristic** models encompass principles of synoptic/incremental approaches, but do not necessarily deal with mathematical formulations, and in turn concentrate more on providing hypotheses and guidelines (Käschel, et al., 2001), (Berens, et al., 2004), (Blohm, et al., 2008). Examples of heuristic models are rules of thumb for proposing hypothetical structures for planning, monitoring and controlling which are strengthened, not necessarily, by providing mathematical formulations. Heuristic models are usually speculative formulation serving as a guideline in problem discovery and solving, and not guaranteeing the best way (Käschel, et al., 2001), (Smith, 2002), (Koen, 2002), (Blohm, et al., 2008). Smith emphasized that "an essential aspect of modeling is the use of heuristics" (Smith, 2002), (Starfield, et al., 1994). It is difficult to define heuristics; however, Koen (Koen, 2002) listed the ideal characteristics of heuristic approaches/models and declared that: " (1) Heuristics do not guarantee a solution, (2) Two heuristics may contradict or give different answers to the same question and still be useful, (3) Heuristics permit the solving of unsolvable problems or reduce the search time to a satisfactory solution, (4) The heuristic depends on the immediate context instead of absolute truth as a standard of validity." (Smith, 2002), (Koen, 2002)[15]. Heuristic models are used to guide, discover and solve problems in the entire process of problem-solving or decision-making (Smith, 2002), (Koen, 2002). Koen's definition of the engineering method has stressed the importance of heuristic modeling as: "the engineering method is the use of heuristics to create the best change in a poorly understood situation within the available resources" (Smith, 2002), (Koen, 2002). Besides, Gigerenzer comprehensively reviewed heuristic approaches to problem-solving in (Gigerenzer, 2008), and later heuristic decision-making in (Gigerenzer, et al., 2011). Gigerenzer (2008) compared statistical optimization procedures and heuristics. He pointed out that "heuristics do not try to *optimize* (i.e. find the best solution), but rather *satisfice*[16] (i.e. find a good-enough solution)" (Gigerenzer, 2008). He exemplified that while "calculating the maximum of a function is a form of optimizing, choosing the first option that exceeds an aspiration level is a form of satisficing" (Gigerenzer, 2008). This statement, in fact, highlights the difference between synoptic approaches and heuristics. However, the border for indicating the difference of such approaches in comparison with incremental or combined (combination of synoptic and incremental) is too narrow.

In the context of operation management, heuristic approaches are compared with ***meta-heuristic*** (Stevenson, 2012), (Blohm, et al., 2008). Meta-heuristic is a confusing term, because it does not address a common understanding by adding the prefix "meta-" to a term for building a new term. For instance, meta-data is a kind of data which provide data about data (e.g. a product catalog). In contrast, meta-heuristic is an independent term referring to optimization or approximation algorithms (Luke, 2009-2012), (Blohm, et al., 2008), (Ólafsson, 2006). So it *does not mean* heuristic for/about heuristics (Luke, 2009-2012). Meta-heuristic approaches provide general patterns for universal problem-solving (i.e. wide range of problem domains) instead of specific situations where heuristics are applicable (Blohm, et al., 2008). They are used basically to find approximate solution(s), especially for the sophisticated and complex problems (Käschel, et al., 2001), (Blohm, et al., 2008). In particular, such methods are used when there is neither an idea/information about the optimal solution (or value) nor the way to approach it, in addition to the problem domain being wide and not

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[15] Cf. (Koen, 1985) and (Koen, 1984).

[16] Decide on and pursue a course of action satisfying the minimum requirements to achieve a goal.

necessarily specific (Luke, 2009-2012), (Blohm, et al., 2008), (Ólafsson, 2006). Of course, any meta-heuristic method does not necessarily equip one for solving any kinds of problem, and in each case the most adequate meta-heuristic solution should be selected through test and usability assessment (Luke, 2009-2012), (Blohm, et al., 2008), (Ólafsson, 2006). Examples are (but not limited to) evolutionary algorithms (e.g. genetic algorithms), local search[17], tabu search, and the nested partitions method (Ólafsson, 2006).

It is too indecipherable to identify which heuristic or meta-heuristic method is synoptic or incremental. For example, the synoptic approach like branch-and-bound can be interpreted in a shortened version as heuristic, i.e. only providing a set of candidate solutions (Blohm, et al., 2008). The genetic algorithm as a meta-heuristic approach, in contrast, is incremental (Blohm, et al., 2008). Therefore, one cannot classify those models in two fully separated categories. The advantages and drawbacks of synoptic/incremental models and their border of similarity to heuristic and meta-heuristic approaches indicate the potential for coexistence of these approaches.

In this sub-section, synoptic, incremental, heuristic and meta-heuristic approaches to problem-solving are reviewed. The goal is to identify which typology of the management models can be used to compensate and resolve the gap of "*planning-monitoring-controlling*" in MCM. This issue is further discussed in sub-section 1.4.2 and section 1.5.

1.4.2 Results of Morphological Analysis

The morphological analysis is conducted through extensive analysis of all 68 surveyed MCM models (cf. Section 1.3 and Appendix 7.1). In particular, eight criteria and associated expressions are used for the analysis (cf. Table 2&3). In the proceedings, the results of the analysis are presented in Table 6. Each column represents a criterion and associated expressions, based on Table 2. Each row shows a model and its association with the criteria. All models are listed in chronological order, based on the content of Section 1.3. The check-mark (✔) is used to indicate whether a model fulfills a certain expression or not. In case of ambiguous situations, a footnote is used to add details. As discussed earlier, some of the reviewed models are interconnected or use the principles of other models. In such cases, all original works and models have been cited as well. One row, therefore, may include more than one model. Once a predecessor (preceding model) is detected, the reference is cited in the footnote. Finally, the findings of Table 6 are discussed with the aim of identifying patterns corresponding to each criterion (cf. sub-sections 1.4.2.1-8). This leads to the identification of the characteristics for developing a novel reference model to MCM (cf. Section 1.5).

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[17] Meta-heuristic methods such as "local search" are discussed in (Käschel, et al., 2001), (Berens, et al., 2004), and (Blohm, et al., 2008).

Table 6. Morphological analysis of the surveyed MCM models

(*Note: This table runs over pages 33 to 41.*)

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
Models																				
(Nathan, 1969)	✔				✔				✔		✔	✔			✔		✔	✔		N.A.
(McLeod, 1973)			✔			✔			✔		✔	✔				✔			✔	N.A.
(Tempest, 1976)			✔			✔			✔	✔		✔				✔			✔	N.A.
(Sule, et al., 1979)	✔				✔				✔	✔		✔					✔		✔	N.A.

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[18] This criterion is determined through indicative explanation by the author(s) of each reviewed article. In the case of no direct indication the personal judgment of the author of this dissertation is reflected.

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Regulinski, et al., 1983)	✔					✔			✔		✔		✔				✔		✔	N.A.
(Collins, 1983)	✔					✔			✔		✔	✔	✔				✔	✔		N.A.
(Goyal, et al., 1985)	✔				✔				✔	✔		✔					✔		✔	Y
(Canfield, 1986)	✔					✔			✔	✔			✔				✔		✔	N.A.
(Blohm, et al., 1988) (Seidenberg, 1989) (Adam, 1989)		✔		✔				✔	✔	✔		✔				✔			✔	Y
(Jayabalan,etal.,1992)	✔				✔				✔	✔		✔					✔	✔		N.A.
(Hahn, et al., 1993)	✔				✔				✔	✔		✔				✔			✔	N.A.
(Sheu, et al., 1994)			✔	✔					✔		✔	✔					✔		✔	N.A.

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Increcremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.a pp. (7.2)**	**Y/N/N.A.**
(van Gestel, 1994)			✔			✔			✔	✔			✔				✔		✔	N.A.
(Al-Najjar, 1996)		✔		✔					✔		✔	✔				✔			✔	N.A.
(Usher, et al., 1998)	✔					✔			✔		✔	✔					✔	✔		Y[19]
(Lim, et al., 1999)	✔				✔			✔		✔			✔				✔	✔		N.A.
(Reineke, et al., 1999a) (Barlow, et al., 1960)	✔				✔				✔	✔			✔				✔	✔		N.A.
(Reineke,et al.,1999b)	✔				✔				✔	✔			✔				✔	✔		N.A.
(Baron, et al., 1999)			✔		✔				✔		✔		✔				✔	✔		N.A.

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[19] Meta-heuristic approach using genetic algorithm.

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Sung, et al., 2000)	✔				✔				✔		✔	✔				✔		✔		Y[20]
(Yam,et al., 2000)	✔		* [21]		✔				✔		✔	✔				✔		✔		N.A.
(Duffuaa, et al., 2001)		✔		✔					✔	✔		✔				✔			✔	N.A.
(Dhillon, 2002)	✔			✔					✔	✔			✔				✔		✔	N.A.
(Maillart, et al., 2002)	✔				✔				✔	✔			✔				✔	✔		N.A.
(Grall, et al., 2002)	✔				✔				✔	✔			✔				✔	✔		N.A.
(Chen, et al., 2003)	✔				✔				✔	✔		✔					✔		✔	N.A.
(Rhee, et al., 2003)	✔			✔					✔	✔			✔				✔		✔	N.A.

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[20] The authors indicated that for future work it is best to use the model through a heuristic procedure.

[21] The authors indicated the need for intelligent decision support systems (DSS).

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Elegbede, et al., 2003)	✔					✔			✔	✔		✔			✔			✔		Y[22]
(Dey, 2004)	✔			✔					✔		✔	✔			✔			✔		N.A.
(Labib, 2004)	✔			✔					✔		✔			✔		✔			✔	N.A.
(Shum, et al., 2004)	✔					✔			✔	✔		✔	✔				✔		✔	Y[23]
(Haarman, et al., 2004)[24]			✔	✔					✔		✔	✔					✔		✔	N.A.
(Jardine, et al., 2005)	✔				✔				✔	✔		✔				✔			✔	N.A.

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[22] Meta-heuristic approach for approximation.
[23] Meta-heuristic approach using genetic algorithm.
[24] Value-driven maintenance (VDM).

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Yao, et al., 2005)	✔				✔				✔	✔			✔				✔	✔		N.A.
(Selman, et al., 2005)	✔			✔				✔		✔		✔				✔		✔		N.A.
(Rishel, et al., 2006)[25]			✔	✔				✔			✔	✔				✔			✔	N.A.
(Lehtonen, 2006)	✔				✔				✔	✔		✔	✔				✔	✔		N.A.
(Wang, et al., 2006)	✔				✔				✔	✔		✔					✔	✔		N.A.
(Kelly, 2006)			✔	✔					✔		✔	✔				✔			✔	N.A.
(Vasiu, et al., 2007) (Nakagawa, 1979)	✔				✔				✔	✔			✔				✔	✔		N.A.

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[25] Based on DuPont model - (Ahlmann, 1984).

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Increcremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Hagmark,et al.,2007)			✔			✔			✔	✔			✔			✔		✔		N.A.
(Nilsson, et al., 2007)	✔				✔				✔		✔	✔			✔			✔		N.A.[26]
(Dersin, et al., 2008)	✔				✔				✔	✔		✔	✔				✔	✔		N.A.[27]
(Zhou, et al., 2008)[28]			✔			✔			✔	✔			✔				✔		✔	N.A.
(Huang, et al., 2008)[29]	✔				✔				✔		✔		✔			✔		✔		N.A.

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[26] The approach itself is heuristic because the model has been developed based on certain situationally confirmable assumptions, but the authors did not address this issue.

[27] The approach itself is heuristic because the model has been developed based on certain situationally confirmable assumptions, but the authors did not address this issue.

[28] Extension of (Linderman, et al., 2005) which is also based on: (Alexander, et al., 1995). The latter work was merging the work of : (Duncan, 1956) and (Taguchi, et al., 1989).

[29] Used the cost model of (Jayabalan, et al., 1992).

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Kister, 2008)	✔			✔					✔	✔			✔				✔		✔	N.A.
(Frenkel, et al., 2009)	✔				✔				✔		✔		✔				✔	✔		N.A.
(Liu, et al., 2010)	✔					✔			✔	✔		✔	✔		✔		✔	✔		Y[30]
(Chen, 2010)	✔					✔			✔	✔			✔				✔	✔		N.A.
(Chea, 2011) (Destri, et al., 2012)[31]			✔	✔					✔		✔	✔				✔			✔	N.A.
(Salonen, et al., 2011)	✔			✔					✔	✔		✔				✔			✔	N.A.

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[30] Meta-heuristic approach using genetic algorithm.

[31] Refer respectively to activity-based costing (ABC) and process-based costing (PBC).

Criteria	1. Type of modeling			2. Type of problem-solving			3. Focus of purpose			4. Extent of the model		5. Reaction of the parameters			6. Consideration of time			7. Scope of application		8. Heuristic[18]
Expressions	**Math. (1.1)**	**Non-math. (1.2)**	**Combined (1.3)**	**Incremental (2.1)**	**Synoptic (2.2)**	**Combined (2.3)**	**Description (3.1)**	**Explanation (3.2)**	**Decision-making (3.3)**	**Partial (4.1)**	**Total (4.2)**	**Deterministic (5.1)**	**Stochastic (5.2)**	**Fuzzy (5.3)**	**Static (6.1)**	**Semi-dynamic (6.2)**	**Dynamic (6.3)**	**Situ. app. (7.1)**	**Uni.app. (7.2)**	**Y/N/N.A.**
(Dandotiya, et al., 2012)	✔			✔					✔		✔		✔				✔	✔		N.A.[32]
(Almgren, et al., 2012)	✔				✔			✔		✔		✔					✔	✔		N.A.
(van Horenbeek, et al., 2012)	✔				✔			✔			✔	✔					✔	✔		N.A.
(Shafiei-Monfared, et al., 2012)			✔	✔				✔		✔				✔	✔				✔	N.A.
(Tinga, et al., 2012)			✔		✔				✔	✔		✔	✔			✔		✔		N.A.
(Rommens, 2012)	✔			✔				✔		✔		✔			✔			✔		N.A.
(Ierace, et al., 2013)	✔			✔					✔	✔		✔			✔				✔	N.A.

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[32] The approach itself is heuristic because the model has been developed based on certain situationally confirmable assumptions, but the authors did not address this issue.

1.4.2.1 Criterion 1: Type of modeling

The reviewed models are mainly established based on a mathematical representation of the operational and economic variables. Of course, they use different mathematical approaches (e.g. stochastic or non-stochastic). However, the mutual aspect is formalizing the strength of the relation between parameters and variables using mathematical equation systems. In a few cases, the mathematical modeling is combined with qualitative approaches. Such models encompass the capability of generalization and provide a kind of guideline and instruction for MCM (cf. Combined models in Figure 7). Combined models are practically usable and can be transferred from application domain X to Y due to their adaptive characteristics. However, they are complex in terms of design and need to be comparatively studied in various application domains. The smallest number of surveyed models is non-mathematical (qualitative). This category of modeling includes incomplete mathematical models which only visualize the abstract relation of economic and operational variables (factors). An example is the model of Hahn and Laßmann (1993). In addition, other non-mathematical models are only presenting conceptual approaches for managing cost elements. For instance, normative models recommend how to decide/to work, and how to improve the cost monitoring-controlling process, by gathering and using feedback and historical data. The results confirm the emphasis on mathematical modeling in MCM, and also indicate the lack of combined approaches (cf. Figure 7). This provides opportunity for integrating the principles of mathematical and qualitative modeling towards creating a novel reference model (cf. Chapter 2).

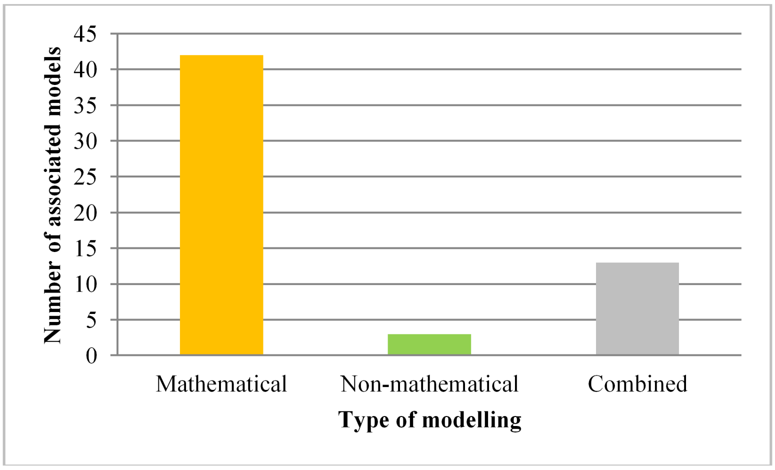

Fig.7. Type of modeling (Criterion 1) and number of the surveyed models associated with each expression.

1.4.2.2 Criterion 2: Type of problem-solving

The pattern for using different types of problem-solving detected through the morphological analysis (cf. Figure 8). It shows that the number of the surveyed synoptic models is higher than incremental ones. This reveals the major aim of surveyed models on minimizing total cost, using straightforward methods instead of continuous approaches. The promising result indicates typology of models deploying incremental *or* synoptic approaches versus combined models (i.e. using synoptic *and* incremental approaches).

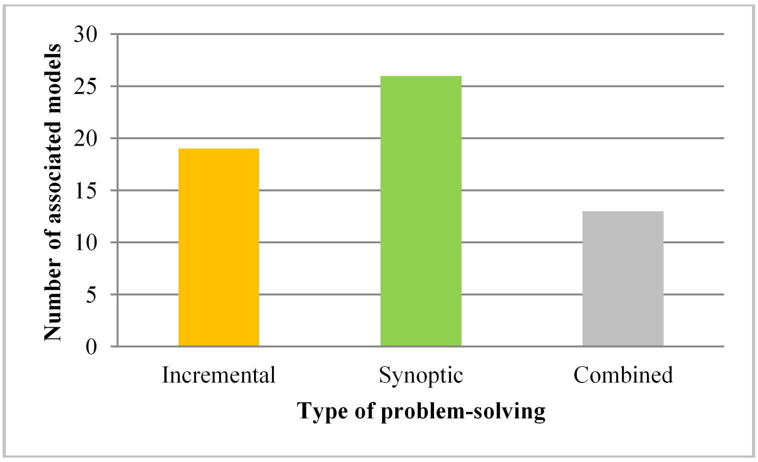

Fig.8. Type of problem-solving (Criterion 2) and number of the surveyed models associated with each expression.

As discussed earlier, incremental models consider "errors" in decision-making and use a feedback/feed-forward loop to compensate errors, and learn for future decisions. In contrast, synoptic models presuppose comprehensive information for decision-making and therefore are based on open control chains. The major characteristics and features of synoptic and incremental approaches to strategic management are presented in Table 4 and 5. The incremental approaches/models also suffer from lack of using and analyzing MCM knowledge assets. This is a barrier to identifying the optimal step size for changes of economic and operational parameters in the status quo, and to plan and reach the minimum of total cost and optimum of maintenance activities. Combining synoptic and incremental approaches, hence, causes synergistic effects in problem-solving, i.e. supporting continuous learning from the past event and improving forthcoming ones. This ultimately leads to bridging the aforementioned gap of *"planning-monitoring-controlling"* in MCM.

1.4.2.3 Criterion 3: Focus of purpose

Most of the surveyed models deal with supporting or assisting the CMO and management for improving policy selection, trading-off between economic and operational variables, and decision-making (cf. Figure 9). Through the morphological analysis, no descriptive model has been detected (cf. Table 6). Clearly descriptive approaches are not in demand, especially dealing with cost and economic attributes. Explanation models can support decision-making and furthermore can be advanced for developing decision models. As discussed earlier, each decision model is built on a class of explanatory models (cf. Table 3). As a result, the analysis reveals that the focus of purpose in MCM has been shifted from what-if analysis (i.e. explanation models) into the selection of desired decision alternatives (i.e. decision models).

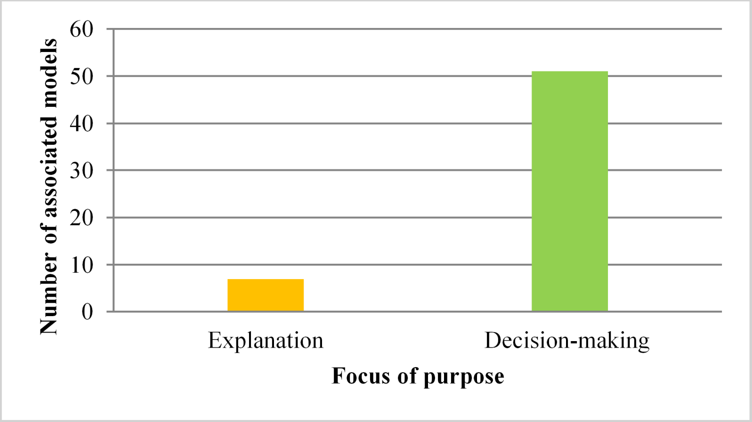

Fig.9. Focus of purpose (Criterion 3) and number of the surveyed models associated with each expression.

1.4.2.4 Criterion 4: Extent of the model

Most of the surveyed models only carry on part of the problem domain of MCM (cf. Figure 10). They do not, therefore, consider the entire economic life cycle, and focus on considering, for example, cost attributes rather than the effect on the value chain and benefits. Only a few of the surveyed models claim total approaches for considering the effect of MCM on the entire maintenance and production economy (cf. Figure 10).

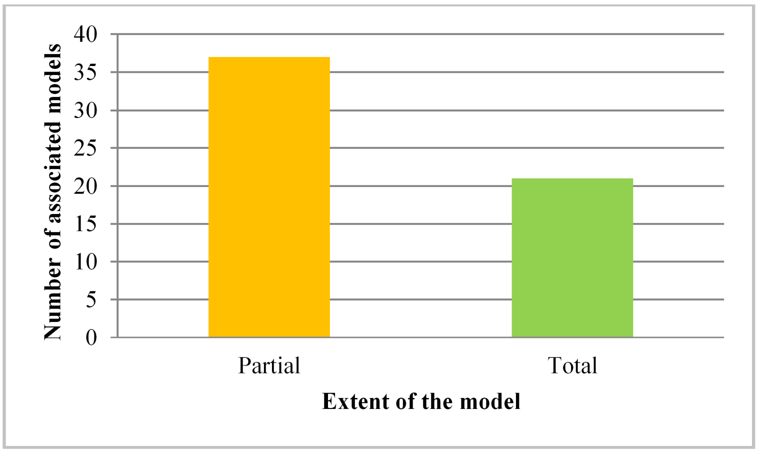

Fig.10. The extent of the model (Criterion 4) and number of the surveyed models associated with each expression.

Moreover, partial and total models are complementary approaches. For instance, partial approaches identify the relations between economic and operational parameters, and thus need to be used in the framework of total models to analyze a cause-effect relation in accordance with expected financial values and benefits.

1.4.2.5 Criterion 5: Reaction of the parameters

Considering the results of the analysis for the type of modeling (cf. Criterion 1), criterion 5 is used to deepen the analysis of mathematical models, and to identify the reaction of parameters based on the predefined mathematical principles (cf. Table 3).

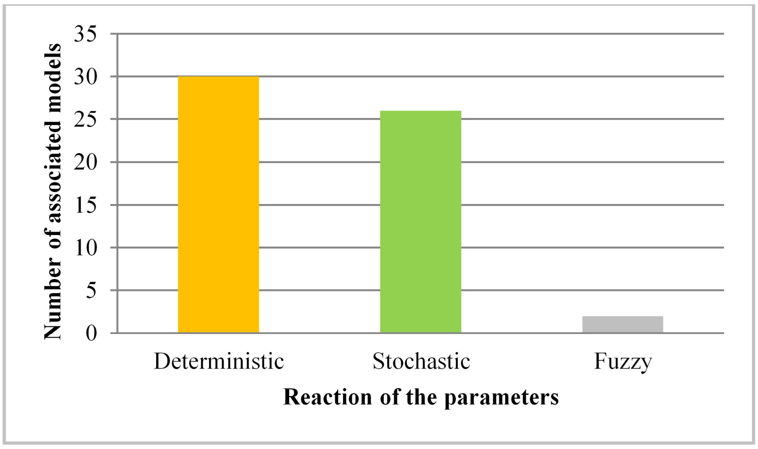

Fig.11. The reaction of the parameters (Criterion 5) and number of the surveyed models associated with each expression.

The study shows that the behavior of parameters in the surveyed models is mainly deterministic *or* stochastic. Only two of the reviewed models include fuzzy parameters. Both are used to support the reasoning process for selection of maintenance policies in the context of MCM.

Notably, six of the reviewed models simultaneously include deterministic *and* stochastic elements. In particular, these models consist of, for example, a deterministic cost model and use a stochastic approach for optimizing the cost values. Such models are considered stochastic.

Although the nature of operational and economic parameters is stochastic, the analysis reveals that deterministic approaches, which do not incorporate probability distribution and the random values, are also applied in the domain of MCM.

1.4.2.6 Criterion 6: Consideration of time

Consideration of time is an important factor for developing the models. The majority of models encompass the explicit or implicit representation of time variables (i.e. dynamic or semi-dynamic). There are two models with mixed characteristics, i.e. one with static and dynamic parts and one with semi-dynamic and dynamic. In Figure 12, these models are counted as dynamic. The results confirm the importance of incorporating time factors in the context of MCM, i.e. developing semi-dynamic or dynamic models instead of static.

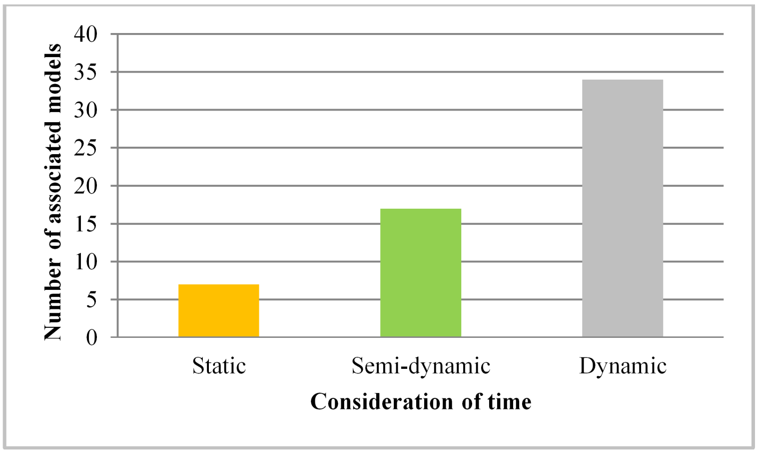

Fig.12. The consideration of time (Criterion 6) and number of the surveyed models associated with each expression.

1.4.2.7 Criterion 7: Scope of application

The bulk of the reviewed models are only applicable for solving unique problems. This issue is revealed through detailed analysis of the surveyed papers. For instance, if the author(s) indicates the application domain of a model with certain constraints for a product or system, the model is considered as situationally applicable. Once the author(s), in contrast, claims a universal solution or reference model, the model(s) is (are) classified in the category of universally applicable (cf. Figure 13).

The large difference in considering the scope of application puts the stress on developing more universal approaches with the capability to be adapted and customized for every particular situation.

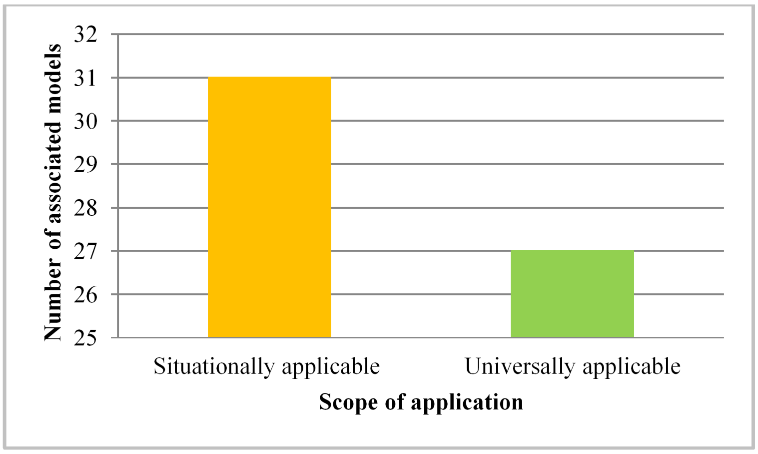

Fig.13. The scope of application (Criterion 7) and number of the surveyed models associated with each expression.

1.4.2.8 Criterion 8: Heuristic

Criterion 2 revealed the patterns for problem-solving in the surveyed MCM models (cf. Figure 8). Criterion 8 extends the analysis and compounds the insight into the use of heuristic *or* meta-heuristic approaches in the context of MCM (cf. Figure 14 & 15).

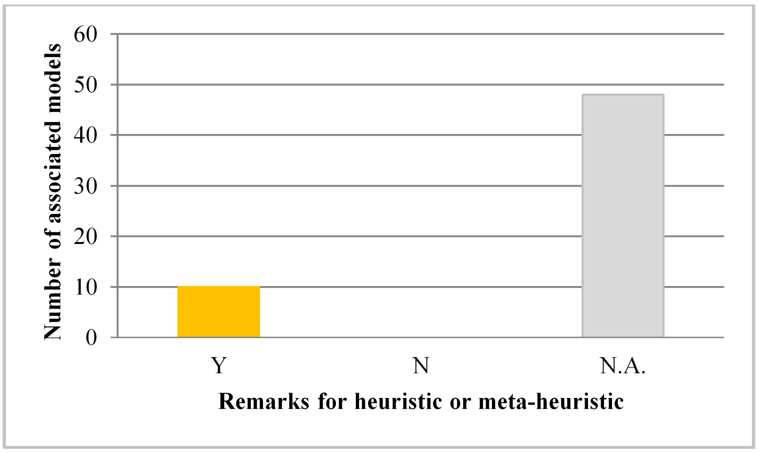

Fig.14. Remarks about using heuristic or meta-heuristic approaches (Criterion 8) in the surveyed models (Y: Yes, N: No, N.A.: Not Available).

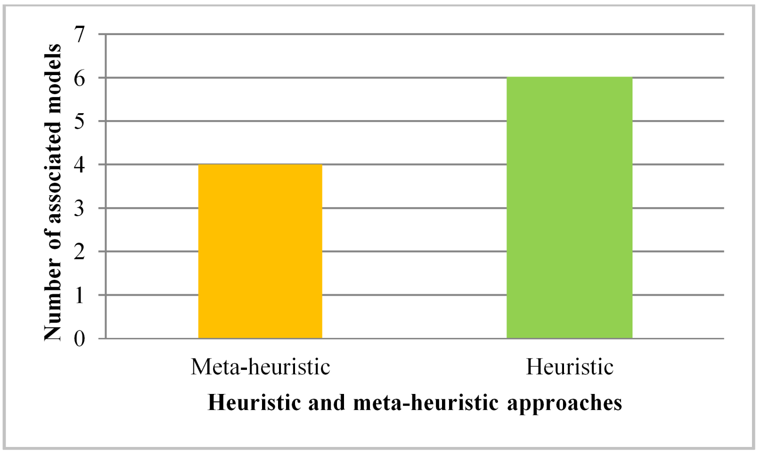

Fig.15. Comparison of the number of heuristic or meta-heuristic approaches in the surveyed models.

Most of the authors (of the surveyed articles) have neither refused nor indicated using heuristic or meta-heuristic approaches in MCM (cf. Figure 14 – Identifiers *N* and *N.A.*). Hence, a substantial lack is detected for denotation and classification of the reviewed models. This leads to three propositions that the heuristic or meta-heuristic approaches, in the context of MCM, are either obscure, unsuitable or not standardized terms. The evidence to confirm or reject the obscureness and unsuitableness of heuristic or meta-heuristic approaches in MCM is rare. However, only (Goyal, et al., 1985) and (Sung, et al., 2000) directly stressed that their approaches are the heuristic method, or that their models can be used in a heuristic procedure. In the case of meta-heuristic models, a confusion of terms might occur because of the use of standard terms such as optimization or approximation methods instead of meta-heuristic. Therefore, it is recommended to consistently define the terms in MCM (cf. Table 3).

Within the morphological analysis, the author has detected few models which can be classified either as heuristic or meta-heuristic (cf. Figure 15). Meta-heuristic approaches are the ones using a genetic algorithm except for the model of ECAY (Elegbede, et al., 2003). Heuristic approaches are determined based on the provision of solutions without guaranteeing the quality of answers, i.e. experience based or trial-and-error approaches (cf. Table 6).

1.5 Discussion on Criterion for Evolution of New MCM Model

Literature of maintenance includes a large number of models. The surveyed models have been selected with a major focus on economic, cost management, and/or business aspects of maintenance. Therefore, one cannot claim that this literature review itself covers all existing models. Nevertheless, the literature survey (cf. Section 1.3 and Appendix 7.1) and the morphological analysis (cf. Section 1.4) which appear in this dissertation are unique in terms of classification of MCM models.

The general pattern, detected through morphological analysis identifies the major characteristics of the surveyed models (cf. sub-section 1.4.2). It reveals the efforts to establish maintenance control models for bridging the gap of "planning-monitoring-controlling", as an important aspect in the literature of MCM. The study brings to the fore the major characteristics for the evolution of a novel reference model in MCM. In terms of problem-solving methodologies, most of the reviewing models use either incremental *or* synoptic approaches. This is a drawback to conventional MCM models (cf. sub-section 1.4.2.1). So a novel MCM model should be established based on new premises, i.e. *ends (goals)-means (alternatives)*[33]: to find the best (optimal) values corresponding to cost or other economic variables, while the evolution of the problem-solving is continuous. The trade-off between *ends* and *means* is achieved deploying knowledge assets of MCM (i.e. historical data, documented experiences, and domain expertise of the CMO) for reviewing the past events and planning future ones.

The objective of this dissertation is to develop a novel model of MCM for combining principles of incremental and synoptic approaches, and to utilize knowledge assets in maintenance cost controlling. The synoptic models cannot bridge the planning-monitoring-controlling gap, because of their limitation with planning. In this context, monitoring and controlling are related only to the operational level: "Did the staff carry out the planned?" But in terms of improvement of the maintenance cost controlling system itself, meta-information about its performance must be available. That is the core of justification and motivation for constructing a new model. In addition, the evolution of the model and its empowerment is achieved through a heuristic proce-

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[33] cf. sub-section 1.4.1 - Table 4

dure of testing and upgrading, i.e. trial-and-error. Hence, continuous learning from past events leads to the improvement of the MCM process, especially assisting the CMO in decision-making activities, i.e. planning-controlling maintenance program with optimum number of maintenance activities corresponding to the minimum of total cost and allocated budget. The combined approach deploys and integrates knowledge assets, either as explicit (or partially implicit) sources which are driven or used within the planning-monitoring-controlling process. This may lead to reinforcing the dynamic of knowledge assets, and support sustainable incremental changes to achieve desired organizational goals. In this way, the process of controlling will be merged with learning from past experiences, and ultimately leads to foster the discovering of improvement potentials for the (re)-design and (re)-formulation of MCM's strategies.

Table 7.Proposed characteristics of evolution of reference MCM model

Criteria	**Expressions**
1. Type of modeling	Combined (1.3).
2. Type of problem-solving	Combined (2.3).
3. Focus of purpose	Assist CMO in Decision-making (3.3).
4. Extent of the model	Partial (4.1).
5. Reaction of parameters	Deterministic (5.1) – (Non-stochastic).
6. Consideration of time	Semi-dynamic (6.2).
7. Scope of application	Universally applicable (Reference model) (7.2).
8. Heuristic	Yes.

As a result, the criteria for the evolution of the novel MCM model are concluded in Table 7. The proposed criteria are used in Chapter 2 and 3 for developing a new model entitled *Costprove*[34] (cf. Chapter 2). *Costprove* consists of mathematical and qualitative models. The mathematical model is formulated, based on the incomplete model of Hahn and Laßmann (1993). The qualitative (non-mathematical) model also originates in two levels: operational and strategic. *Costprove* aims at continuous improvement of MCM, through learning from past experiences (events). In order to realize *Costprove* as a tool to assist the CMO, CMMIS packages are analyzed and existing deficiencies are detected. The analysis results in defining requirements for implementing software tools for meta-analysis of structured and unstructured knowledge assets in the context of MCM (cf. Chapter 3). The *Costprove* Toolbox (software) is presented in Chapter 3.

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[34] *Costprove* stands for *two-level maintenance cost controlling system for continuous learning and improvement in MCM.*

2 *Costprove* - Mathematical and Qualitative Reference Model for MCM

2.1 Overview

The main objective of Chapter 2 is to develop a ***two-level maintenance cost controlling system for continuous learning and improvement in MCM*** *(Acronym:* ***Costprove****). Costprove* is a novel reference model to MCM and should encompass the proposed characteristics listed in Table 7 (cf. Chapter 1). It consists of mathematical and qualitative components.

The mathematical representation (model) is developed based on the incomplete mathematical model of Hahn and Laßmann (1993). *Costprove* considers deterministic and semi-dynamic behavior of parameters. The mathematical model provides the rationale to distinguish planned and unplanned maintenance costs. It coherently represents a minimum of total maintenance cost corresponding to the optimum number of maintenance activities. In particular, the model considers the cost/activity ratio for PM of single production machines, and calculates the optimal value corresponding to a number of activities and minimum of total cost. The scope of analysis is also extended to include all cost attributes of PM and CM activities for a number of non-associated machines. Finally, the calculated cost should be compared with the assigned budget subject to the forthcoming planning period. The shortage situation might occur due to the hidden/ignored costs of associated machines (i.e. series, parallel, or combined), or internal/external disturbances. In order to transfer the prevailing theory of Hahn and Laßmann (1993) and formulate the relations in terms of mathematical representation, two case distinctions are assumed in this dissertation.

- ***Case I*** is to formulate a cost / activity ratio and derive the optimum number of maintenance activities, and minimum of total maintenance cost. It is developed for **a single production machine,** and only considers PM costs (cf. Section 2.2). *Case I* is extended to employ a method for calculating total maintenance cost, based on time-dependent/independent cost items (including PM and CM costs) of maintenance for **disassociated (non-associated) single production machines** (cf. Section 2.3).
- ***Case II*** is to verify the outcomes of *Case I* by examining whether the net total cost (excluding unplanned cost) is less or more than the assigned budget. This may lead to further investigations for identifying the planned/unplanned cost raised due to the association of the machines, or internal/external disturbances. They directly have an effect on overall maintenance costing. In other words, it is to broaden the assumption of *Case I* and consider **the effect of *shortage situation*** (cf. Section 2.4).

The non-mathematical (qualitative) architecture of *Costprove* is designed with a premise of using combined principles of problem-solving, namely, synoptic and incremental. *Costprove* incorporates the mathematical representation and considers both operational and management level of maintenance to continuously improve MCM. *Costprove* is used for selection of the most desirable (optimal) decision alternative. The alternatives are developed based on heuristic procedure using the aforementioned cases as well as knowledge assets of MCM (e.g. historical data, documented experiences (reports), and domain expertise of the CMO).The model is, therefore, used to assist the CMO in decision-making activities. The algorithm for deploying the mathematical model is created (cf. Section 2.6) using the qualitative model of *Costprove*. In addition, the mathematical model is simulated and validated by interviewing people working within the relevant departments in industry and using real use-case scenarios (cf. Section 2.7 and 3.3).

2.2 Formulation of *Case I*

The total maintenance cost of a single production machine is calculated as the summation of planned and unplanned maintenance cost. It comprises the planned cost of downtime, inspection, or repair, and unpredicted downtime, including failure and repair costs, and loss of contribution margin (i.e. marginal profit per unit sale) in the case of a bottleneck. Figure 16 reveals the ideal and synoptic representation of maintenance cost attributes in terms of number of standardized PM activities over planning period t.

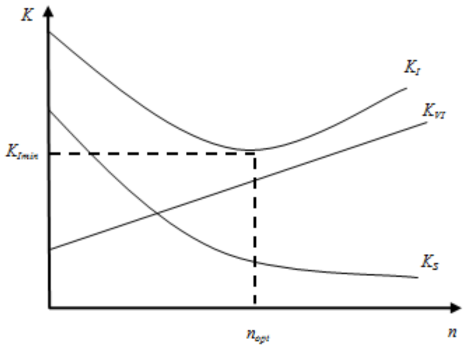

Fig.16. Maintenance cost of single production machine in terms of number of standardized PM activities (Hahn, et al., 1993).

The total maintenance cost (K_I) is interpreted through indication of planned (K_{VI}) and unplanned maintenance costs (K_S) as: $K_I = K_{VI} + K_S$[35]. The domain of the function $K_I = K_I(n)$ is the nonnegative real numbers $\mathbb{R}_+ = [0, \infty)$, however, practically n is calculated on the basis of nonnegative integers. The function image belongs to the nonnegative real numbers $\mathbb{R}_+$ as well. The argument n refers to the intensity of maintenance activities in a certain period that affects the planned and unplanned maintenance cost of operation in that period. The aim is to indicate the minimum (or desired value) of total maintenance costs ($K_{I_{min}}$), and consequently to determine the optimum number of maintenance activities (n_{opt}). Time-, age- and condition-based

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[35] The subscripts for total (I), planned (VI) and unplanned (S) costs are identical with the ones used in the incomplete mathematical model of Hahn and Laßmann (1993). The original source is in German (cf. (Hahn, et al., 1993)).

PM policies cause certain effects on the value of n. In fact, n is identified based on indication of the probability of failure in the context of aforementioned PM policies.

The approach of this dissertation, however, is to concentrate on economic parameters (mainly cost and budget), propose the desired value of cost and operation figures in each planning period, and control the deviations between actual and desired values to improve the forthcoming planning period. Since the approach is heuristic, the desired value is reached depending on the quality of records obtained by the CMO from operation, and also availability of historical data and documented experiences of the past events. Otherwise, the CMO needs to deepen his/her knowledge within a trial-and-error process.

Planned cost is defined in a valid manner, whereas unplanned cost is determined through investigating influential factors such as (1) monetary/tactical (e.g. number of affected machines in the downstream value chain), and (2) non-monetary/technical (e.g. probability of failure). Therefore the best choice that matches with reality should be decided in practice by the domain expert, for instance the CMO should select the most suitable curve representing unplanned maintenance cost. In this dissertation, two types of functions are used for modeling unplanned cost of a single machine, namely decreasing exponentiation and power functions. These two types cover a wide range of curves and are quite likely to resemble real cases.

Since the unplanned cost function is non-linear, the summation curve is expected to have a single (global) minimum that reveals the optimum number of maintenance activities (n_{opt}) for a single production machine in a certain planning period (e.g. per month). This optimum is directly associated with the minimum of total maintenance cost ($K_{I_{min}}$) in the corresponding maintenance costing period (cf. Figure 16). $K_{I_{min}}$ is the desired value for total maintenance cost.

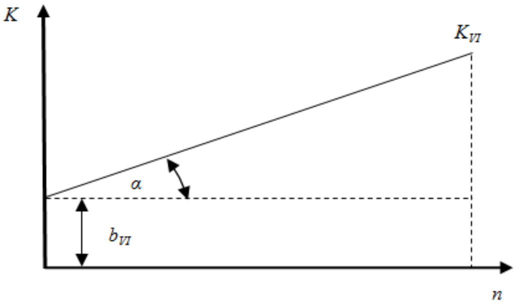

Fig.17. Attributes of the linear function for planned maintenance cost.

The planned maintenance cost ($K_{VI}(n)$) is assumed to be a linear function. K_{VI} consists of variable ($a_{VI} \cdot n$) and fixed costs (b_{VI}) which are represented in Equation 1 as:

$$K_{VI}(n) = a_{VI} \cdot n + b_{VI} \qquad \textbf{(1),}$$

a_{VI} ($a_{VI} = \tan \alpha$) is a slope of the linear function and is related to its angle of cline(α) (cf. Figure 17). b_{VI} is the K_{VI}-*intercept*. It points to the intersection between the graph of the function and the K-axis. b_{VI} Indicates a cost of doing nothing at $n = 0$, or invariable (constant) cost at $a_{VI} = 0$. The latter is, in fact, non-realistic. The parameters are supported on the interval $[0\ ,\infty)$ except $\alpha \in [0,\frac{\pi}{2})$.

The unplanned maintenance cost ($K_S(n)$) may be assumed to be a decreasing linear function. In this case, if K_{VI} tends to upward with a greater slope than the K_S tends to downward, K_I will be an increasing function (cf. Figure 18 – Left graph). Otherwise, function leads to find n_{opt} only at the intersection point of unplanned cost and the n–axis (cf. Figure 18 – Right graph). This means that the optimum number of maintenance activities and the minimum of total cost are only reached, when the unplanned cost reaches to zero. Such a case never happens in reality, and therefore this assumption cannot be approved.

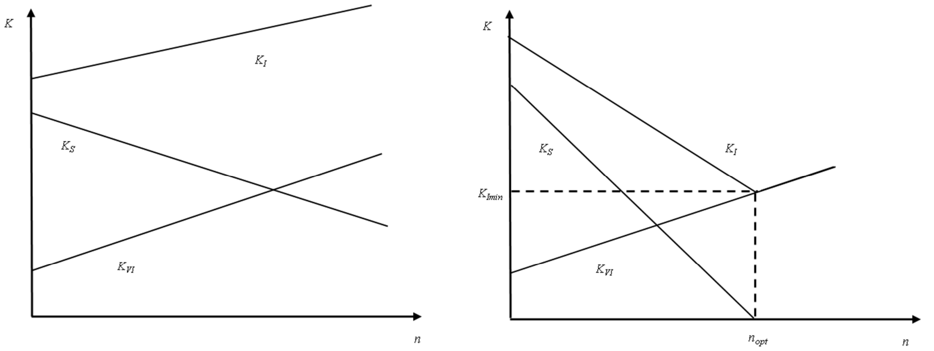

Fig.18. The adopted model of Hahn and Laßmann (1993) for linear representation of unplanned cost.

In the following, the unplanned cost is formulated using two major groups of **non-linear monotonic functions**; first exponentiation and second power function (cf. subsection 2.2.1 & 2.2.2).

2.2.1 Formulation of Unplanned Cost with Exponential Functions

A decreasing exponentiation function[36] representing unplanned cost is formulated in Equation 2:

$$K_S(n) = a_S \cdot A^{-(a_S^*)\cdot n} + b_S \qquad \textbf{(2),}$$

where A is the base and n is the power (index). A is a real number greater than 1 ($A > 1$). In the formulation, the minus sign is directly incorporated in the power. This stresses the decreasing nature of the function. n is normally a non-zero integer and cannot be expressed as fraction in the real world scenarios. a_S and a_S^* are rate parameters. The decreasing rate of unplanned cost might differ using the fractions or integers

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[36] In this section, “exponential formulation” refers to the entire group of exponentiation functions, and the term “exponential function” particularly refers to a case when $A = e$.

for the rate parameters specially a_S^*. b_S is a fixed parameter of unplanned cost which shows a constant value of $K_S(n)$ as n approaches infinity. The rate parameters can be equal or non-equal. These parameters are supported in the interval $[0, \infty)$.

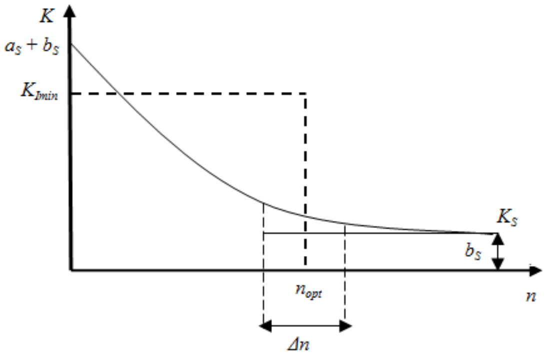

Fig.19. Attributes of the decreasing exponential function for unplanned cost.

Equation 3 presents the special formulation (exponential function) of unplanned cost where $A = e$.

$$K_S(n) = a_S \cdot e^{-(a_S^*)\cdot n} + b_S \qquad \textbf{(3)}$$

e is an irrational number approximately equal to 2.71828. As depicted in Figure 19, $K_S(n)$ has a global maximum at $n = 0$ which indicates the unplanned cost of doing nothing ($= a_S + b_S$). It is interpreted as K_S-*intercept* as well. The total maintenance cost of the single production machine in terms of number of standardized PM activities is elaborated in Equation 4 as:

$$\boldsymbol{K_I(n) = K_{VI}(n) + K_S\,(n) = [a_{VI} \cdot n + b_{VI}] + [a_S \cdot e^{-(a_S^*)\cdot n} + b_S]} \qquad \textbf{(4)}$$

$K_I(n)$ has a global minimum ($K_{I_{min}}$) at $n = n_{opt}$ $(n \in \mathbb{R}_+)$. It is distinguished by using the first derivative test of the Equation 4 as:

$$\frac{dK_I}{dn} = 0 \Rightarrow -(a_S \cdot a_S^*) \cdot e^{-(a_S^*)\cdot n_{opt}} + a_{VI} = 0$$

Equation 5 includes the results for equal and non-equal rate parameters of the exponential function.

$$\begin{cases} a_S \neq a_S^* \Rightarrow \boldsymbol{n_{opt}} = -\frac{\boldsymbol{1}}{\boldsymbol{a_S^*}} \cdot \boldsymbol{Ln}\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) \\ a_S = a_S^* \Rightarrow n_{opt} = -\frac{1}{a_S} \cdot Ln\left(\frac{a_{VI}}{{a_S}^2}\right) \end{cases} \qquad \textbf{(5)}$$

n is a nonnegative value, therefore, $Ln\left(\frac{a_{VI}}{{a_S}^2}\right)$ and $Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)$ must be negative, considering that the slope and rate parameters are non-negative too. This is the case if $\left(\frac{a_{VI}}{{a_S}^2}\right) < 1$ and $\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) < 1$. The natural logarithm ($Ln(x)$) is only defined for positive inputs, and thus the domain of the function with non-equal or equal rate parameters is:

$$\begin{cases} \mathbf{0} < \left(\frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S \cdot a_S^*}}\right) < \mathbf{1} \\ 0 < \left(\frac{a_{VI}}{{a_S}^2}\right) < 1 \Rightarrow 0 < \sqrt{a_{VI}} < a_S \end{cases} \tag{6}$$

Equation 5 (and supported criteria of Equation 6) calculates the optimum number of PM activities of a single machine, based on the slope (a_{VI}) and rate ters$(a_S\ \&a_S^*)$. If the calculated value for n_{opt} is used in Equation 4, then $K_{I_{min}}$ is computed. The process is shown in Equation 7:

$$\begin{cases} K_{I_{min}} = K_I(n_{opt}) = a_{VI} \cdot n_{opt} + b_{VI} + a_S \cdot e^{-(a_S^*) \cdot n_{opt}} + b_S \\ a_S \neq a_S^* \\ \Rightarrow K_{I_{min}} = -\frac{a_{VI}}{a_S^*} \cdot Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) + b_{VI} + a_S \cdot e^{(a_S^*) \cdot [\frac{1}{a_S^*} \cdot Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)]} + b_S \\ \Rightarrow K_{I_{min}} = -\frac{a_{VI}}{a_S^*} \cdot Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) + b_{VI} + \frac{a_{VI}}{a_S^*} + b_S \\ \Rightarrow \boldsymbol{K_{I_{min}}} = \frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S^*}} \cdot \left(\mathbf{1} - \boldsymbol{Ln}\left(\frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S \cdot a_S^*}}\right)\right) + (\boldsymbol{b_{VI}} + \boldsymbol{b_S}) \end{cases} \tag{7}$$

The formulation for non-equal rate parameters reveal the representation of $K_{I_{min}}$ when $A = e$. The same procedure is applied for generalizing the formulation when $A \neq e$. Equation 8 shows the result of the first derivative test.

$$\begin{cases} K_I(n) = K_{VI}(n) + K_S(n) = [a_{VI} \cdot n + b_{VI}] + [a_S \cdot A^{-(a_S^*) \cdot n} + b_S] \\ \frac{dK_I}{dn} = 0 \Rightarrow -(a_S \cdot a_S^*) \cdot A^{-(a_S^*) \cdot n_{opt}} + a_{VI} = 0 \\ a_S \neq a_S^* \Rightarrow \boldsymbol{n_{opt}} = -\frac{\mathbf{1}}{\boldsymbol{a_S^*}} \cdot \mathbf{log}_{\boldsymbol{A}}\left(\frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S \cdot a_S^*}}\right) \\ \mathbf{0} < \left(\frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S \cdot a_S^*}}\right) < \mathbf{1} \\ a_S = a_S^* \Rightarrow n_{opt} = -\frac{1}{a_S} \cdot \log_A\left(\frac{a_{VI}}{{a_S}^2}\right) \\ 0 < \left(\frac{a_{VI}}{{a_S}^2}\right) < 1 \Rightarrow 0 < \sqrt{a_{VI}} < a_S \end{cases} \tag{8}$$

It yields to calculate $K_{I_{min}}$ when $A \neq e$ for non-equal rate parameters (cf. Equation 9).

$$\boldsymbol{K_{I_{min}}} = \frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S^*}} \cdot \left(\mathbf{1} - \mathbf{log}_{\boldsymbol{A}}\left(\frac{\boldsymbol{a_{VI}}}{\boldsymbol{a_S \cdot a_S^*}}\right)\right) + (\boldsymbol{b_{VI}} + \boldsymbol{b_S}) \tag{9}$$

Obviously the simplified form (without major changes) will be used when rate parameters are equal $(a_S = a_S^*)$.

Table 8 presents the summary of findings for non-equal rate parameters $(a_S \neq a_S^*)$.

Table 8. Summary of formulations for exponential modeling of unplanned cost

Condition	Formulation
$A = e$	$n_{opt} = -\frac{1}{a_S^*} \cdot Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)$ $K_{I_{min}} = \frac{a_{VI}}{a_S^*} \cdot \left(1 - Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)\right) + (b_{VI} + b_S)$ $0 < \left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) < 1$
$A \neq e$	$n_{opt} = -\frac{1}{a_S^*} \cdot log_A\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)$ $K_{I_{min}} = \frac{a_{VI}}{a_S^*} \cdot \left(1 - log_A\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)\right) + (b_{VI} + b_S)$ $0 < \left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) < 1$

2.2.2 Formulation of Unplanned Cost with Power Functions

The unplanned cost can also be formulated with a decreasing power function as shown in Equation 10:

$$K_S(n) = a_S \cdot n^{-r} + b_S \qquad \textbf{(10),}$$

where a_S is a rate parameter, and b_S is a fixed unplanned cost which is the limit of $K_S(n)$ as n approaches infinity (i.e. $n \longrightarrow \infty$). a_S and b_S are supported in the interval $[0, \infty)$. r is a constant real number. Clearly, if $r = 0$, then the unplanned cost is constant. This assumption is out of the scope in real world scenarios. In the formulation, the minus sign is directly incorporated in the power. This stresses the decreasing nature of the function. n is normally a non-zero integer and cannot be expressed as fraction. Figure 20 depicts the adopted version of the model of Hahn and Laßmann (1993) using power function for formulating unplanned cost.

The total maintenance cost is calculated by Equation 11:

$$K_I(n) = K_{VI}(n) + K_S\,(n) = [a_{VI} \cdot n + b_{VI}] + [\,a_S \cdot n^{-r} + b_S\,] \qquad \textbf{(11)}$$

The global minimum of the Equation 11 is discovered using the first derivative test. The process is shown by Equation 12:

$$\frac{dK_I}{dn} = 0 \Rightarrow a_{VI} - \frac{r \cdot a_S}{n^{(r+1)}} = 0 \;\; \Rightarrow \boldsymbol{n_{opt}} = \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}} \qquad \textbf{(12)}$$

n_{opt} is a nonnegative value ($n_{opt} > 0$) which should be expressed as round number (non-zero integer) in practice.

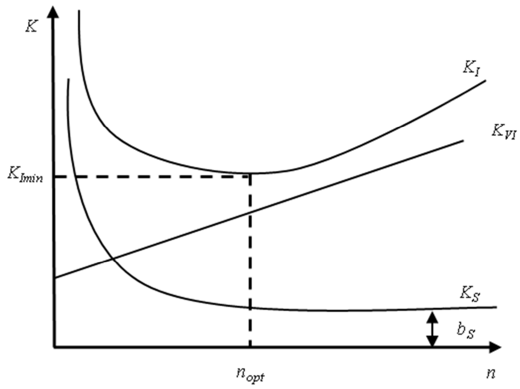

Fig.20. The adopted model of Hahn and Laßmann (1993) for representation of unplanned cost with power function.

Finally $K_{I_{min}}$ is calculated employing Equation 13:

$$K_{I_{min}} = [a_{VI} \cdot \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}} + b_{VI}] + [\, a_S \cdot (\left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}})^{-r} + b_S\,]$$

$$\Rightarrow \boldsymbol{K_{I_{min}}} = (\boldsymbol{a_{VI}} \cdot \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}} + \boldsymbol{a_S} \cdot \left(\frac{a_{VI}}{r \cdot a_S}\right)^{\frac{r}{r+1}}) + (\boldsymbol{b_{VI}} + \boldsymbol{b_S}) \quad \textbf{(13)}$$

A special type of power function is reciprocal (multiplicative inverse), where $r = 1$. In this context, the unplanned maintenance cost is represented in a simplified form in Equation 14:

$$K_S(n) = \frac{a_S}{n} + b_S,\ n \in (0, \infty) \quad \textbf{(14)}$$

The total maintenance cost in terms of number of PM activities is elaborated in Equation 15 as:

$$K_I(n) = K_{VI}(n) + K_S\,(n) = [a_{VI} \cdot n + b_{VI}] + [\frac{a_S}{n} + b_S\,], n \neq 0 \quad \textbf{(15)}$$

Employing the general formulation developed earlier (cf. Equation 12), it yields to calculate n_{opt} in Equation 16 as:

$$\boldsymbol{n_{opt}} = \sqrt{\frac{a_S}{a_{VI}}} \quad \textbf{(16),}$$

where $n \in (0, \infty)$. Using the optimum number of maintenance activities leads to compute minimum of total maintenance cost in Equation 17 as:

$$\boldsymbol{K_{I_{min}}} = (\boldsymbol{a_{VI}} \cdot \sqrt{\frac{a_S}{a_{VI}}} + \boldsymbol{a_S} \cdot \sqrt{\frac{a_{VI}}{a_S}}) + (\boldsymbol{b_{VI}} + \boldsymbol{b_S}) \quad \textbf{(17)}$$

Table 9 presents the summary of findings.

Table 9. Summary of formulations for modeling of unplanned cost with power function

Condition	Formulation
$r = 1$ Reciprocal	$n_{opt} = \sqrt{\frac{a_S}{a_{VI}}}$ $K_{I_{min}} = (a_{VI} \cdot \sqrt{\frac{a_S}{a_{VI}}} + a_S \cdot \sqrt{\frac{a_{VI}}{a_S}}) + (b_{VI} + b_S)$ $n \neq 0$
$r \neq 1$	$n_{opt} = \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}}$ $K_{I_{min}} = (a_{VI} \cdot \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}} + a_S \cdot \left(\frac{a_{VI}}{r \cdot a_S}\right)^{\frac{r}{r+1}}) + (b_{VI} + b_S)$ $n \neq 0$

2.3 Extension of *Case I*

PM policies (e.g. time-, age- or condition-based maintenance) have certain implications on CM activities. CM costs are, therefore, important in the calculation of the minimum of the total cost. PM and CM costs are interconnected and the border to differentiate them is not totally clear in all circumstances. For example, repeating of a certain type of failure may lead to revise the maintenance program and assign more inspection events rather than applying CM. Although *Case I* principally centers on PM, its basic propositions for representing cost attributes cover cost of CM. In this section, the scope of *Case I* is extended to deal with all cost items of each single (non-associated) machine, i.e. planned and unplanned subject to PM and CM such as (but not limited to) cost of maintenance of machines, material, manpower, process. Cost of maintenance activities is mostly estimated per unit of time. So, it is possible to establish a generic expression for representing the total maintenance cost of non-associated single production machines $\mu = (1, 2, \dots, m)$, based on time-dependent and time independent cost-intensive items. Equation 18 formulates the relation as:

$$\begin{cases} K_{I,11} \; = \; t_{11} \cdot C_{11} + t_{12} \cdot C_{21} + \cdots + t_{1\sigma} \cdot C_{\sigma 1} + K_{e,11} \\ \vdots \\ K_{I,\mu 1} = t_{\mu 1} \cdot C_{11} + t_{\mu 2} \cdot C_{21} + \cdots + t_{\mu\sigma} \cdot C_{\sigma 1} + K_{e,\mu 1} \end{cases} \quad \textbf{(18),}$$

where the cost of maintenance activity σ is defined in relation to constant cost-rate parameter $(C_{\sigma\rho})$, which stands for a rate of the activity $(\frac{Cost}{Time})$. $C_{\sigma\rho}$ represents cost-rates for both PM and CM activities of a machine. For instance, the charge per unit of time for regular inspection, planned/unplanned operation downtime, renting equipment, and manpower to perform activities like repair, adjustment, set-up, or assembly. Time-dependent parameter $(t_{\mu\sigma})$ is multiplied by $C_{\sigma\rho}$. It symbolizes duration of a certain maintenance activity of a single machine (e.g. regular inspection time). Moreover, the **residual cost** of PM and CM of a machine $(K_{e,\mu\rho})$ needs to be determined. $K_{e,\mu\rho}$ is calculated on the basis of the charge per activity (i.e. independent of time), e.g. cost of purchasing a spare part, material, equipment or new machine. Like time-dependent cost items, residual costs are raised due to planned or unplanned maintenance activities. Machine stoppage (idleness), for example, causes marginal costs such as the cost of downtime in the upstream machine.

Considering Equation 18, the arrays of expression are composed matrices for calculating the total maintenance cost of each single machine over a certain maintenance plan, which leads to Equation 19:

$$\begin{bmatrix} K_{I,11} \\ \vdots \\ K_{I,\mu 1} \end{bmatrix} = \begin{bmatrix} t_{11} & \cdots & t_{1\sigma} \\ \vdots & \ddots & \vdots \\ t_{\mu 1} & \cdots & t_{\mu\sigma} \end{bmatrix} \cdot \begin{bmatrix} C_{11} \\ \vdots \\ C_{\sigma 1} \end{bmatrix} + \begin{bmatrix} K_{e,11} \\ \vdots \\ K_{e,\mu 1} \end{bmatrix} \tag{19}$$

In Equation 19, PM activities are scheduled in a certain planning period ($\rho = 1$). However, maintenance activities of a machine are generally scheduled in $\rho = (1, \dots, p)$ planning periods. For example, a year can be divided into four planning periods (quartering), and thus $p = (1, 2,3,4)$. The CMO is responsible to define the maintenance program, including the time-plans and schedules. Considering various maintenance plans and a group of non-associated machines, the formulation of Equation 19 should be further developed. In particular, for p numbers of maintenance events (maintenance schedules) and m non-associated machines, the matrix representation in ($\mu \times \rho$) dimension is elaborated in Equation 20:

$$\begin{bmatrix} K_{I,11} & \cdots & K_{I,1\rho} \\ \vdots & \ddots & \vdots \\ K_{I,\mu 1} & \cdots & K_{I,\mu\rho} \end{bmatrix} = \begin{bmatrix} t_{11} & \cdots & t_{1\sigma} \\ \vdots & \ddots & \vdots \\ t_{\mu 1} & \cdots & t_{\mu\sigma} \end{bmatrix} \cdot \begin{bmatrix} C_{11} & \cdots & C_{1\rho} \\ \vdots & \ddots & \vdots \\ C_{\sigma 1} & \cdots & C_{\sigma\rho} \end{bmatrix} + \begin{bmatrix} K_{e,11} & \cdots & K_{e,1\rho} \\ \vdots & \ddots & \vdots \\ K_{e,\mu 1} & \cdots & K_{e,\mu\rho} \end{bmatrix} \tag{20}$$

$$\underline{\boldsymbol{K}_I} = \underline{\boldsymbol{t}} \cdot \underline{\boldsymbol{C}} + \underline{\boldsymbol{K}_e}$$

The outcome of Equation 20 is a matrix ($\underline{\boldsymbol{K}}$) in which each element is representing total maintenance cost of a single production machine $\mu = (1, 2, \dots, m)$ over distinctive maintenance plans $\rho = (1, 2, \dots, p)$. Table 10 reveals the expression of parameters of Equation 20.

In the formulation of Equation 20, two types of terms are used. First is planned/unplanned, second time-dependent/independent. These terms might be confusing. In the context of the mathematical model, these terms are defined as follows:

- Planned/unplanned refers to any type of maintenance activities which is identifiable/non-identifiable in a valid manner. So it does not address the time parameter or dependency of the item. For example, inspection is planned and time-dependent, while purchase can be planned but it is time independent. Here, time dependency means that the item can be rated as $\frac{cost}{time}$.
- In Equation 20, matrices ($\underline{\boldsymbol{C}}$) and ($\underline{\boldsymbol{K}_e}$) are time-dependent and independent, respectively.

Table 10. Expressions of the parameters of the matrix equation

Parameter	Dimension	Expression
$\boldsymbol{K_{I,\mu\rho}}$	Total maintenance cost (i.e. identifiable planned or unplanned cost) for the machine $\mu = (1, \dots, m)$ within the maintenance plan $\rho = (1, \dots, p)$	*Cost unit*
$\boldsymbol{t_{\mu\sigma}}$	Time-dependent parameter for maintenance of machine $\mu = (1, \dots, m)$ corresponding to maintenance activity $\sigma = (1, \dots, s)$	*Time*
$\boldsymbol{C_{\sigma\rho}}$[37]	Cost rate of maintenance activity $\sigma = (1, \dots, s)$ over maintenance plan $\rho = (1, \dots, p)$	*Cost/Time*
$\boldsymbol{K_{e,\mu\rho}}$	The residual maintenance cost for machine $\mu = (1, \dots, m)$ within the maintenance plan $\rho = (1, \dots, p)$	*Cost unit*
$\boldsymbol{m}$	Number of machines	---
$\boldsymbol{p}$	Number of maintenance plans	---
$\boldsymbol{s}$	Maintenance activity	---

Furthermore the cost-rate parameters and residual maintenance cost can be broken down into sub-components considering the classification of cost into two categories of planned and unplanned.

$$\underline{C} = \underline{C}_{Pl} + \underline{C}_{Unpl} = \begin{bmatrix} C_{11} & \cdots & C_{1\rho} \\ \vdots & \ddots & \vdots \\ C_{\sigma 1} & \cdots & C_{\sigma\rho} \end{bmatrix}_{Pl} + \begin{bmatrix} C_{11} & \cdots & C_{1\rho} \\ \vdots & \ddots & \vdots \\ C_{\sigma 1} & \cdots & C_{\sigma\rho} \end{bmatrix}_{Unpl} \qquad \textbf{(21)}$$

$$\underline{K}_e = \underline{K}_{e_{Pl}} + \underline{K}_{e_{Unpl}} = \begin{bmatrix} K_{e,11} & \cdots & K_{e,1\rho} \\ \vdots & \ddots & \vdots \\ K_{e,\mu 1} & \cdots & K_{e,\mu\rho} \end{bmatrix}_{Pl} + \begin{bmatrix} K_{e,11} & \cdots & K_{e,1\rho} \\ \vdots & \ddots & \vdots \\ K_{e,\mu 1} & \cdots & K_{e,\mu\rho} \end{bmatrix}_{Unpl} \qquad \textbf{(22),}$$

where subscripts $(\boldsymbol{Pl})$ and $(\boldsymbol{Unpl})$ refer to planned and unplanned classification of the matrices of cost-rate parameter and residual cost, respectively. Therefore, Equation 20 is extended as (cf. Equation 23):

$$\underline{K}_I = [\underline{t}_{Pl} \cdot \underline{C}_{Pl} + \underline{t}_{Unpl} \cdot \underline{C}_{Unpl}] + [\underline{K}_{e_{Pl}} + \underline{K}_{e_{Unpl}}] \qquad \textbf{(23)}$$

As a result, **extension of *Case I*** leads to the formulation of the matrix expression for computing total maintenance cost of **non-associated single machines**, based on time-dependent and independent cost-intensive maintenance activities. *Case I* and its extension have a substantial contribution to develop the mathematical components of *Costprove*. The incomplete mathematical model of Hahn and Laßmann (1993) repre-

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[37] A standard list of cost rates can be created to fill the matrix $(\underline{C})$. However, all considered cost items are not necessarily applied in each plan or for each machine. They should be identified in each use-case scenario.

sents the cost-activity relations without any indication regarding cost-time relation, and it indirectly considers the maintenance plans. So the matrix representation provides a basis for validating the calculated values for minimum of total cost corresponding to the optimum number of maintenance activities. In this context, the outcomes of equations presented in Table 8 and 9 can be validated or adjusted using the extension of *Case I*. The cooperation of both groups leads to the upgrading of the accuracy of calculations and estimations of coefficients and parameters. This issue is further discussed in Section 2.5 and 2.6.

2.4 Formulation of *Case II* for Preventing Shortage Situation

Case I and its extension mainly discuss maintenance costing of a single machine and further disassociated single machines. It fundamentally bridges analysis of a single machine to a set of machines. However, *Case I* does not consider the connection and association of machines. In production systems, two major types of association are distinguishable as ***serial*** and ***parallel***. These two types can be joined as schematically sketched in Figure 21.

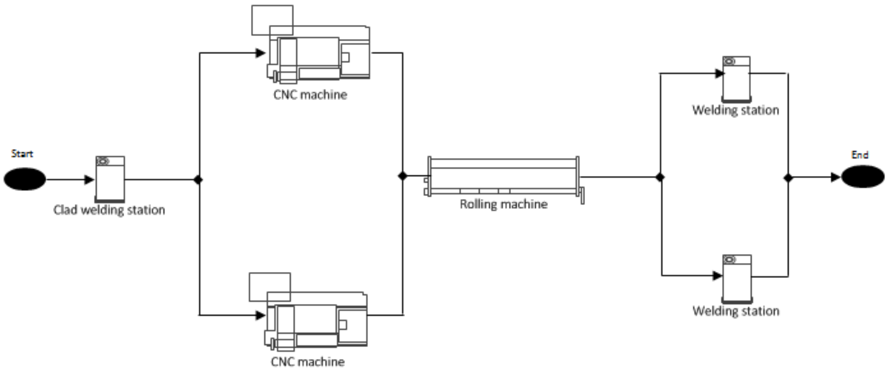

Fig.21. Schematic arrangement of machines in combination of serial and parallel association[38].

In practice, the CMO should assign a certain budget for maintenance activities of (a set of) machines in a certain period (p). He/she essentially should know how to reach the minimum of total maintenance cost through the optimal distribution of maintenance activities and estimation of the association effect of the machines. Coincidentally, the CMO needs to prevent exceeding the budget limit (i.e. shortage situation). Therefore the budget is known and distribution of maintenance activities with respect to the type of association is unknown. In addition to the effect of association, internal and external disturbances may raise extra costs. Examples are operational disturbances like sudden lack of physical or human resources, and also business disturbances such as economic crises and changes. A figure of merit is required here to examine:

(i) in the planning phase, whether the planned cost is sufficient, and
(ii) in the controlling phase, whether the planned cost was significant.

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[38] The image is sketched by the author for a better understanding of the content.

This process ultimately leads to learning from past experiences within the planning-monitoring-controlling of MCM.

A shortage situation occurs when the total budget for a set of machines (including serial or parallel association), in the presence or absence of disturbances, is less than the net sum of total maintenance cost. The figure of merit for the shortage situation is represented in Equation 24 as:

$$\boldsymbol{Shortage\ situation}\text{:}\,\boldsymbol{TMB} < \textstyle\sum_{\boldsymbol{i=1}}^{\boldsymbol{m}}(\boldsymbol{K}_{\boldsymbol{I_{min}}}^{\boldsymbol{i}} - \boldsymbol{TUC_i}) \qquad \textbf{(24),}$$

where TMB stands for the "*Total Maintenance Budget*" assigned to the CMO by the top management. $K_{I_{min}}^{i}$ is the minimum of total maintenance cost of a machine i (cf. Table 10 where $m = i$). $K_{I_{min}}^{i}$ is calculated using *Case I* and its extension (cf. Tables 8 & 9, and Equation 20). TUC_i denominates the *"Total Unplanned Cost"* of the machine (i) in the certain planning period (p). TUC_i is formulated in Equation 25 as:

$$\underline{\boldsymbol{TUC}} = \underline{\boldsymbol{t}}_{\boldsymbol{Unpl}} \cdot \underline{\boldsymbol{C}}_{\boldsymbol{Unpl}} + \underline{\boldsymbol{K}}_{\boldsymbol{e}_{\boldsymbol{Unpl}}} \qquad \textbf{(25)}$$

Firstly, Equation 24 calculates the net value corresponding to the minimum of total maintenance cost of a single machine (i.e. subtracting unplanned cost from total cost). Minimum of total maintenance cost is used to incorporate the lower limit that is applied for each machine. Then the summation ($\sum_{\boldsymbol{i=1}}^{\boldsymbol{m}}(\boldsymbol{K}_{\boldsymbol{I_{min}}}^{\boldsymbol{i}} - \boldsymbol{TUC_i})$) produces the net sum of total maintenance costs of m single machines. The net summation is required, because maintenance budget mainly covers planned and identifiable maintenance cost. The unplanned cost is the unidentifiable portion of the cost, either as time-dependent ($\underline{\boldsymbol{t}}_{\boldsymbol{Unpl}} \cdot \underline{\boldsymbol{C}}_{\boldsymbol{Unpl}}$) or residual ($\underline{\boldsymbol{K}}_{\boldsymbol{e}_{\boldsymbol{Unpl}}}$). The result of net summation is coherently compared with the assigned budget for the planning period p.

In conclusion, the figure of merit (Equation 24) is a measure for examining the accuracy in the planning phase of forthcoming events, learning from the past experiences, and preventing the occurrence of a shortage situation. In the case of a shortage situation, the CMO must recalculate the minimum of total maintenance cost of the machines. He/she in turn should redistribute the budget based on the riskiness of machines for the next period (e.g. due to ageing). Basically risky machines are very sensitive in terms of unplanned maintenance cost, and therefore the maintenance budget should be distributed in a way to provide adequate coverage for high risk machines.

2.5 Overall Findings and Limitations of Mathematical Modeling

As mentioned earlier in Section 2.2, planned cost (K_{VI}) of a single machine is determined in a valid manner (mode). *Case I* is developed within a heuristic procedure whereby the CMO identifies K_{VI}, based on existing documentation (e.g. historical data or technical reports) as well as his/her domain expertise. Here the quality of accumulated maintenance records (in CMMIS databases) and competence of the CMO are significant. In contrast to planned cost, determining unplanned cost (K_S) is difficult in an empirical way and requires the investigation of downtime consequences (e.g. for associated machines, processes, human resources, logistics and business process). K_S , therefore, is an opportunity cost which provides a possibility for improving MCM. Using the *Case I*, the CMO needs planned or unplanned costs to find the minimum of total cost and optimal number of maintenance activities. The extension of *Case I* also supports the CMO for improving the modeling of the maintenance cost by scaling up the number of machines (production lines), and considering different maintenance planning periods (including past and forthcoming events).

Table 11. The developed formulations of *Costprove* (*Case I* and *Case II*)

	Expression		Formulation
Case I	**Single machine**	Modeling of unplanned cost with exponential function	$n_{opt} = -\frac{1}{a_S^*} \cdot Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)$ $K_{I_{min}} = \frac{a_{VI}}{a_S^*} \cdot \left(1 - Ln\left(\frac{a_{VI}}{a_S \cdot a_S^*}\right)\right) + (b_{VI} + b_S)$ $0 < \left(\frac{a_{VI}}{a_S \cdot a_S^*}\right) < 1$
		Modeling of unplanned cost with power function	$n_{opt} = \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}}$ $K_{I_{min}} = (a_{VI} \cdot \left(\frac{r \cdot a_S}{a_{VI}}\right)^{\frac{1}{r+1}} + a_S \cdot \left(\frac{a_{VI}}{r \cdot a_S}\right)^{\frac{r}{r+1}}) + (b_{VI} + b_S)$ $n \neq 0$
	Disassociated Single machines	Total maintenance cost	$\underline{K_I} = \underline{t} \cdot \underline{C} + \underline{K_e}$ $\begin{bmatrix} K_{I,11} & \cdots & K_{I,1\rho} \\ \vdots & \ddots & \vdots \\ K_{I,\mu 1} & \cdots & K_{I,\mu\rho} \end{bmatrix} = \begin{bmatrix} t_{11} & \cdots & t_{1\sigma} \\ \vdots & \ddots & \vdots \\ t_{\mu 1} & \cdots & t_{\mu\sigma} \end{bmatrix} \cdot \begin{bmatrix} C_{11} & \cdots & C_{1\rho} \\ \vdots & \ddots & \vdots \\ C_{\sigma 1} & \cdots & C_{\sigma\rho} \end{bmatrix} + \begin{bmatrix} K_{e,11} & \cdots & K_{e,1\rho} \\ \vdots & \ddots & \vdots \\ K_{e,\mu 1} & \cdots & K_{e,\mu\rho} \end{bmatrix}$ $\underline{K_I} = [\underline{t}_{Pl} \cdot \underline{C}_{Pl} + \underline{t}_{Unpl} \cdot \underline{C}_{Unpl}] + [\underline{K}_{e_{Pl}} + \underline{K}_{e_{Unpl}}]$
Case II	**Associated machines**	Shortage situation	$TMB < \sum_{i=1}^{m}(K_{I_{min}}^{i} - TUC_i)$ $\underline{TUC} = \underline{t}_{Unpl} \cdot \underline{C}_{Unpl} + \underline{K}_{e_{Unpl}}$

Moreover, the CMO on his/her own cannot assure whether all calculations are right. A kind of system should assist the CMO to get a good grasp of modeling for calculating the maintenance cost of machines. *Case II* is used to review and control the previous planning period and improve the calculations for the forthcoming ones. In particular, it examines whether the estimated costs in *Case I* is realistic in comparison with the assigned budget. Otherwise the reasons for extra cost should be investigated (i.e. by indicating deviation from the desired values) and the calculations should be repeated.

In practice, a certain budget is assigned by the department of accounting for overall maintenance of the machines arranged in association or disassociation in the manufacturing/production line. *Case I* hypothetically estimates the unplanned costs of each machine through curve matching (cf. Section 2.2). The CMO starts calculating for a new planning period, and selects a curve which gives adequate results. This result is used for a maintenance costing, and accordingly related outcomes and monetary implications will be monitored and controlled for improving the next planning period, so called *planning-monitoring-controlling*. *Case I* and *II* together are the components of the mathematical reference model of *Costprove*. Table 11 summarizes the formulations developed in the context of *Costprove* for *Case I* and *II*.

The mathematical reference model is built through the use of a certain assumption and therefore has certain limitations. In terms of mathematical representation, only monotonic functions are used for modeling planned and unplanned maintenance cost (cf. Section 2.2 - *Case I*). Basically a monotonic function preserves the given order. A function is monotonically decreasing, if for all x and y such that $x \leq y \Rightarrow f(x) \geq$

$f(y)$. A monotonically increasing function fulfills the reverse inequality $(f(x) \leq f(y))$ whenever $x \leq y$. The representations of planned and unplanned maintenance cost are assumed as monotonically increasing and decreasing functions, respectively. Monotonic representation of planned and unplanned cost assumes no impulse/drifts in the cost. The total maintenance cost has a global minimum which is a turning point to change the slope of its function as well. Before the global minimum, the total maintenance cost is monotonically decreasing and after likewise increasing. This phenomenon is expected in practice. However, it does not determine disturbances to maintenance costing originating from internal/external sources, and business processes (such as effects of financial crises, unexpected lack of resources). In addition, the formulations always assume that the curves are developed in a continuous form. In reality cost and operational entities are scattered and the relation between selected values of x and observed value of y should be discovered using statistical methods. The mathematical model is not aimed at interpolating empirical data. It is used in a heuristic procedure to assist the CMO. The model is designed to provide reference values for assisting the CMO in planning-monitoring-controlling of MCM. It requires the interaction of the CMO, because the model is not self-adaptive. Notably, the model only considers maintenance cost and not the entire economic aspects of maintenance life cycle.

As a result, the mathematical reference model provides entries for meta-analysis of maintenance cost figures which enables the CMO to adapt and improve maintenance costing, and consequently the management of maintenance (cf. Chapter 3- Section 3.4). The qualitative model and algorithm for deploying *Case I* and *II* in a real world scenario are presented in Section 2.6. To prove the capability and usability of the model, Section 2.7 discusses the simulation and validation of the model using a sample use-case scenario.

2.6 Qualitative Modeling and Conception of *Costprove*

The primary objective of this dissertation is to establish a combined model to support the CMO in the cost controlling processes. The model, *Costprove*, should deploy knowledge assets of maintenance for improving MCM through continuous learning from the past events (former planning periods) and experiences. The reason is that the CMO is usually engaged in decision-making activities. So he/she should employ knowledge assets such as maintenance records, technical reports, his/her domain expertise and experiences.

The desired characteristics of the model have been discussed in Table 7 (cf. Chapter 1). Development of the mathematical model is a major step to fulfill Criterion 1 (i.e. type of modeling), and also Criterion 4 to 7 (i.e. extent of the model, reaction of parameters, consideration of time, and scope of application). At this point, it is important to establish a qualitative model to combine a mathematical and non-mathematical approach to modeling. The combined model should also simultaneously encompass synoptic and incremental principles of problem-solving (cf. Criterion 2 of Table 7). In addition, the model should be applied in a heuristic procedure. This ultimately results in exploring existing knowledge assets and exploiting new knowledge in MCM. In this section, aforementioned features are considered for qualitative modeling and conception of *Costprove*.

In the context of MCM, the CMO needs to understand not only the way the plant operates, but also its relationship to the business objectives and annual budget provided by the CEO[39]. He/she should know the precise maintenance capacity, i.e. physical, human, and intellectual resources. Furthermore, there are numerous inter- and intra-organizational factors influencing the MCM process, such as department relationship, industrial relation, safety, or labor market. Figure 22 depicts the two-level structure of *Costprove* (i.e. Qualitative model). It consists of a meta-level (A-B-C), and basic or object-level (D-E-F). The process flow consisting of the blocks D-E-F is a closed loop, in that maintenance operation is planned and conducted. Sub-loop D-E is to monitor the maintenance process and related activities. The attainment of the planned goals is monitored and reported to meta-level, i.e. fulfilling operational objectives (PM and CM programs and work orders) based on planned cost and available budget. The CME uses standard mathematical models/KPIs (cf. Component E) to plan and monitor maintenance operations and related expenditures. These mathematical models or KPI can differ based on the requirements for each special use-case scenario (cf. Appendix 7.1). He/she is, therefore, assisted to plan, conduct or predict maintenance schedules, programs and events in the plant (cf. component F). Ultimately the CME can estimate required resources, budget and planned costs for the financial calendar (such as forthcoming months, or year). Also the CME can optimize workload and interval of tasks to comply with the given budget (cf. component C). Only those activities which are successfully tested in the sub-loop will be realized, and, of the realized ones, only the approved activities are documented and reported by the CME. Thus the object-level includes an internal step in learning from the initial estimations and improving the planning and monitoring of maintenance.

Moreover, the chief aim of the CME is to efficiently employ physical resources and labors within the maintenance schedule to keep the operation system (production system) available and reliable. To this extent, he/she deals with operation and engineering disturbances such as lack of physical or human resources, environmental, safety and longevity requirements. Both types of disturbances impose additional (unplanned) costs. Thus, the CME has to utilize monitoring, planning and evaluation tools/models to regularly analyze collected data, and combine the empirical analysis with statistical or probabilistic models to predict upcoming event and preserve the maintenance operation stable. In practice, the CEO uses the CMMIS and computer-aided solutions for managing the activities of the object-level (D-E-F)[40].

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[39] Since the CMO is responsible for strategic management of maintenance, he/she should be able to co-operate and communicate with the CME to capture operational data. The responsibility of the CMO and CME might differ based on organizational structures. In this dissertation, operational tasks are assigned to the CME and strategic tasks to the CMO. Thus the CME is working under the authority of the CMO (cf. Chapter 1- sub-section 1.2.2).

[40] Features and functionalities of the CMMIS are discussed in Chapter 3.

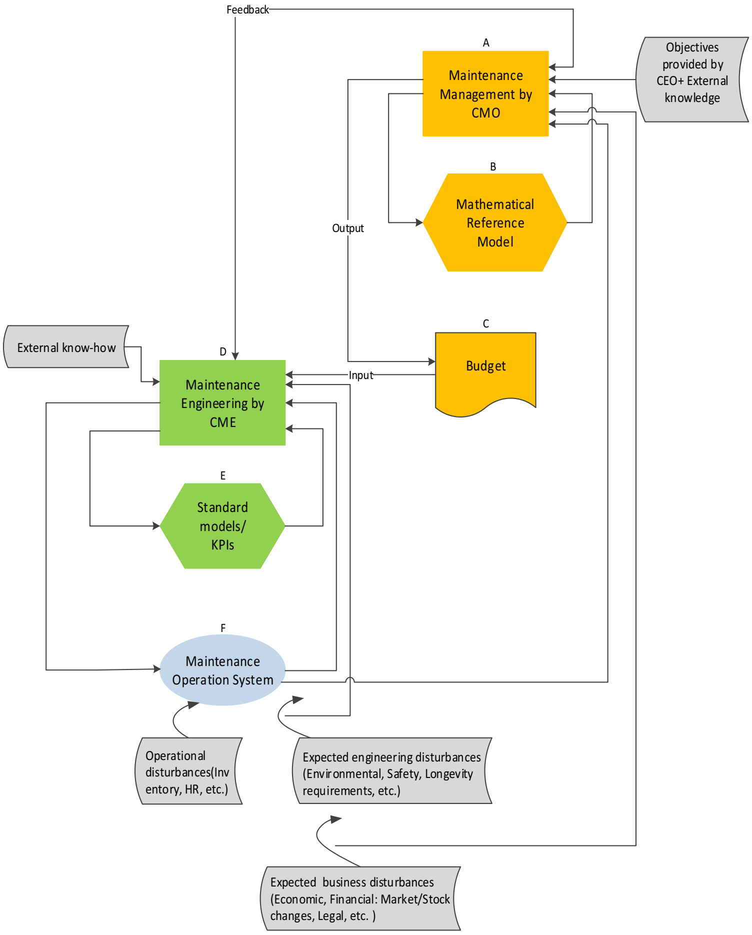

Fig.22. Qualitative modeling of *Costprove*– Conception[41].

At the meta-level, the CMO is responsible of controlling whether the planned operational objectives are achieved, based on estimated (planned) cost and available budget. The process of controlling is to (1) assess and examine the desirability of the current (actual) state, (2) detect improvement potentials, and (3) (re)formulate strategies for the next planning period (e.g. financial year). The CMO receives feedback via multiple channels. He/she monitors the activities of the CME and has direct access to operational information. The CMO has to communicate with senior managers (CEO)

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[41] The theory of designing multilevel systems was initiated by Mihajlo D. Mesarovic cf. (Mesarovic, et al., 1970). A two-level (dual loop) model for production management was originally proposed by Hans Blohm cf. (Blohm, 1977). Both approaches have inspired the conception of *Costprove*.

to assure accomplishment of business (production economy) objectives. Therefore, he/she should consider multiple factors in making decisions. The CMO is bridging the "*planning-monitoring-controlling*" gap, by indicating deficiencies and improvement potentials, (re)design of strategies, and refining the budget estimates. Thereby the CMO controls and supervises the proper function of the D-E-F loop, and considers organizational preferences and expected business disturbances (e.g. increase of wages due to economic crises, financial or stock market changes, legal issues). To make a decision, the CMO needs to identify assumptions, define certain alternatives, estimate risks and select the best solution (cf. sub-loop A-B). The CMO can distinguish and describe the problem, but to (re)design strategies he/she crucially should be aware of historical data and collected information within maintenance activities. The CMO uses the CMMIS database to review the documentations regarding the current state of operation and expenditures. He/she, therefore, may effectively use his/her domain expertise, and combine it with related objective analysis of maintenance records. Considering the substantial contribution for further development of the synoptic model of Hahn and Laßmann (1993) (cf. Table 11), the CMO has a reference model that can be used to incrementally improve planning-monitoring-controlling activities. The mathematical model is used to estimate planned and unplanned cost, calculate a minimum of total maintenance cost and accordingly optimize the number of maintenance activities (i.e. economic approach to MaM). The model benefits the CMO to prove/reject the hypotheses deduced through analysis and review process.

The qualitative model of *Costprove* (cf. Figure 22) consists of both operational and managerial layers. In the D-E-F loop, the maintenance operations are conducted e.g. for production system/plant, including manufacturing machines like rolling, welding, drilling, etc. The association of machines can differ from serial, parallel or hybrid (combination of serial and parallel). *Costprove* mainly deals with financial data, i.e. planned/unplanned cost and budget as well as operational meta-data, e.g. number of PM activities. Financial data collected from maintenance operation system are used firstly to plan and monitor the system, and secondly to control achievement of the predefined objectives of maintenance costing. Firstly, in the loop D-E-F, it is significantly important to consider major operational factors such as number of maintenance activities, time intervals, assigned physical and human resources, a machine's lifetime, and secondly to distribute the planned budget for the operational expenditures. It is also necessary to comply with availability and reliability requirements of the production system. In this way, standard PM or CM methods can be used. For the cost life cycle, it is important to document expenses in accordance with budget. This process should monitor accomplishing planned cost of the financial calendar, and identify unplanned cost raises within the time period. In the A-B-C loop, the major data sources are cost and budget sheet acquired from the operational layer. Plus, the CEO's objective should be taken into account, such as the assigned budget for new financial calendar and related production economy's objectives, which may be influenced by expected business disturbances (e.g. intra-organizational factors). Evaluating the current situation is tailored to monitoring the cost life cycle and detecting improvement potentials in the estimation of planned and unplanned cost as well as distribution of budget for maintenance of machines. In this line of reason, two case distinctions are useful (cf. Section 2.2, 2.3 and 2.4). The analysis firstly starts by focusing on the cost of a single machine or disassociated machines (*Case I and its extension*), and resumes the examination of whether the estimated cost is realistic and valid in corresponding to the given budget (*Case II*). In *Case II* the association of machines may cause extra maintenance cost. For example in the value chain, stoppage of a machine can raise overload for upstream or minor load for downstream machines. This is an important factor to discover unrecognized (planned and unplanned) costly-items in *Case I*. Additional influential factors are internal and external disturbances such as operational, engineering and business-related disturbances. In the case of a shortage situation, the CMO should investigate ignored or hidden cost items. The CMO can iteratively repeat the steps to prove his/her hypotheses, and decide for assigning and (re)distributing the budget for the next planning period. Also, the CMO has enough evidence to discuss with the CEO and CAO for the adoption of the budget, if necessary, and to (re)-formulate or (re)-design operation strategies in cooperation with the CME. Hence a learning process occurs which should be documented. The entire process is continued by applying the updated strategies and gathering new data for the next planning period.

Table 12. Guideline to identify tasks of planning-monitoring-controlling in *Costprove*

	Planning (in period t with figures for period $t+1$)	**Monitoring** (in period $t+1$ with figures for period $t+1$)	**Controlling** (in period $t+1$ with figures for periods t and $t+1$)
Planned maint. cost	Defining the parameters a_{VI}, b_{VI} as targets, based on experience, historical data, and actual goals of the company	Achieving the real parameters from the period $t+1$	Comparison of planned and realized figures, analyzing the deviations **Outcome:** Information to improve efficiency of maintenance and efficiency of planning
Unplanned maint. cost	Formulation of the cost function, including defining the parameters as a prognosis, based on assumptions, historical data, etc.	Achieving the real parameters from the period $t+1$	Comparison of predicted and realized figures, analyzing the deviations **Outcome:** Information to improve the forecast of the parameters of unplanned cost in period $t+2$
Total maint. cost	Calculating the sum of planned and unplanned costs	Calculating the sum of planned and unplanned costs	See above
Number of maint. activities	Calculating optimum by minimizing total cost	Ascertaining the actual number	Analyzing the deviations, improvement of the planning process in period $t+2$

The tasks of planning-monitoring-controlling in the context of *Costprove* are described and detailed in Table 12. It elaborates the major tasks in each phase (i.e. planning, monitoring and controlling) in relation to the parameters of the mathematical model (i.e. planned/unplanned cost, total cost and number of maintenance activities).

On this basis the algorithm for employing *Costprove* is developed (cf. Figure 23). The algorithm is executed in 18 steps which are instructed as follows.

Step 1: Start implementing the Equation 23
→**Knowledge assets:** (1) documentations of each machine, (2) documentation of past/running planning period, and (3) documentation of the given budget for the forthcoming period

Step 2: Generate matrices for planned cost rates ($\underline{C}_{Pl}$) and residual cost ($\underline{K_e}_{Pl}$)

Step 3: Generate time matrix ($\underline{t}_{Pl}$) for each planned maintenance activity

Step 4: Multiply time matrix cost rate for planned maintenance cost (cf. Step 2)

Step 5: Sum results of Step 4 and residual cost (cf. Step 2)
→ **Outcome:** Total planned cost matrix of each single machine ($\underline{K_I}_{Pl}$)

Step 6: Identify desired value for the attributes (a_{VI}, b_{VI}) of the planned cost (cf. Equation 1)

Step 7: Identify the planned cost function (K_{VI}) of each single machine

Step 8: Estimate parameters of unplanned cost (a_s, b_s) (cf. Table 8 and 9)
→ **Note:** Also a_S^* and r should be estimated depending on the type of selected curve (cf. Table 11)

Step 9: Identify unplanned cost function of each single machine (K_S)

Step 10: Calculate total cost function of each single machine (K_I)

Step 11: Estimate and generate unplanned cost rates ($\underline{C}_{Unpl}$) and residual cost ($\underline{K_e}_{Unpl}$), considering $\underline{K_I}_{Pl}$ and K_I

Step 12: Examine the estimations of unplanned costs in comparison with historical data, IF (the results are not realistic) THEN (Redo steps 8-9-10-11) OR ELSE proceed to Step 13

Step 13: Estimate and generate time matrix ($\underline{t}_{Upl}$) of unplanned maintenance activities (cf. Table 11)

Step 14: Calculate matrix of total unplanned cost ($\underline{TUC}$) (cf. Equation 25)

Step 15: Calculate total cost matrix ($\underline{K_I}$)

Step 16: Calculate minimum of the total maintenance cost ($K_{I_{min}}$)
→ Use results of Steps 6 and 8 (cf. Table 11)

Step 17: Calculate the optimum value of the number of maintenance activities (n_{opt}) (cf. Table 11)

Step 18: Examine the shortage situation (cf. Equation 24)
→IF (Shortage occurs) THEN (redo from Step 1)
OR ELSE start forthcoming planning period

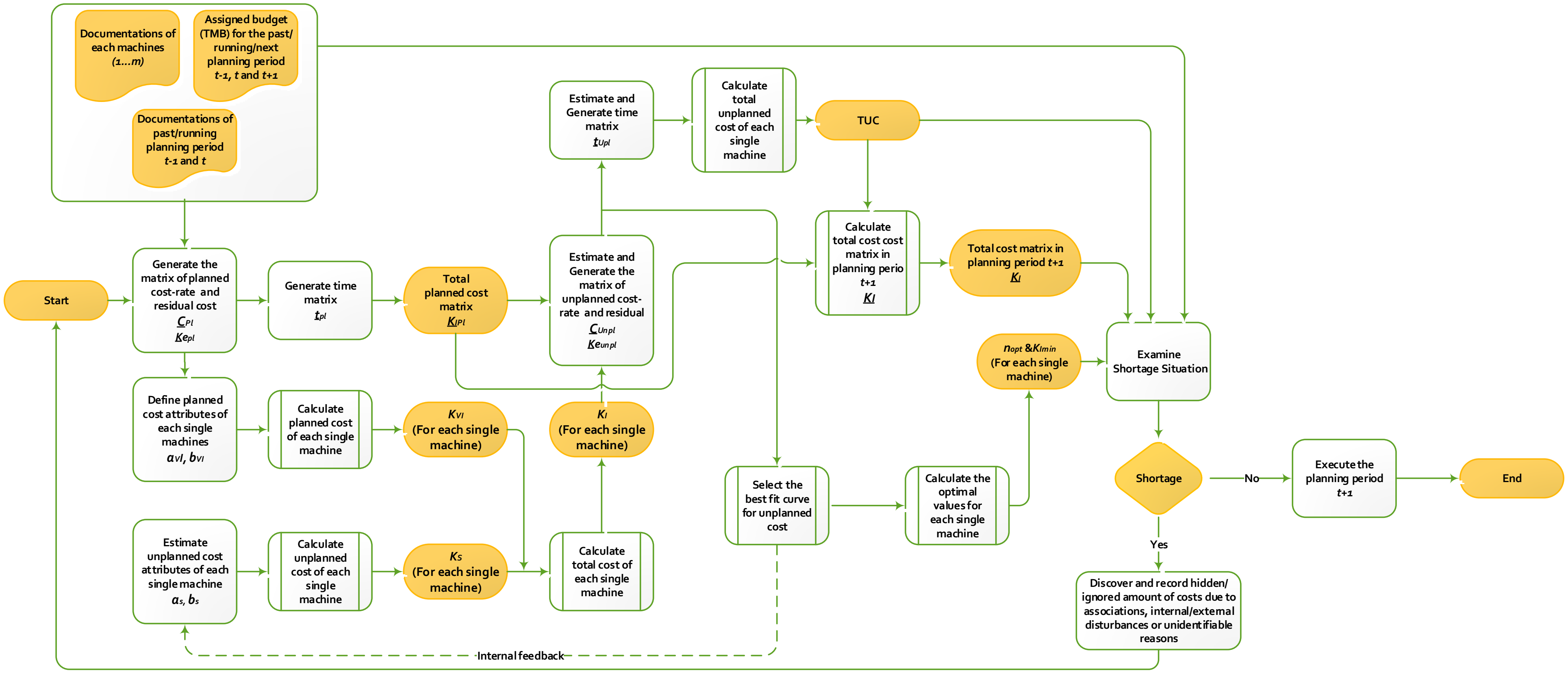

Fig.23. The algorithm for deploying the mathematical model in the context of *Costprove*.

As a result, *Costprove* is a cost controlling model made up of components which support the entire process of planning, monitoring and thus controlling in MCM. It uses a feedback loop to exchange data between meta- and object-level, transmit feedback information from object- to meta-level, and in contrary objectives and budget information from meta- to object-level. *Costprove* also employs feed-forward to employ expected business and engineering disturbances before their impacts reach the system (cf. Figure 22).

The *Costprove* model presents a general approach that should be customized for various application contexts. This issue is discussed in Section 2.7.

2.7 Application Study of *Costprove*

In this section the *Costprove* model is simulated for a sample use-case scenario. Firstly, an overview about the use-case is given. Secondly, the opportunities detected for improving MCM through use of the *Costprove* model are discussed.

The vessel manufacturing company (VMC)[42] produces pressure and storage vessels, vessels' parts and also provides manufacturing services. The production type is engineer-to-order. The annual percentage of the production tonnage is depicted in Figure 24.

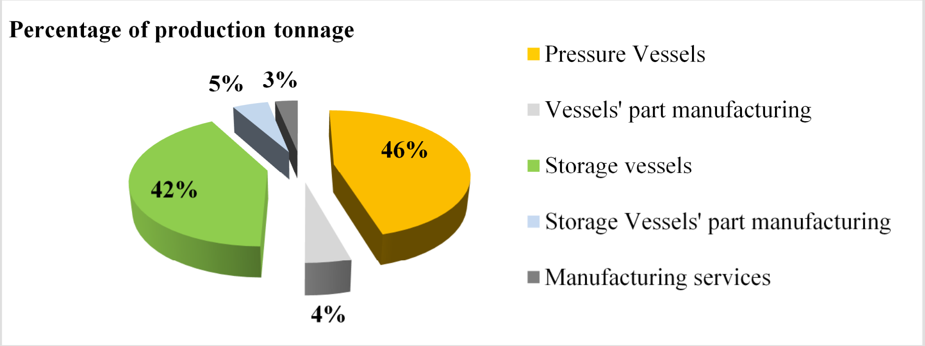

Fig.24. Annual percentage of production tonnage for product and manufacturing services.

The manufacturing plant of VMC consists of nine work stations (WS). The layout of the plant is sketched in Figure 25. VMC implements PM, emergency maintenance and CM programs. Considering work orders and the type of products, the annual maintenance cost varies between 5-15% of the total production costs. Table 13 reveals details of VMC's maintenance costs.

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[42] Detailed information about the company is available with the author.

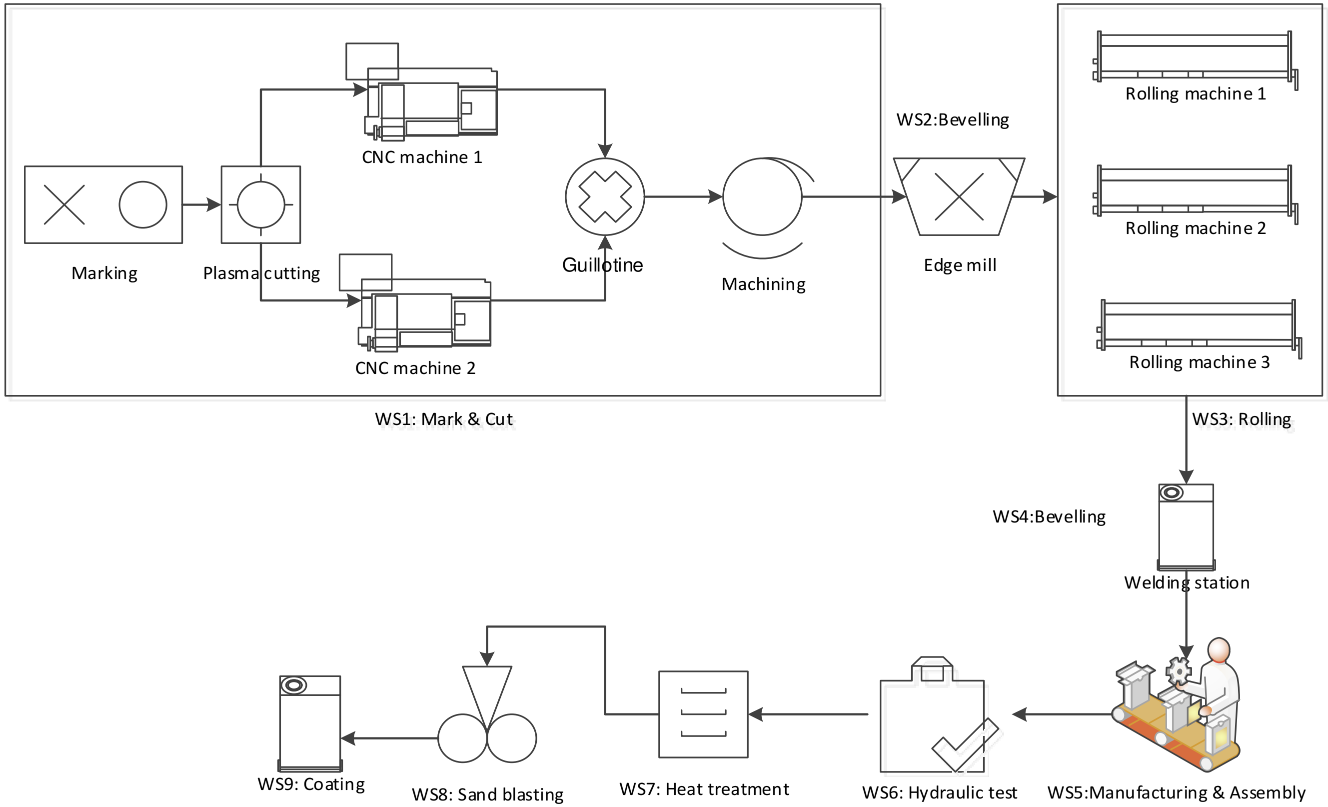

Fig.25. Layout of the use-case production plant sketched by the author

Table 13. Type and percentage of maintenance cost at VMC

Type of maintenance cost	**Percentage**
Preventive repairs	15 %
Spare parts	55 %
Human resources	10 %
Process-related	15 %
IT and information systems	~2 %
Management	~3 %

The task of finding an appropriate use-case is quite difficult due to the importance and security of cost data for manufacturing companies. The case study in the context of VMC is defined based on the real data and accordingly the records have been adjusted by defining criteria for simulation of the results. Therefore the values do not express the real cost or the number of activities, and the records have been adopted to fulfill required test data for validation of the mathematical model in collaboration with the domain expert. The case study is implemented for cost controlling of two computerized numerical control (CNC) machines shown in Figure 25. Both machines are identical; however, CNC_1 reached 60% of its lifetime while CNC_2 passed 30%. The analysis is applied in the course of annual cost planning periods of the machines.

The **procedure** of the analysis is defined in certain steps as:

1. CMO provides the actual number of PM activities and associated total cost over the planning periods as well as his/her estimations for optimal values
2. CMO uses the mathematical model (based on the algorithm presented in Figure 23) and starts initiating the calculations based on his/her domain expertise
3. CMO validates the calculations based on the procedure described in Figure 23 (criteria for shortage situation)

Propositions used by the CMO:

1. Maximum budget assigned to PM is 8,000 for both machines in each planning period
2. Maximum number of PM activities should not exceed 70 per planning period for each machine

The actual state of maintenance planning does not fully match with the desired values in all planning periods. The results of the analysis are presented in Table 14. It consist of four columns representing (1) empirical data gathered from reports of the engineers and operators, (2) the optimal situation estimated by the CMO without use of the mathematical model, (3) the optimal situation estimated by the CMO with the use of the *Costprove* and (4) the detected opportunity cost. Notably, the cost quantities are disassociated with standard units of measurement.

Table 14. Result of the case study in VMC

Empirical data recorded from the actual situation in planning period p				**Optimal situation estimated by CMO without *Costprove* model for planning period $p + 1$**		**Optimal situation estimated by CMO with *Costprove* model for planning period $p + 1$**		**Opportunity cost (difference between optimal estimations)**	
Maintenance plan	Type of machine	Number of actual PM	Actual total cost	Optimum number of PM	Optimum total cost	Estimated PM	Estimated cost	Saved cost	Percentage
1	CNC_1	67	5834.00	62	5500.00	58	5389.00	111.00	~ 2.02 %
1	CNC_2	54	2510.00	52	2300.00	48	2134.50	165.50	~ 7.20 %
2	CNC_1	75	6200.00	69	5800.00	63	5450.00	350.00	~ 6.04 %
2	CNC_2	58	2590.00	52	2450.00	49	2185.50	264.50	~ 10.79 %
Total			**17134.00**		**16050.00**		**15159.00**	**891.00**	**~ 5.55 %**

2.8 Discussion

Costprove is a reference model for assisting the CMO in the MCM and related decision-making activities. The model reinforces cost controlling and leads to durable decisions in the long-run. The model is innovative and effective due to the integration of two-level in one frame, and also the use of knowledge assets, respectively. In Table 15, the identifiers of the criteria for the design and development of *Costprove* are summarized. It assures the achievement of the predefined objectives (cf. Chapter 1 – Table 7).

Table 15. Identifiers of predefined criteria in the *Costprove* model

Criteria	Expression	Identifiers
1.Type of modeling	Combined (1.3)	✓ Mathematical reference model (cf. Table 11). ✓ Qualitative model of *Costprove* (cf. Figure 22). ✓ Guideline to identify tasks (cf. Table 12). ✓ Algorithms for deploying the mathematical model (cf. Figure 23).
2. Type of problem-solving	Combined (2.3)	✓ Synoptic: Targeting optimum and minimum values for maintenance activities and total cost. ✓ Incremental: Iterative approach, use of maintenance records such as historical data or experience, integration of feedback, closed-loop architecture.
3. Focus of purpose	Assist CMO in Decision-making (3.3)	✓ Providing evidences (facts/artifacts) for assisting CMO in decision-making. ✓ Deepening CMO's insight into MCM.
4. Extent of the model	Partial (4.1)	✓ Covers only cost/activity ratio. ✓ Does not cover all maintenance cost life cycle and production economy factors.
5. Reaction of parameters	Deterministic (5.1) – (Non-stochastic)	✓ There is no probability distribution in the formulations. ✓ Uses non-random evolution of parameters.
6. Consideration of time	Semi-dynamic (6.2)	✓ The mathematical model does not include explicit time parameters. ✓ The model considers evolution of parameters over time span. ✓ Only time rates are used in the matrices for calculating cost of time-dependent activities (cf. Table 11).
7. Scope of application	Universally applicable (Reference models) (7.2)	✓ *Costprove* is developed in a generic form to be customizable for a group of problems not only for one type of machines.
8. Heuristic	Yes	✓ The model is developed in heuristic procedure and therefore could not guarantee the attainment of the desired result in the first use. ✓ The formulation is simplified to support easy-use of CMO.

The case study is carried out using real data provided by VMC (cf. Section 2.7). It compares the actual state of cost controlling and optimal situations estimated by the CMO in two different ways, first using his/her domain expertise and second with the assistance of the mathematical model. Use of the *Costprove* model, in this example, has raised opportunity for cost saving, for instance, through comparing the calculations of the CMO without and with the use of the mathematical model (cf. Table 14).

At this point it is quite important to consider conditions and restrictions for using the *Costprove* model. These are listed in the Table 16.

Table 16. Conditions and restrictions for employing *Costprove* in practice

<table>
<tr><th>Recommended situations</th><th>Scope of use</th></tr>
<tr><td>Planning</td><td>• Zero-based budgeting.
• History-based budgeting.
• Identification and analysis of MCM alternatives.</td></tr>
<tr><td>Monitoring</td><td>• Comparing the actual and planned state of cost and activities.
• Early stage detection of shortage situation.</td></tr>
<tr><td>Controlling</td><td>• Detecting of planning gaps, i.e. hidden/ignored costs.
• Improving the forthcoming planning.
• Providing feedback for the operations, i.e. engineers and operators.</td></tr>
<tr><th colspan="2">Restricted situations</th></tr>
<tr><td colspan="2">Real time planning: The model is used once the planning is initiated or should be closed. Therefore, it cannot provide real time assistance.</td></tr>
<tr><td colspan="2">Condition monitoring: The model only provides assistance in post-analysis of maintenance programs, i.e. once maintenance plan <i>X</i> is closed and the forthcoming plan <i>Y</i> should be initiated.</td></tr>
<tr><td colspan="2">Intelligent assistance: The model does not provide automatic decision support.</td></tr>
</table>

The *Costprove* model assists the CMO in decision-making towards bridging the gap of "*planning-monitoring-controlling*" using a heuristic procedure. Thus, it employs undefined constants and parameters that should be valued for every certain use-case scenario, through investigation of historical data (if any available) and interaction of the CMO (domain expert). Moreover, *Costprove* should support continuous improvement and learning from past events (decision on cost planning). To this extent, the model supports (1) cost planning, (2) monitoring attainment of predefined goals/outcomes, and (3) controlling the outcomes, detecting knowledge gaps in planning, and upgrading the hypotheses for the forthcoming planning period. Hence the evolution of the model is occurring within a heuristic procedure. Even though the nature of some of the employed variables might be stochastic, the model deploys a combined approach that initially calculates the optimum values in a synoptic way, and then corrects/updates the calculation and compensates any drifts from empirical values incrementally. So the initial instance of planning (decision-making) is straightforward; for instance the CMO identifies planned cost, estimates unplanned cost, calculates the minimum of total cost and accordingly identifies the number of maintenance activities (cf. Table 12). But the drift from reality (empirical data) is corrected in the controlling process. In this way the model bridges the gap of "*planning-monitoring-controlling*".

The main approach used in *Costprove* is underlying a premise that *planning-monitoring-controlling* is implemented by the interaction of humans such as the CMO. The MCM is, thereby, controlled semi-automatically. The estimations of the model become accurate through the development of *planning-monitoring-controlling* especially when the CMO learns from the failures and lacks of the past planning period, and applies required changes in the forthcoming one. Thus, implementing and evolution of the model within a heuristic procedure with the interaction of the domain expert provides the possibility for continuous learning and improvement. Considering the above-mentioned procedure, internal and external disturbances to the MCM can be predicted in the early stage of planning, their effect can be optimized in the monitoring, and their causes can be eliminated in the forthcoming period using new/updated strategies.

Moreover, the model is effective, particularly for maintenance costing of a number of machines, otherwise one machine can be managed in a very simple way. Normally, the CMO suffers difficulties when he/she has to analyze accumulated data from various production lines including the number of machines. In this situation, an assistant system can supply the right information for decision-making.

In comparison with the reviewed literature in Chapter 2, few models provide similar features and characteristics (cf. Section 1.3 and 1.4 - Table 6 and Appendix 7.1 – Table 24). Differences between *Costprove* and the reviewed models make it difficult, comparatively to study them corresponding to the eight predefined criteria. Another important issue is identifying ideal requirements for use-case study. The model, by its nature, is generic and universally applicable; for instance it has not been specially designed for a certain use-case and thus can be customized. This leads to the opportunity for pilot-testing the model in various domains. Previously mentioned issues on data privacy and security of "cost data" are the major challenge towards executing a pilot test-study. The validation, in Chapter 1 and 2, therefore, is only limited to two major methodologies, (a) literature survey (comparison with state-of-the-art), and (b) simulation (based on real data and interview with domain expert of VMC). In Chapter 3, the validation is extended into realization of the *Costprove* Toolbox (software) based on the detected constraints and deficiencies of CMMIS packages (cf. Section 3.2). In addition, the usability and applicability of the software prototypes are validated through cooperation with industry and interviewing maintenance professionals. This issue is discussed in Chapter 3 (cf. Section 3.3).

In conclusion, several approaches to MCM deal with optimizing cost and trade-off between cost and operational variables through finding optimal values for a number of maintenance activities, and save the associated cost. In the economic point of view, it is also promising to investigate the vice versa approach, i.e. defining the minimum/ optimum cost and accordingly adopting the number of activities so the expenses do not exceed the desired value of total costs. This is only possible if the process of cost *planning-monitoring-controlling* simultaneously uses principles of synoptic and incremental approaches to problem-solving, and incorporates knowledge assets, especially maintenance records, experiences and expertise of the CMO. *Costprove* is, therefore, unique in terms of conception and realization of qualitative and mathematical models and centering dynamics of knowledge assets in the field of maintenance cost controlling.

3 Realization and Implementation of *Costprove* Toolbox

3.1 Overview

This chapter reflects the design and realization process of the *Costprove* Toolbox (software). The toolbox is an add-on for the CMMIS. The main focus is, therefore, to implement the algorithm for deploying the *Costprove* model (cf. Figure 23).

Section 3.2 presents an extensive review of CMMIS features, functionalities and constraints. It includes a review of the commercial tools, especially in terms of providing *cost-planning-controlling* and *cost-based decision support*.

Section 3.3 expresses outcomes of needs analysis with industry (i.e. interviews with maintenance professionals).

Section 3.4 describes the conceptual design of the toolbox. It considers essential features of the *Costprove* Toolbox to support the CMO in meta-analysis of MCM knowledge assets.

Section 3.5 discusses meta-analysis methods. In this dissertation, mathematical and textual meta-analyses are taken into account. The former refers to the use of the *Costprove* model (cf. Figure 23), and the latter to the text-mining methods (Ansari, et al., 2014a). The meta-analysis, however, is not limited to these methods. Several statistical approaches can be used which are out of the scope of this work.

Section 3.6 presents the implemented prototypes of *Costprove* Toolbox. Mainly three kindes of prototypes are developed for:

(1) Cost planning-monitoring-controlling using *Costprove* algorithm
(2) Extracting knowledge from MCM reports with the aid of text-mining methods
(3) Combining mathematical and textual meta-analysis of MCM reports

The presented prototypes are developed in cooperation with industry partners.

Finally, Section 3.7 discusses the summary of findings.

3.2 Analyzing Functionalities and Constraints of the CMMIS

A CMMIS is “an integrated set of computer programs and data files designed to provide its user with a cost-effective means to manage the massive amounts of data that are generated by maintenance and inventory control organizations” (Mobley, 2008). The CMMIS is “designed to assist in the planning, management, and administrative functions required for effective maintenance” (Bagadia, 2006). The CMMIS has existed for more than 40 years (Kans, 2009). Other common names for computerized or information systems used in maintenance such as computer-based maintenance management system (CMMS), computerized asset management system (CAMS), computer-aided maintenance (CAM), or enterprise asset management (EAM)[43]. Notably, “with EAM, the CMMS functionality is extended to include financial modules such as

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[43] Cf. (Kans, 2009), (Wireman, 2008), (Bagadia, 2006), (Lee, et al., 1999).

accounts payable, advanced cost recording, and advanced human resource management" (Bagadia, 2006). In this dissertation, the term CMMIS is used for MaM software packages and information systems. The CMMIS comprises standard features/sub-systems listed in Table17. CMMIS features support MaE and MaM, i.e. both operational and management level of maintenance. Details of functionalities may differ, based on implementation strategies, target industry sectors, qualification of maintenance staff and existing infrastructure.

Table 17. Standard subsystems/features of the CMMIS[44]

Subsystems/Features of CMMIS	Details
Equipment/asset management	• Identification and specifications • Hierarchies • Bill of materials
Inventory control	• Spare parts and store inventory • Cross references to equipment/asset
Work order management	• Requisition and creation • Planning and scheduling o Preventive maintenance plans o Project plans o Emergency maintenance plans o Unplanned orders o Corrective maintenance plans o Repetitive maintenance plans • Execution and completion • Storage of historical data
Human resource management	• Cross references to work orders for planning, monitoring and accounting • Craft and skill data
Accounting/Finance	• Purchase requisitions • Purchase orders • Invoice matching and accounting • Maintenance budgeting • Reporting tool

The main usage domains of the CMMIS in manufacturing industries and production management are specified in Table 18.

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[44] The list presented in Table 17 has been created by the author based on the comprehensive study of the CMMS by (Mobley, 2008). Later it is upgraded by the author through review of further sources, especially studies of (Lamb, 2009), (Wireman, 2008), (Bagadia, 2006), and (Mather, 2003).

Table 18. Usage domains of CMMIS-Adopted from (Mobley, 2008)

Organizational level of Maintenance	**Domains of usage**	**Functions**
MaE with partial overlap with MaM especially in terms of MCM	Maintenance	• Initializing of work orders • Planning of work orders • Planning of preventive maintenance • Scheduling of work orders and resources • Requisition of non-stock parts, materials or services (Direct-Buy) • Analyzing of equipment/asset repair history • Craft utilization • Budgeting and tracking • Cost planning and monitoring
MaE	Engineering	• Project Planning and tracking • Review of equipment/asset specifications • Review of equipment/asset modification history
MaE	Production	• Scheduling of downtime • Managing repair request backlog (unprocessed requests) • *Cause and effect* analysis of the repair history of equipment/assets
MaE	Inventory control	• Recording part usage history • Cross referencing of parts to equipment/asset • Advance notice of parts requirements for planned work • Automatic requisitioning of parts to meet reorder/stocking requirements • Work order to purchase order cross reference for Direct-Buy items • Storage and retrieval of material safety data sheets
MaE	Purchasing	• Automatic requisition of stores stock inventory • Consolidation of requisitions for same vendor to single purchase order • Receipts against the purchase order
MaM	Accounting/Finance	• Automatic cost allocation • Review and evaluation of cost history records
MaM	Executive management	• Budget preparation and tracking • Cost planning and monitoring, controlling • ISO 9000 compliance (for standardization of documentations and compliance)

The process of maintenance order in the CMMIS is initialized/triggered by receiving a work request (cf. Figure 26). The work request can be submitted as verbal, telephone call (e.g. via hotline), written via email or short text message by means of desktop, laptop, mobile phone or tablet, or direct input to the CMMIS. Afterward, the request should be reviewed and, upon approval, the planning process will be started.

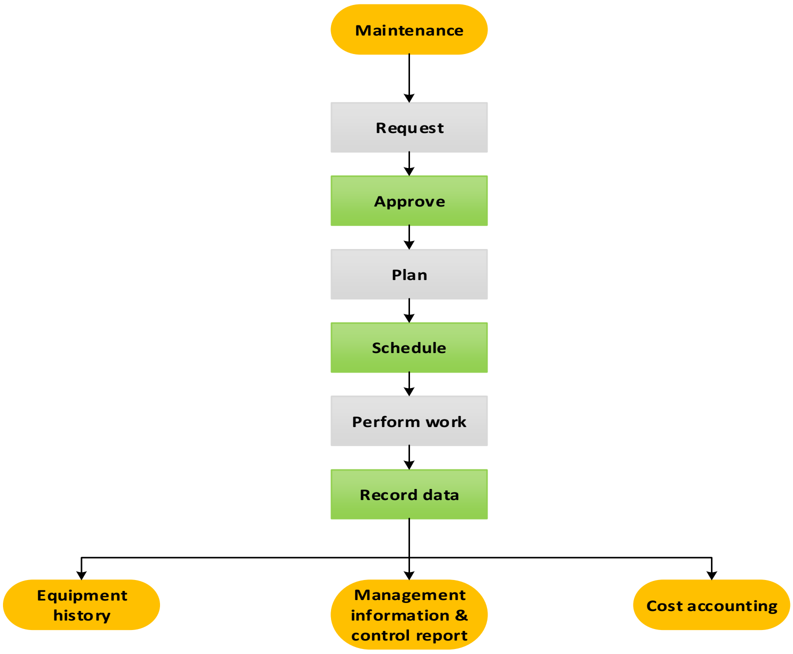

Fig.26. Key steps to manage the maintenance order in the CMMIS-Adopted from (Bagadia, 2006).

Work order planning includes identifying the maintenance job, defining physical or human resources such as labor, parts, materials, tools, and contracts required to perform the job, and related guidelines or procedures for executing the job. Work order planning is an overriding and strongly influential issue to MCM. In the scheduling, “all open work orders are maintained in a file that is referred to as the *work order backlog*” (Mobley, 2008). The scheduling involves certain meta-data (indicator) such as “work order type, status and priority, equipment/asset criticality, and a requested completion date” (Mobley, 2008). After execution of the work order (backlog), the entire process should be documented and maintenance data be recorded. The data recording may vary from listing time spent in executing each task and related subtasks, to collecting comprehensive records of material charges, equipment identification, work assigned and performed, responsible person identification, remarks of maintenance staff (in a free text format), and other precisely relevant data. The recorded data can be assigned or cross referenced to equipment history. The recorded data are the most important source of information for MaM and particularly MCM activities. Improving quality of data recording is, therefore, a major challenge to the CMMIS (Wireman, 2008). A standard CMMIS provides functions for different domains of production management. The CMMIS supports not only maintenance personnel, but also the other units/departments along the organization such as engineering, production, inventory control, purchasing, accounting, and top (executive) management.

Table 19. Major constraints to successful implementation of the CMMIS-Adopted from (Mobley, 2008)

Constraints	Remarks
Intelligence/Personal expertise	• CMMIS **cannot** replace a CMO, CME or other maintenance personnel and decision-makers. • CMMIS **cannot** automatically assign the work orders to individuals/groups and monitor them. • CMMIS itself **cannot** improve reliability and product quality. • CMMIS itself **cannot** decrease maintenance cost or labor requirements.
Total implementation	• CMMIS is effective and efficient when all its capabilities are fully implemented. • The implementation process is complex and like long-term projects; it requires strong management and leadership. • In-house personnel might have lack of knowledge to implement CMMIS. In some cases it can be outsourced. • In the case of outsourcing, it might be that the capability of the outsourced contracted institution is not adequately verified. • Some organizations try to modify CMMIS to match their existing business practice, instead of using it the other way around. • CMMIS should be selected based on developing required specification through comprehensive evaluation and assessment of the current operations, including maintenance, engineering, production, inventory control, accounting, purchasing, human resources and information systems. • In some cases, there are parallel systems available with partially identical functionality to CMMIS. In such cases, an interface should be developed. The absence of the interface may lead to two major problems: (1) Double data entry (2) Lack of data integrity
Provision of resources	• CMMIS is failed due to inappropriate/lack of provision of required resources because of two major reasons: (1) Poor planning of the required manpower and financial resources. (2) Lack of management/labor commitment.
Organizational resistance/ Change management	• CMMIS can provide expected benefits only through a radical change in the human factors. • Full changes are required in work methods, procedures, organization, employee attitude, skills, etc. • Project master plan for the implementation of CMMIS can resolve “poor communication”, “confrontation”, and overpass “work culture restrictions”.

In conclusion, the CMMIS is used to effectively conduct data collection and analysis, automatize and control PM, assure reliable inventory replenishment program, and also provide accurate job scheduling underlying resource availability (Kans, 2009), (Wireman, 2008). Despite the advantages and usability, the CMMIS is engaged with constraints which cause it to fail in practice. Table 19 reveals the major constraints to successful implementation of a CMMIS, and elaborates underlying reasons. Recent studies on the advancement of a CMMIS mark endeavors to overpass the aforementioned constraints. For example, a survey of "97 scientific papers in the period 1998 to 2003" revealed significant changes in four aspects during the evolution and advancement of a CMMIS as (Kans, 2009):

- First, the focus is shifted from technology to use of CMMIS.
- Second, CMMIS is seen more as an integrated business solution rather than the maintenance function.
- Third, it is used to support predictive-proactive maintenance through "avoiding damage initiation by detecting the damage causes".
- Fourth, the economic advantages of the CMMIS are taken into account, which reveals a shift from operational to strategic maintenance.

Moreover, the study of commercial CMMIS packages by (Labib, 2004) pointed out that "all the systems offer data collections and more expensive systems offer formalized modules for the data analysis, real time data logging and networked data sharing". The study stressed that all the observed systems do not offer decision analysis support for MaM (Labib, 2004). This lack is called as a *black hole* that exists in the CMMIS (Labib, 2004). In this dissertation, the lack of the CMMIS in bridging the gap of "planning-monitoring-controlling" in MCM is anticipated. Hence, an independent analysis is performed on the commercial CMMIS packages (ranging in price from $2k to$30k for a single user license). The reviewed packages are selected from the well-known software suppliers. Their information is available in Appendix 7.2 (cf. Table 25). The selected CMMIS packages have been analyzed against 10 criteria (cf. Table 20) by the author in 2013. The **Criterion 1-4** examines the provision of standard features (cf. Table 17). **Criterion 5-7** follows the study of basic data management features by (Labib, 2004). **Criterion 8-9** considers two specific features or subsystems for advancement of cost controlling, namely (**Criterion 8**) **Cost planning-monitoring-controlling** with indicators such as provision of guideline and strategy, feedback analysis and continuous learning, KPIs, and heuristic problem discovery and solving, and (**Criterion 9**) **Cost-based decision support** with indicators like managing planned and unplanned cost, providing mathematical analytics/tools, and utilizing decision model and optimization algorithms. **Criterion 10** deals with identification of features for improving MCM through analyzing contents of maintenance reports. The packages are analyzed through review of the brochures/catalogs, demo/trial versions provided on the websites of the suppliers. The results are presented in Table 20. As expected, all reviewed packages support Criterion, 1-4 i.e. standard features of the CMMIS (cf. Table 17). They also include at least basic data management features targeting Criterion 5-7. Criterion 8 is partially fulfilled by four of the packages in the price range ≥ $5k. Such packages use KPIs for cost and budget monitoring, and none appears to deploy any special deterministic/stochastic cost model. Concerning Criterion 9 and 10, no special features corresponding to the predefined indicators have been detected. Thus, this study shows that the ***black hole* in MCM** subject to Criterion 8, 9 and 10 still exists. The objective of *Costprove* Toolbox is to compensate this gap, using the mathematical and qualitative approach discussed in Chapter 2, as well as other existing methods for analyzing the contents of maintenance reports. This issue is further discussed in the following sections.

Table 20. Study of features of commercial CMMIS packages by the author

	Software packages	**AMMS & MP software**	**BENCH-MATE & CMMS PRO**	**Ivara**	**IBM-Maximo®**	**SAP®-EAM**	**Oracle®-eAM**	**MaintiMizer™**	**CHAMPS-CMMS**	**Infor-EAM**
Criterion	**Indicator**									
1	Equipment/asset management	✔	✔	✔	✔	✔	✔	✔	✔	✔
2	Inventory control	✔	✔	✔	✔	✔	✔	✔	✔	✔
3	Work order management	✔	✔	✔	✔	✔	✔	✔	✔	✔
4	Human resource management	✔	✔	✔	✔	✔	✔	✔	✔	✔
5	Data collection & analysis	✔	✔	✔	✔	✔	✔	✔	✔	✔
6	Real time logging	✔	✔	✔	✔	✔	✔	✔	✔	✔
7	Networked data sharing	✔	✔	✔	✔	✔	✔	✔	✔	✔
8	Cost planning-controlling			KPIs for cost controlling		Budget utilization	Cost mapping/ Cost estimation			Automated budget monitoring &control
9	Cost-based decision support	**Black hole in MCM**								
10	Analyzing the content of reports (text) for improving MCM									
Price Range		**$2k +**	**$2k +**	**$5k +**	**$5k +**	**$5k +**	**$5k +**	**$15k +**	**$ 25k +**	**$30k +**

3.3 Verifying *Costprove* and Needs Analysis with Maintenance Professionals

Taking into account the study of the CMMIS and existing commercial packages in Section 3.2, a worthy approach is to interview maintenance professionals and find out existing needs in the world of work. Maintenance professionals of two manufacturing companies located in Germany have participated in this survey and evaluated the *Costprove* model. These companies are referred to in this section as C#1 and C#2. C#1 is a developer and manufacturer of semiconductor-based system solutions. C#2 is a manufacturer of electromagnetic actuators and supplier of primary equipment components for the automotive industry.

Team leaders of maintenance engineering from both C#1 and C#2 participated in the survey[45]. First the motivations to develop the model and achievements are presented and explained, and then the team leaders provide answers to the given questions, identify the priority and provide their opinions. Each interview and meeting took an hour on average. The collected answers are summarized in Table 21. In this table, five questions are listed. Next to each question, the priorities are assigned. Priority of the question is graded in importance from 1- 5; relative unimportance of the question is shown by 1, rising to five as importance increases.

They addressed high importance and practical implication of the distinction between planned and unplanned costs. In addition, the model is evaluated as general; however, they stressed that the model should be further studied for fulfilling prerequisites and required components of each company.

They found the approach for learning from past experiences reasonable and useful in a practical manner. They mentioned that experiences should not be limited to historical records (i.e. numeric values) and in fact maintenance reports (i.e. text documents) need to be taken into account.

To apply the *Costprove* model in practice they pointed out the need for developing a software tool which can interoperate with existing CMMIS tools and modules in each of the companies. In general, the surveyed companies are using existing CMMIS packages, however, they do not hold any similar features to the *Costprove* model for planning and controlling of maintenance costs, especially planned, unplanned and total cost. The existing approaches are classical accounting methods, which do not allow the CMO to use experiences effectively, and continuous improvement of the MCM. They also pointed out that the end user should be trained to know how to deal with the formulations, so the qualitative model and guidelines as well as software documentations is essentially required.

As a result, the surveyed professionals found the *Costprove* model useable and identified important aspects of designing a software toolbox. Section 3.4 discusses this issue more in details.

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[45] Information given by interviewees is available from the author.

Table 21. Results of verification and needs analysis for realization of *Costprove* Toolbox with maintenance professionals of C#1 and C#2

Question	Priority (1-5)	Remarks of C#1 and C#2
Distinction of *planned* and *unplanned* cost in *Costprove* subject to maintenance is reasonable in your field of practice?	C#1: 4 C#2: 5	• C#1: It makes it easy to save money. • C#1: Unexpected events are not planned. • C#2: The classification is applied without any special software tools in our field of practice.
Does the case distinction of *Costprove* cover all important cost attributes?	C#1: 4 C#2: 4	• C#1 & C#2: One challenge is the quality of records. • C#1: The Matrix representation can be useful. • C#1: Historical approaches allow incorporation of maintenance records. • C#1 & C#2: It is usable at least for optimizing the amount of (preventive) maintenance. • C#1 & C#2: The model should be adopted for each company.
Is the use of *figure of merit* for indicating shortage situation reasonable in your case?	C#1: 4 C#2: 4	• C#1 & C#2: It is reasonable for learning from the past experience.
Is the model applicable in your field of practice? (If not, what changes do you suggest?)	C#1: 4 C#2: 4	• C#1 & C#2: The model could be good for analysis, based on the knowledge of maintenance officer. • C#1: Need to train end users.
Is it useful to establish a software toolbox for assisting CMO in planning-monitoring-controlling?	C#1: 5 C#2: 5	• C#1: It should be studied in the context of each company. • C#2: Existing tools and databases should be taken into account.
Is it useful to develop features for analyzing the contents of maintenance reports?	C#1: 4 C#2: 5	• C#2: Knowledge Management is in demand by maintenance departments. • C#2: It may save time to read documents and search in databases. • C#1: Knowledge and experience of personnel is valuable. Someone may know a machine better than others do.

3.4 Design of *Costprove* Toolbox

The model of *Costprove* is a managerial tool which is designed and developed based on theoretical analysis of a large body of literature concerning MCM and MaM and *needs analysis* in practice (cf. Chapter 2 and Section 3.3). The *Costprove* can be realized as a software tool, subsystem or add-on of the CMMIS. The toolbox gains profit in two major directions:

(1) compensating the aforementioned gap of "planning-monitoring-controlling" of MCM activities, which still exists even by use of the CMMIS (cf. Table 20), and

(2) supporting the CMO in MCM related decision-making activities by providing managerial reference measures. The reference measures are used to compound the CMO's insight into accumulated knowledge assets of MCM.

Therefore integration of the *Costprove* in the framework of the CMMIS leads to a development of an assistance system for MaM, particularly MCM, in both operational and strategic levels. It ultimately indicates advantages of using knowledge-based approaches in MCM (Ansari, et al., 2014a), (Ansari, et al., 2012a).

Costprove Toolbox is realized by considering documented knowledge assets of MCM. Maintenance records stored in the CMMIS database, either in structured, semi-structured or unstructured formats[46], are used. In this dissertation, structured data (records) are understood to be data that are assigned to MCM (also in a broader scope to MaM and MaE) that can be thereby directly processed with subsystems of the CMMIS and *Costprove* Toolbox. Unstructured data (records) are mainly text-based which require preprocessing and thus cannot be directly used by the CMMIS. Other information sources include semi-structured records. Examples are emails[47] exchanged between maintenance staff, research paper repositories dedicated to the field of maintenance, web pages providing information on maintenance, and annual reports from the CMO. Information sources (including all aforementioned types of records) specifically used in MCM can be listed in the following classes:

(1) Cost history records of work orders, including engineering costs
(2) Budget history records
(3) Cost records of production/value chain loss
(4) Inventory and purchasing cost records
(5) Personnel and management cost records

In practice, the above-mentioned classes may differ due to the context of work.

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[46] The classification of the maintenance records is adopted by the author from (Baars, et al., 2008).

[47] In fact, content of the emails are only reports or recommendations of maintenance staff for improving operation and management. Therefore, the content is related to the maintenance works and it does not present any conflicts of interest with the private data.

The records include tables of numeric data as well as text records of MCM such as description of MCM's cause and effects (e.g. description of extra cost for a repaired machine). The collected records should be analyzed to discover essential features, and interpret them in a meaningful way for managers. Methods of meta-analysis support this process. These methods are discussed in the Section 3.5.

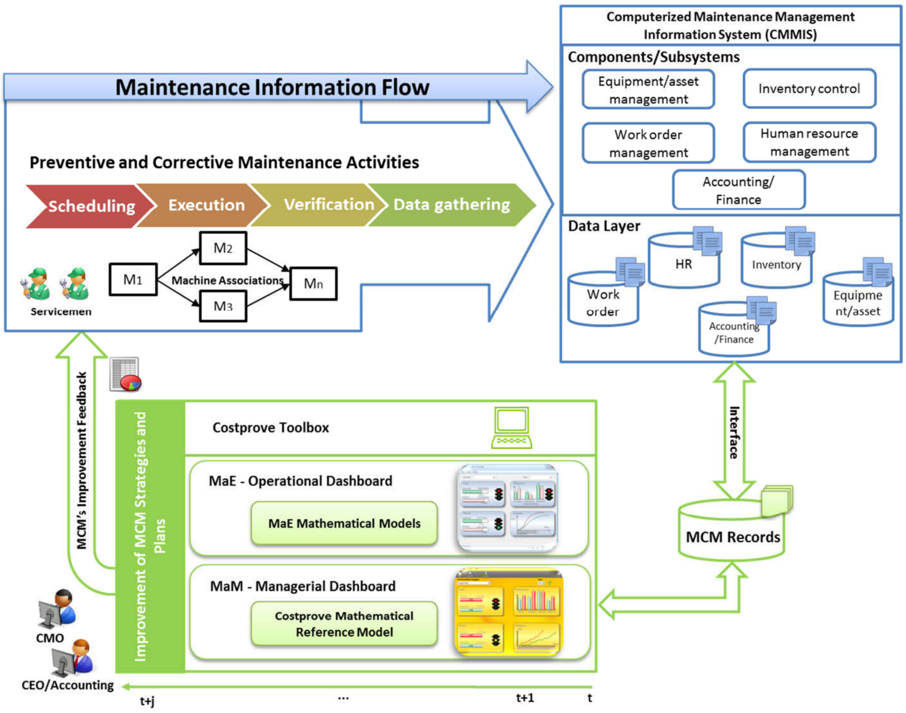

Fig.27. Design of *Costprove* software tool as an add-on of the CMMIS.

Figure 27 depicts the generic concept of the *Costprove* software tool. It reveals the information flow of maintenance through use of a CMMIS. The CMMIS (Blue-colored component) is a major tool for conducting maintenance activities and consists of standard features and a central database for storing the maintenance records. The *Costprove* software tool (green-colored component) is to capture cost related records from the maintenance database, analyze them and store the outcomes in the database. The *Costprove* Toolbox employs MaE reference models, and the mathematical reference model (cf. Chapter 2) to support the CMO for cost controlling and budget management, and provides strategies for operation level (feedback). Thus the *Costprove* Toolbox provides two types of dashboard for visualization and analysis of calculated results as **operational** and **managerial**.

Figure 28 reveals the design of the **operational dashboard** of *Costprove*. The process is initiated by the submission of the work request. The dashboard deploys KPIs for analysis of the current state of the machines, based on the historical data and monitoring records of the machines. In this context, standard KPIs are used such as availability, reliability; failure rate. (cf. Chapter 1). In the failure analysis dashboard, the indicators support diagnosis, and accordingly certain hypotheses for solving the problem/work request are generated, which are predefined in the system. Afterward the operational intervention will be identified considering the type of the work request. Finally the CMO and CME will review the results and decide on the work order, which will then be transmitted to the servicemen. The work order and analysis results, including cost/budget, are recorded in the MCM database.

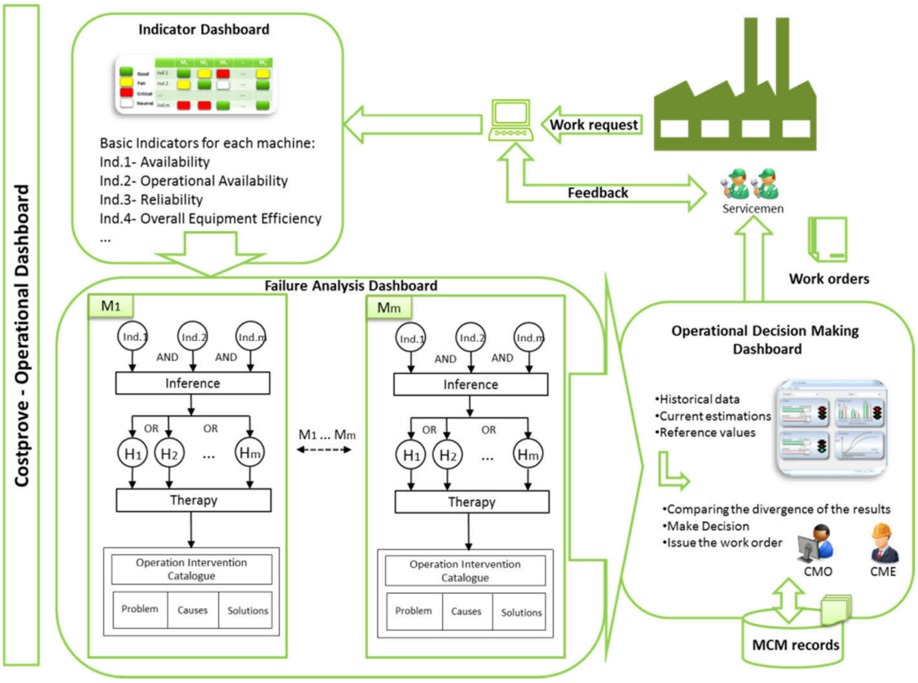

Fig.28. Design of *Costprove* operational dashboard for visualization and meta-analysis of machine-related maintenance information.

MCM records are also used in the managerial level. Figure 29 presents the design of the **managerial dashboard**. It supports cost planning and utilizes the **meta-analysis** for monitoring and controlling the state of expenses as well as shortage situation. The reference model is used to generate hypotheses for resolving the problem/improving the current state in the forthcoming planning period. The hypotheses are mapped to the therapy solutions on the basis of the judgment of the CMO and CEO. In this way, the dashboard assists the CMO and CEO for compounding their insight into the analysis of (documented) knowledge assets and learning from the past events.

Using the *Costprove* software tool, CMMIS functionalities are extended and advanced especially for maintenance costing. In other words, meta-analysis is employed in the meta-level of the *Costprove* model (cf. Figure 22) for provision of (meta) indicators, examination of the documented knowledge assets, and visualization of the findings in the dashboards. The findings give the CMO (i.e. domain expert) evidence for evaluating the MCM state and adapting/improving maintenance strategy. Therefore the gap of "planning-monitoring-controlling" is compensated and the CMO is assisted by utilizing a KM solution for continuous improvement of MCM.

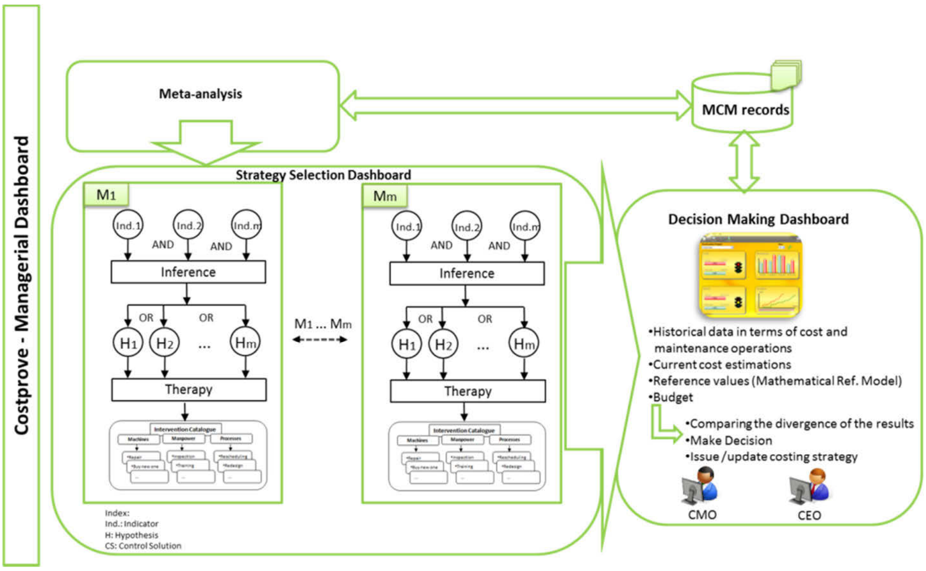

Fig.29. Design of *Costprove* managerial dashboard for visualization and meta-analysis of maintenance costing information.

Section 3.5 discusses the meta-analysis in the context of *Costprove*. Accordingly, Section 3.6 presents the results of the implementation and prototyping of the operational and managerial dashboards.

3.5 Meta-Analysis in the Context of *Costprove*

This section discusses meta-analysis methods[48]. First, an overview about meta-analysis is given. Second, the meta-analysis methods deployed in *Costprove* Toolbox are described.

The term meta-analysis was defined by (Glass, 1977). He introduced most of the used procedures to psychology (Glass, 1977). The effort of Glass was the fundament of further research and publications in this field, for example, (Lyons, 2000 (Last revised: 30.01.2003)), (Salgado, et al., 2003), and (Murphy, 2013). Meta-analysis refers to three methods for (1) statistical, (2) mathematical, and (3) textual analysis of a large collection of results from individual data sources for the purpose of integrating the findings (Murphy, 2013). Meta-analysis is applied to two types of knowledge assets: (1) hard-facts and numeric values by means of statistical and mathematical methods, and (2) text-based documents by means of text-mining or text-clustering methods.

Besides, meta-analysis is performed by using an automatic/semi-automatic software or a manual framework. In contrast to automatic software solutions, the semi-

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[48] This section is adopted from (Ansari, et al., 2014a).

automatic software deploys the expertise of a domain expert (e.g. CMO) to approve the result of the meta-analysis. The meta-analysis methods are summarized in Figure 30.

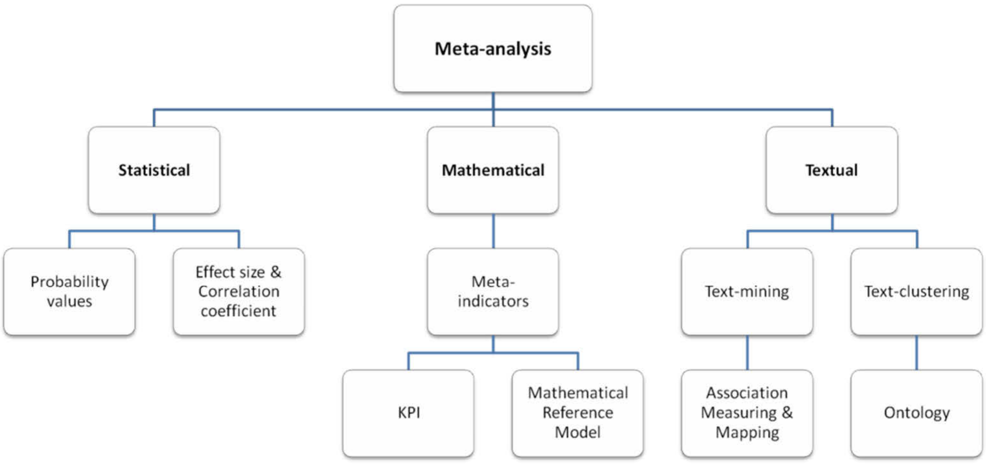

Fig.30. Three methods of meta-analysis – Adopted from (Ansari, et al., 2014a).

There are two general types of statistical meta-analysis (Lyons, 2000 (Last revised: 30.01.2003)). One method involves the combination of probability values, while the second technique combines effect sizes and the correlation coefficient (Lyons, 2000 (Last revised: 30.01.2003)), (Hartung, et al., 2008). There are other statistical methods like the Bayesian approach to meta-analysis, which are examined in (Hartung, et al., 2008).

Mathematical meta-analysis models and formulates meta-indicators, for instance, KPI or mathematical reference model (cf. Chapter 2). Meta-indicators summarize instances of data sets and interpret them in a unique form. In this context, mathematical meta-analysis concentrates on meta-indicators (e.g. availability), which represent the required information based on aggregation of relevant data, for instance, mean time between failure (MTBF) and mean down time (MDT).

Textual meta-analysis refers to the use of text-mining and text-clustering algorithms and methods (Heyer, et al., 2012). Although, text-mining methods use statistical approaches, they especially deal with other types of entities such as words and texts. So one can distinguish between statistical and textual approaches on the basis of application. Text-mining and clustering are utilized for analyzing the unstructured content of documents (i.e. text). Review of the text-analytics literature shows that textual meta-analysis is mainly supported by (1) the association measuring and mapping, and (2) ontology engineering. The former is used in the context of *Costprove* and further elaborated in this section. The latter is to establish a relational ontology of detecting keywords in a text. Ontology “defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extension to the vocabulary” (Maier, 2007), (Staab, et al., 2003), (Staab, et al., 2001). The ontology visualizes and represents the relation between keywords (e.g. *Machine X is Repaired by Engineer Y*). Applying ontology engineering for meta-analysis is discussed by several authors such as (Hotho, et al., 2002), (Yang, et al., 2008), (Tar, et al., 2011), and (Ma, et al., 2012). Ruiz et al. also proposed an ontology-based method for modeling the information present in the experiences stored in the CMMIS (Ruiz, et al., 2014). They used a rule-mining algorithm to extract association rules from past experiences, and conceptual graphs for analyzing the extracted knowledge (Ruiz, et al., 2014).

Costprove Toolbox utilizes mathematical and textual meta-analysis for MCM. MCM, as a systematic and effective process, encompasses the information flow for acquiring and accumulating data and information. Data include the number of maintenance activities such as repair, inspection, stoppage. Further examples are the number of associated technicians/administrators, frequency of failures, and in-use-resources. Aggregation of the accumulated data in a meaningful context leads to the generation of information about the current state of maintenance particularly for administration of the underlying business process. For instance, an annual maintenance budget worksheet is a collection of data concerning the estimation of annual expenses associated with cost-intensive maintenance items such as labor, equipment, materials, operations and resources (cf. Table 22). The numeric values are regularly generated and stored by means of the CMMIS. The stored data are used by the CMO, accounting department, and CEO.

The mathematical model of *Costprove* deployed in meta-analysis has been studied and discussed earlier (cf. Chapter 2). The mathematical model represents the strength of the relationship between two major indicators in MCM: (1) Minimum of total PM cost ($K_{I_{min}}$), and (2) Optimum number of maintenance activities (n_{opt}). Using the mathematical model, the CMO compounds his/her insight and knowledge into the crucial attributes of maintenance cost administration (i.e. planned and unplanned, and total maintenance cost). This has been focused on in Chapter 2. The findings for the use and implementations of mathematical models and KPIs appear in the publications of the author (Ansari, et al., 2011), (Ansari, et al., 2012a), (Ansari, et al., 2012b), (Ansari, et al., 2012c). Although processing and analyzing accumulated numeric data assists the CMO, the knowledge assets of maintenance are not limited to hard-facts or statistics. In practice, technicians, maintenance engineers and the CMO document and report the orders, activities, troubleshooting, diagnoses, and prognoses. The major parts of documents are texts, where a practitioner explains and infers on a certain issue for handling a specific problem. For example a technician specifies the oil leakage of a machine and in turn records the change of the seal.

Table 22. Example of an annual maintenance budget worksheet (Ansari, et al., 2014a)

Work Order ID no.	**Description**	**Personnel Hours**	**Personnel number**	**Total personnel hours**	**Labor cost**			**Total cost**				
					Quantity	Rate	Cost	Labor	Equipment	Material	Other/ Contracts	**Total**
					Hours	€/ hours	€	€	€	€	€	**€**
M2D	**Daily activities**	858.00	1.00	858.00	858.00	15.00	7722.00	7722.00	250.00	300.00	….	**8272.00**
M2W	**Weekly activities**	104.00	1.00	104.00	104.00	20.00	936.00	936.00	52.00	104.00	….	**1092.00**
M2ER	**Buying equipment and repair activities**	24.00	1.00	24.00	24.00	25.85	236.40	236.40	30.00	500.00	….	**766.40**
….	….	….	….	….	….	….	….	….	….	….	….	**….**
Total →1156.70					**….**	**….**	**….**	**10498.93**	**433.00**	**1459.00**	**225.00**	**12615.93**

Maintenance documents and reports which are stored in the CMMIS contextually include facts (e.g. report of engineer concerning certain evidence of a failure in a machine), or combination of facts and artifacts (e.g. personal judgment of an operator regarding failure or extra cost of component repair in the future). In other words, not only the explicit knowledge of maintenance personnel is regularly documented, but also the documents encompass their former experiences e.g. with a certain type of machine or failure. The CMO exploits existing knowledge wisely. However, continuous improvement of MCM is reinforced by exploring and generating new knowledge from experience (i.e. learning from past events). Textual meta-analysis of documents discovers hidden improvement potentials such as between certain entities like machine, maintenance activity and personnel. In particular, comprehensive analysis of maintenance knowledge assets is advantageous for maintenance and service management. For instance, in order to manage maintenance cost and budget, the CMO requires the precise evaluation of historical data and collected information. It is used, for instance, to detect which machinery has been frequently repaired, or to indicate risk intensity of certain machines/equipment. Then he/she can estimate the cost of single/associated machines and determine maintenance budget. In this way, numeric data are highly usable. Text-based documents include practicable notes and recommendations as well as diagnoses or prognoses which can be applied to improve the decision-making process. For instance, a text-based report may include an engineering comment which addresses the repair or purchasing of a certain component/machine in the upcoming budgeting interval. Such contribution can be considered in the overall estimation of the CMO for calculating and validating planned cost of maintenance with higher certainty.

According to the findings and a detailed investigation of a commercial CMMIS by the author (cf. Table 20), most of the maintenance information systems only provide standard document management tools (e.g. search engines). However, commercial systems do not incorporate textual meta-analysis of maintenance documents. The constraints of the CMMIS and the demands of maintenance professionals are discussed in Section 3.2 and 3.3. As a result, the study reveals the need to utilize the knowledge discovery methods/technologies (i.e. textual meta-analysis) to improve quality and cost effectiveness of maintenance processes and services.

Meta-analysis of text-based documents has two major possibilities; text-mining and text-clustering (cf. Figure 30). The CMMIS uses standard text-mining features like search or keyword detection, and document mapping. Figure 31 depicts a sample of employing search, keyword detection and document mapping for basic textual meta-analysis of documents stored in the CMMIS database. In this example, each of the stored documents is analyzed and a summary is provided (cf. upper part of Figure 31). The summary includes the name of the author, date of recording, ID number, title, and major keywords (e.g. inspection and repair). Summarizing documents is helpful in providing an overview of related content without opening and reading the document. In addition, the search engine is extendable to combine the search for a certain entity and map the results with stored documents in the CMMIS database (cf. Figure 31).

Author	**Thomas Mueller**	**Date**	**20.04.2012**
ID no.	**ID2X54F**		
Title	**Inspection of drilling machine**		
Priority	**High**		
Keywords	**Inspection, Repair, Failure**		
Results	**Report IDs**	**Corresponding engineers**	**Documents**
Inspection	ID2X54F	Thomas Mueller	ID2X54F.docx ID2X54F.csv
	ID1Y84C	Alex Schmidt	ID1Y84C.pdf ID1Y84C.csv
Repair	ID9X83F	Patrick Haberkorn	ID9X83F.csv
	ID2Z31G	Max Weber	ID2Z31G.docx ID2Z31G.csv
	ID6Z90R	Christina Schmidt	ID6Z90R.csv
Failure	ID0Z71R	Patrick Haberkorn	ID0Z71R.docx ID0Z71R.csv
	ID7X08H	Alex Schmidt	ID7X08H.csv ID7X08H.pdf
	ID4Y59L	Max Weber	ID4Y59L.csv ID4Y59L.docx

Fig.31. Example of basic textual meta-analysis of documents stored in the CMMIS database using search, keyword detection and document mapping – Adopted by author from (Ansari, et al., 2014a).

In a joint research work, on the one hand the aim is to visualize the associations between certain predefined entities like ontology approaches. On the other, it is to interpret the associations in a numerical way for the CMO (i.e. to determine the strength of the associations in numeric values). It links mathematical- and textual meta-analysis. This approach does not concentrate on developing standard features like a search engine or document mapping tool. Also, it does not only consider visualization of word associations as is the case in ontology approaches. The "*Concept for the Imitation of the Mental Ability of Word Association*" (CIMAWA)[49] - (Uhr, et al., 2013) - is used as the fundament of word association measuring for textual meta-analysis of

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[49] CIMAWA method is developed on the basis of co-occurrence data (Dagan, et al., 1999), (Manning, et al., 1999), (Bordag, 2008) in a large text corpus. CIMAWA is carefully examined in several areas of application i.e. in detecting multi topic structures in text documents (Klahold, et al., 2013), and for real time context-based analysis of text documents in the product development process (Uhr, et al., 2012) and (Dienst, et al., 2012).

maintenance's knowledge assets (Ansari, et al., 2014a). CIMAWA measures are used as the core logic to develop a virtual application (prototype) as an add-on for the CMMIS presented in (Ansari, et al., 2014a). Discovering association between words and computing the strangeness or weakness of the association is a progressive field research (Rapp, et al., 1991), (Matsukawa, 1993), (Rapp, 2002), (Zizka, et al., 2003), (Washtel, et al., 2009).

CIMAWA computes the significance of the human word associations. It identifies the association between two words, e.g. $word1(machine) \leftrightarrow word2\ (repair)$. The larger the value calculated by CIMAWA, the higher the association between $word1$ and $word2$. It calculates a value that represents a measure for dependency of the response to the stimulus word (Uhr, et al., 2013).

Section 3.6 presents the implementation of *Costprove* Toolbox. CIMAWA is utilized for textual meta-analysis of maintenance documents, particularly in terms of indication of associations between predefined entities. The implementation results of the joint research work on textual meta-analysis are presented in sub-section 3.6.2.

3.6 Implementation Results of *Costprove* Toolbox

This section discusses the implementation and realization results of *Costprove* Toolbox using mathematical and textual meta-analysis methods. The realization is carried out on the basis of the conceptual design of the *Costprove* Toolbox (cf. Section 3.4).

In sub-section 3.6.1, *Costprove* mathematical model (cf. Chapter 2- Figure 23) is implemented. A prototype is developed which supports mathematical meta-analysis of maintenance records (i.e. planned, unplanned and total cost, budget and number of maintenance operations) in planning-monitoring-controlling of MCM activities.

In sub-section 3.6.2, a prototype for textual meta-analysis of maintenance records (i.e. text documents) is presented. The prototype analyzes text documents stored in CMMIS databases and represents the association of certain predefined entities (i.e. machines, maintenance personnel and activities).

In sub-section 3.6.3, a prototype for combining mathematical and textual meta-analysis is introduced. The prototype processes maintenance work reports and estimates the total cost with respect to three detected categories of entities in the text namely, tasks, material and labor. The above-mentioned prototypes represent *Costprove* Toolbox.

The results are presented in sub-section 3.6.1, 3.6.2, and 3.6.3 respectively. Detailed information about the technical specifications of each prototype has appeared in related software documentation. These are cited in numerical order in a separate bibliography at the end of this dissertation.

3.6.1 Prototype I: Mathematical Meta-Analysis Tool of *Costprove*

In order to employ *Costprove's* algorithm (cf. Figure 23), it is crucially important to develop software prototypes with graphical user interface (GUI). In practice, therefore, the CMO can use *Costprove* as an add-on interoperating with the CMMIS. A prototype is designed and developed as a generic tool which supports all features of the *Costprove* mathematical model (cf. Chapter 2). The prototype consists of five modules (dashboards) covering cost planning, monitoring and controlling.

Module I (cf. Figure 32 – Left screenshot) is used to execute *Case I* for calculating planned, unplanned and total cost through defining number of machines, identifying machines' names, connection to succeeding and proceeding machines and type of connection, selection of cost functions, and estimation of parameters. It results in the calculation of minimum of total maintenance cost ($K_{I_{min}}$) and accordingly optimum of maintenance activities (n_{opt}) for each single machine.

Module II (cf. Figure 32 – Right screenshot) is used to generate matrices for time ($\underline{t}$), cost-rate ($\underline{C}$), and residual cost ($\underline{K_e}$) (cf. Chapter 2- Table 11), based on identifying the number of planning periods and maintenance activities. The CMO can define a desired value for each element of matrices according to distinctions of planned and unplanned activities. For example, using the button "*Input* $\underline{C}$", the sub-matrices for planned and unplanned cost-rate appear ($\underline{C_{Pl}}$,$\underline{C_{Unpl}}$), and each element of matrices can be valued by typing and entering numbers. The same procedure is applied to time and residual cost matrices. Hence, the CMO can calculate the total cost of each machine in various planning periods (i.e. $\underline{K_I}$).

Module III examines the shortage situation (cf. Chapter 2 - Table 11) through assigning the budget and comparing it with the calculation of Module I and II. A light indicator is used to notify whether the shortage occurs or not. It provides possibilities for a CMO to recalculate budget and redistribute it for risky machines.

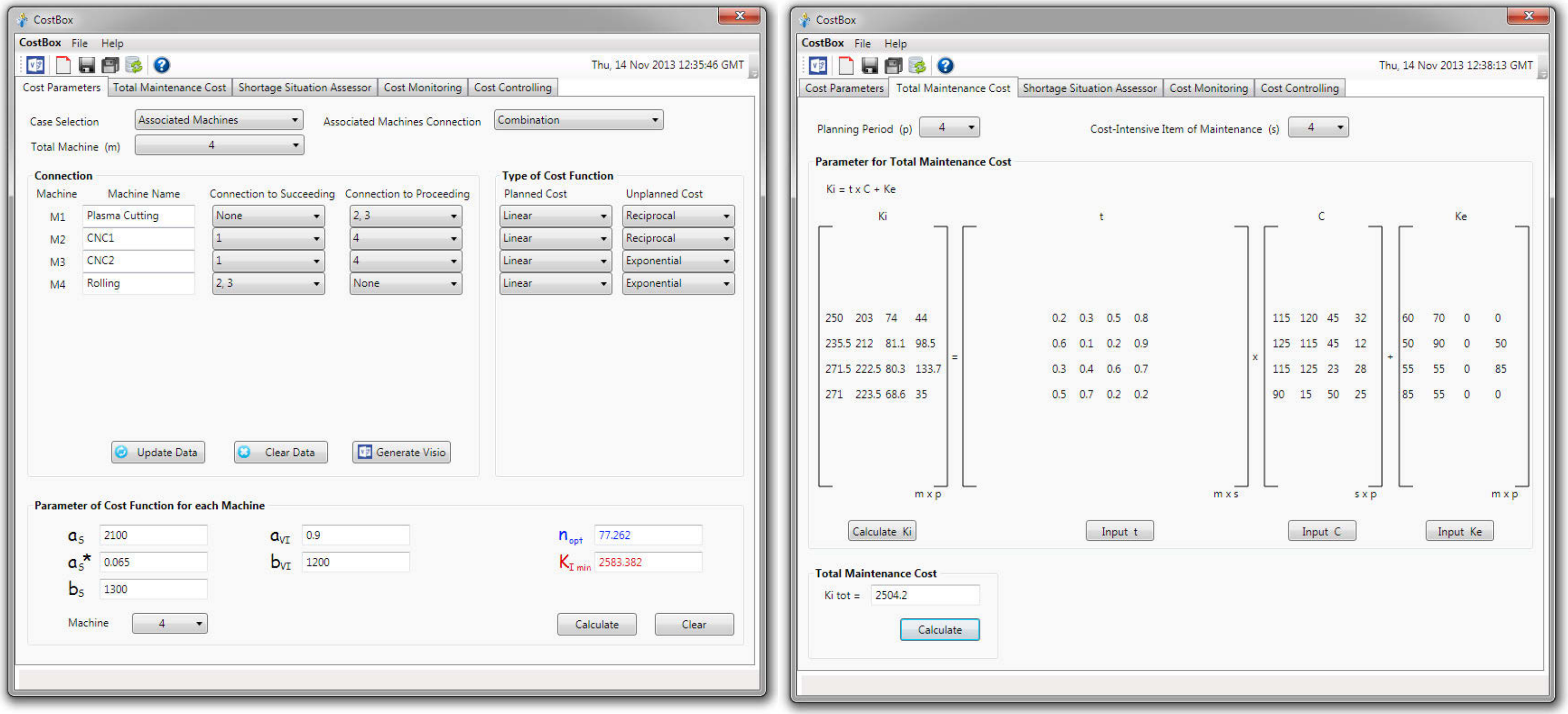
Module IV (cf. Figure 33 – Left screenshot) visualizes the calculations of Module I and II for each machine. It supports the CMO for proper selection of the cost functions, defining right values for $K_{I_{min}}$and n_{opt}, and documenting the results of each planning period.

Module V (cf. Figure 34) is used for controlling and documenting the MCM process. In this module, a summary of calculations appears. The CMO should fill out two forms regarding his/her recommendations for further investigations (such as diagnosis, repair, inspection), and evaluate the state of cost controlling through identifying the quality of records and cost planning. He/she can specify whether any external knowledge sources require upgrading in the process. In addition, the CMO can generate a report by adding his/her comments in a free text box, defining important keywords and meta-data (i.e. date, time, topic, keywords and position of the author). The report, including all calculations and graphs, will be issued in Microsoft® Word format and the CMO can update or edit it later.

Table 23 provides a summary of features in accordance with each module.

Table 23. Details of modules provided by prototype I

Modules	**Features**
Case I & Extension of Case I (Module I and II)	• Providing the formulation represented in Table 11 for planned and unplanned cost • Identifying the types of association of machines • Calculating n_{opt} and $K_{I_{min}}$ for each machine • Automatic generating of the layout of the production line in Microsoft® Visio 2013 • Providing all matrices represented in Table 11 • Dimensioning of the matrices based on $\boldsymbol{m}, \boldsymbol{p}$ and $\boldsymbol{s}$ (cf. Table 10) • Providing possibility to insert value for each element and update the calculations
Case II (Module III)	• Providing shortage situation assessor based on the formula represented in Table 11 • Deploying status indicators for shortage (red), critical plan (yellow) and expected (desired) plan (green) • Providing possibility to recalculate budget distribution and estimations (in case of shortage or critical plan) for each machine based on the type of associations towards upgrading the next planning period
Cost Monitoring & Controlling (Module IV and V)	• Visualization of the curves planned, unplanned and total costs similar to the model of Hahn and Laßmann (1993) • Summarizing the calculations of *Case I* and *Case II* for decision-making • Providing questionnaire to capture opinion of the user (CMO, CEO, CME) regarding the following issues: o State of planning (current/running phase) o Need to control the planning o Quality of data o Need for external knowledge • Capturing recommendation of the CMO or CME regarding standard PM and CM activities such as diagnosis, inspection, repair, replace or others • Capturing recommendation of the users in a free text format for documentations of their opinion that could not be covered in the previous steps, and providing possibility of textual meta-analysis with other prototypes presented in sub-sections 3.6.2 and 3.6.3 • Generating editable report in Microsoft® Word 2010



Thu, 14 Nov 2013 12:35:46 GMT

Case Selection: Associated Machines
Associated Machines Connection: Combination
Total Machine (m): 4

Connection

Machine	Machine Name	Connection to Succeeding	Connection to Proceeding
M1	Plasma Cutting	None	2, 3
M2	CNC1	1	4
M3	CNC2	1	4
M4	Rolling	2, 3	None

Type of Cost Function

Planned Cost	Unplanned Cost
Linear	Reciprocal
Linear	Reciprocal
Linear	Exponential
Linear	Exponential

Parameter of Cost Function for each Machine

a_S 2100
a_S^* 0.065
b_S 1300
a_{VI} 0.9
b_{VI} 1200
n_{opt} 77.262
$K_{I\ min}$ 2583.382
Machine 4

Thu, 14 Nov 2013 12:38:13 GMT

Planning Period (p): 4
Cost-Intensive Item of Maintenance (s): 4

Parameter for Total Maintenance Cost

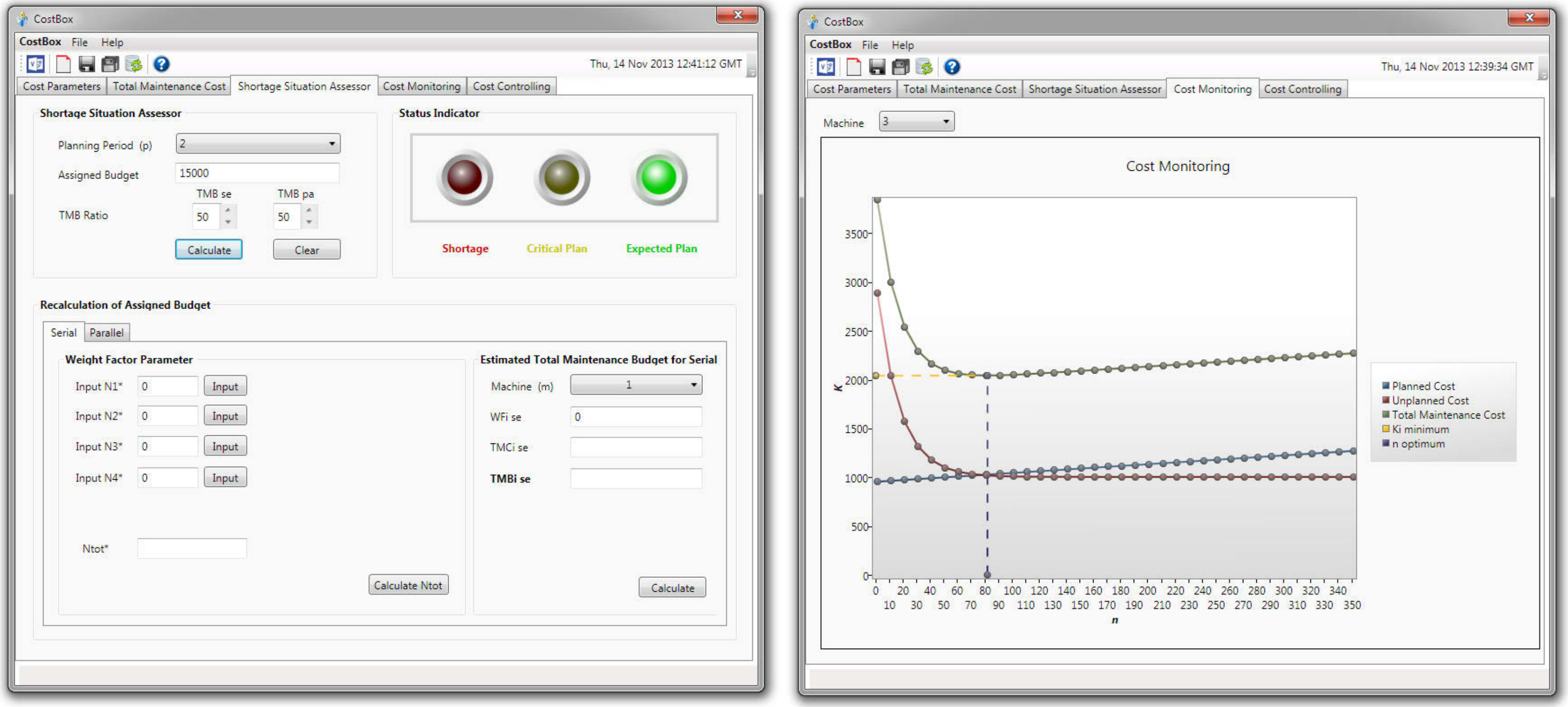
Ki = t x C + Ke

$$\underset{m \times p}{\overset{Ki}{\begin{bmatrix} 250 & 203 & 74 & 44 \\ 235.5 & 212 & 81.1 & 98.5 \\ 271.5 & 222.5 & 80.3 & 133.7 \\ 271 & 223.5 & 68.6 & 35 \end{bmatrix}}} = \underset{m \times s}{\overset{t}{\begin{bmatrix} 0.2 & 0.3 & 0.5 & 0.8 \\ 0.6 & 0.1 & 0.2 & 0.9 \\ 0.3 & 0.4 & 0.6 & 0.7 \\ 0.5 & 0.7 & 0.2 & 0.2 \end{bmatrix}}} \times \underset{s \times p}{\overset{C}{\begin{bmatrix} 115 & 120 & 45 & 32 \\ 125 & 115 & 45 & 12 \\ 115 & 125 & 23 & 28 \\ 90 & 15 & 50 & 25 \end{bmatrix}}} + \underset{m \times p}{\overset{Ke}{\begin{bmatrix} 60 & 70 & 0 & 0 \\ 50 & 90 & 0 & 50 \\ 55 & 55 & 0 & 85 \\ 85 & 55 & 0 & 0 \end{bmatrix}}}$$

Total Maintenance Cost

Ki tot = 2504.2

Fig.32. Module I and II for calculation of mathematical reference model: *Case I* (Left) & Extension of *Case I* (Right) – Screenshots are taken from the student work supervised by the author [1].



Thu, 14 Nov 2013 12:41:12 GMT

Planning Period (p): 2

Assigned Budget: 15000

TMB Ratio: TMB se 50, TMB pa 50

Input N1*: 0

Input N2*: 0

Input N3*: 0

Input N4*: 0

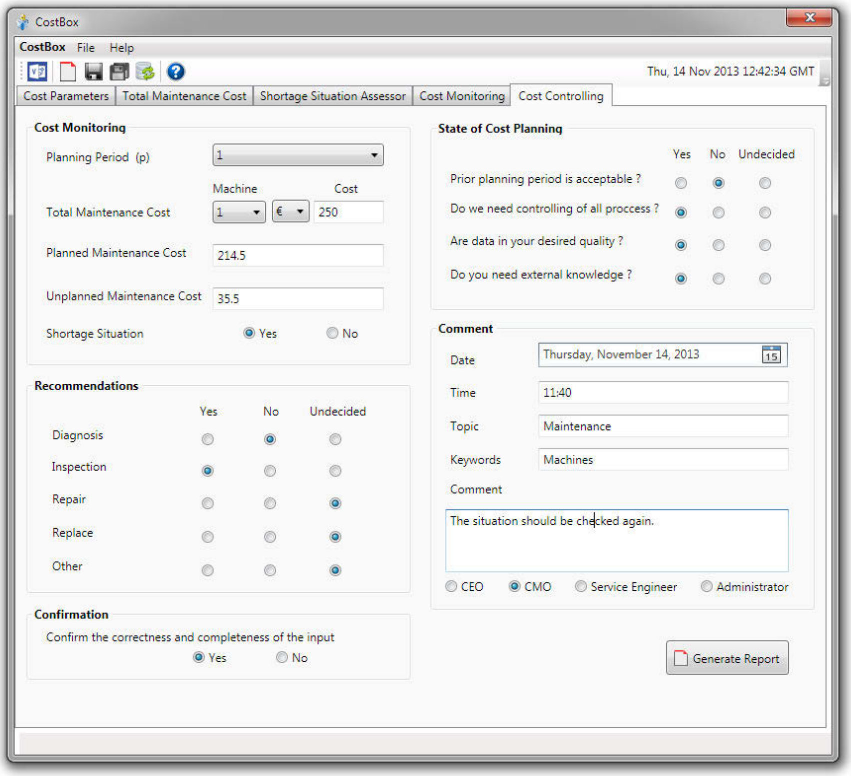
Machine (m): 1

WFi se: 0

Thu, 14 Nov 2013 12:39:34 GMT

Machine: 3

Fig.33. Module III and IV for calculation of mathematical reference model: *Case II* (Left), and for visualization of the calculation for each machine (Right) - Screenshots are taken from the student work supervised by the author [1].



Cost Monitoring

Planning Period (p): 1

	Machine	Cost
Total Maintenance Cost	1	€ 250

Planned Maintenance Cost: 214.5

Unplanned Maintenance Cost: 35.5

Shortage Situation: ● Yes ○ No

Recommendations

	Yes	No	Undecided
Diagnosis	○	●	○
Inspection	●	○	○
Repair	○	○	●
Replace	○	○	●
Other	○	○	●

Confirmation

Confirm the correctness and completeness of the input
● Yes ○ No

State of Cost Planning

	Yes	No	Undecided
Prior planning period is acceptable ?	○	●	○
Do we need controlling of all process ?	●	○	○
Are data in your desired quality ?	●	○	○
Do you need external knowledge ?	●	○	○

Comment

Date: Thursday, November 14, 2013
Time: 11:40
Topic: Maintenance
Keywords: Machines
Comment: The situation should be checked again.

○ CEO ● CMO ○ Service Engineer ○ Administrator

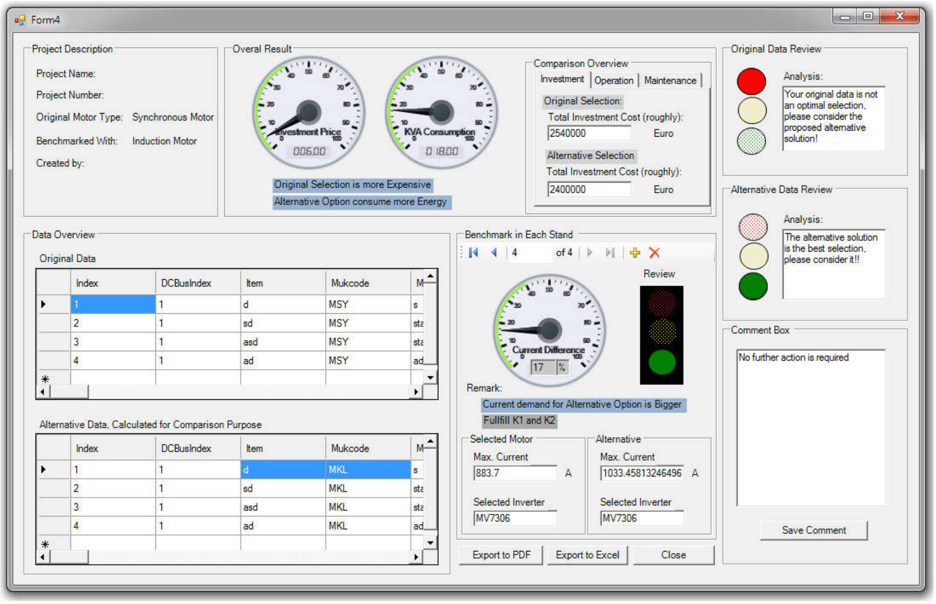
Fig.34. Module V for cost controlling: Documentation and reporting -Screenshots are taken from the student work supervised by the author [1].

Technical specifications of the prototype and the software development process are presented in [1]. The preliminary version of the prototype is developed and tested, in a separate work, based on the case study of vessel manufacturing company (VMC) (cf. Chapter 2 – Section 2.7) [2].

Besides developing *Costprove* Toolbox, a prototype of an assistance tool for supporting the CME is designed, implemented and tested in a separate work. The prototype consists of features that enable maintenance engineers to select drive system components based on meta-analysis of vendors' offers as well as customer's requirements. Mathematical meta-analysis is performed using a benchmarking dashboard. The dashboard provides technical and nontechnical indicators (i.e. KPIs) for selection of drive system components. Technical indicators are mainly acquired from dimensioning of the drive system (drive system specifications) as well as the basic requirements, e.g. for power consumption and operational availability (maintenance-related factors). Nontechnical indicators are primarily to consider business administration activities, especially through indication of investment and PM/CM costs of drive systems which have directly affected a customer's/company's business process.

As shown in Figure 35, the CME can define the requirements and compare the desired value with the offers of various vendors existing in the database. The benchmarking dashboard provides alternatives for selection of the desired drive system. The indicators are used to define thresholds. The results of calculations are visualized in graphical form with the use of light indicators. This facilitates the comparison of alternatives. Using the benchmarking dashboard, the CME can summarize the calculation, add his/her comment, and issue the order considering maintenance factors for purchasing the drive components or system.

To sum up, the benchmarking dashboard broadens and deepens the CME's knowledge for optimal selection of drive components and improves decision-making activities.



Project Description
Project Name:
Project Number:
Original Motor Type: Synchronous Motor
Benchmarked With: Induction Motor
Created by:

Original Selection is more Expensive
Alternative Option consume more Energy

Original Selection:
Total Investment Cost (roughly): 2540000 Euro
Alternative Selection
Total Investment Cost (roughly): 2400000 Euro

Data Overview

Original Data

Index	DCBusIndex	Item	Mukcode	M
1	1	d	MSY	s
2	1	sd	MSY	sta
3	1	asd	MSY	sta
4	1	ad	MSY	ad

Alternative Data, Calculated for Comparison Purpose

Index	DCBusIndex	Item	Mukcode	M
1	1	d	MKL	s
2	1	sd	MKL	sta
3	1	asd	MKL	sta
4	1	ad	MKL	ad

Current Difference: 17 %

Remark:
Current demand for Alternative Option is Bigger
Fullfill K1 and K2

Selected Motor
Max. Current 883.7 A
Selected Inverter MV7306

Alternative
Max. Current 1033.45813246496 A
Selected Inverter MV7306

Original Data Review
Analysis: Your original data is not an optimal selection, please consider the proposed alternative solution!

Alternative Data Review
Analysis: The alternative solution is the best selection, please consider it!!

Comment Box
No further action is required

Fig.35. Benchmarking dashboard for assisting the CME in selection of vendors' offers based on meta-analysis of technical and economic criteria with KPIs (Ansari, et al., 2012c).

The prototype of a benchmarking dashboard has been designed and developed in cooperation with industry partners aiming at considering maintenance factors for purchasing drive systems and later for condition monitoring of the components[50].

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[50] This work is supervised by the author. It is initiated in [3] and further developed by adding the condition-monitoring module in [4]. The results are also published in (Ansari, et al., 2012c).

3.6.2 Prototype II: Textual Meta-Analysis Tool of *Costprove*

This sub-section presents conception and development of a prototype for textual meta-analysis of maintenance management's knowledge assets. The prototype supports the CMO by means of measuring the association between certain instances of maintenance entities (underlying the stored text documents in the CMMIS database) as well as visualization and representation of the results in a graphical form. The prototype is an add-on in the framework of the CMMIS.

Firstly, the technical preconditions of the CMMIS with the available data sources and entity structures are shown in detail. Afterwards, how the association measuring method (i.e. CIMAWA) can be implemented to create an add-on for CMMIS packages is examined. Finally the prototype is realized using real datasets provided by an industry partner.

In order to implement a textual meta-analysis tool, the CMMIS needs to comprise concrete structures of maintenance entities of certain classes. In this work, three classes of entities are considered as **practitioners**, **machines**, and **maintenance operations**. The classes are identified based on the major categories defined in DIN 13306 (DIN, 2010-12) and the use-case of VMC presented in Figure 25 (cf. Chapter 2 – Section 2.7). Each class has sub-entities, which are shown in Figure 36, 37 and 38. It is possible to extend or eliminate the sub-entities depending on the domain of the application.

As shown in Figure 36, the subclasses of the class of **practitioners** are the **CMO, chief engineer, engineer, technician,** and **administrative** personnel. Several subcategories can be defined underlying required domain expertise and availability of specialists (e.g. **component engineer, assembling engineer, sensor-system engineer**, etc.). Notably, the work breakdown structure depends on the organization of the maintenance department.

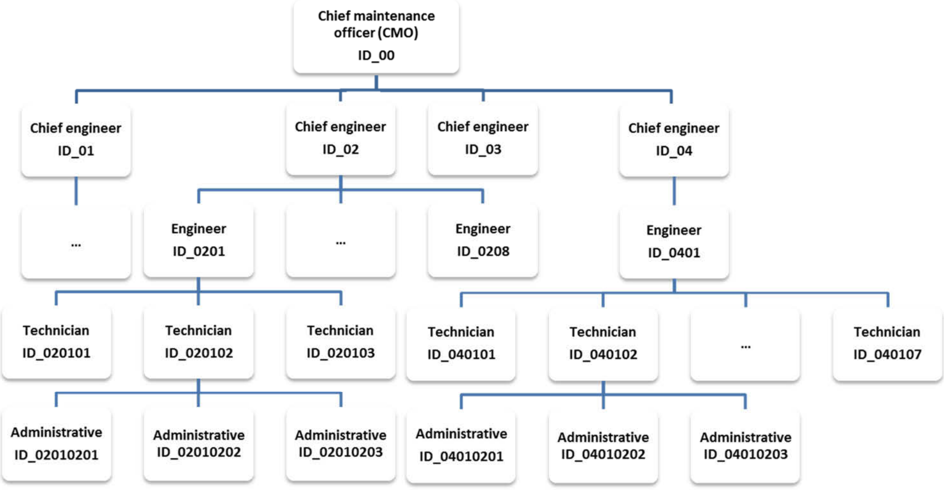

Fig.36. Class of **practitioners**−Adopted by the author from (Ansari, et al., 2014a).

Like the class of **practitioners**, **the class machines** and **maintenance operations** and related subclasses are presented in Figures 37 and 38.

For example, the class of **machines** consists of certain categories (e.g. **marking, beveling, rolling,** etc.) which differs between overall 15 certain instances of machines in the use-case scenario.

The class of **maintenance operations** is divided into two main subclasses: **preventive maintenance** and **corrective maintenance**. The subclasses are **clock-based, age-based** and **condition-based** which refer to PM activities. Likewise **repair** and **compensating** are related to CM activities.

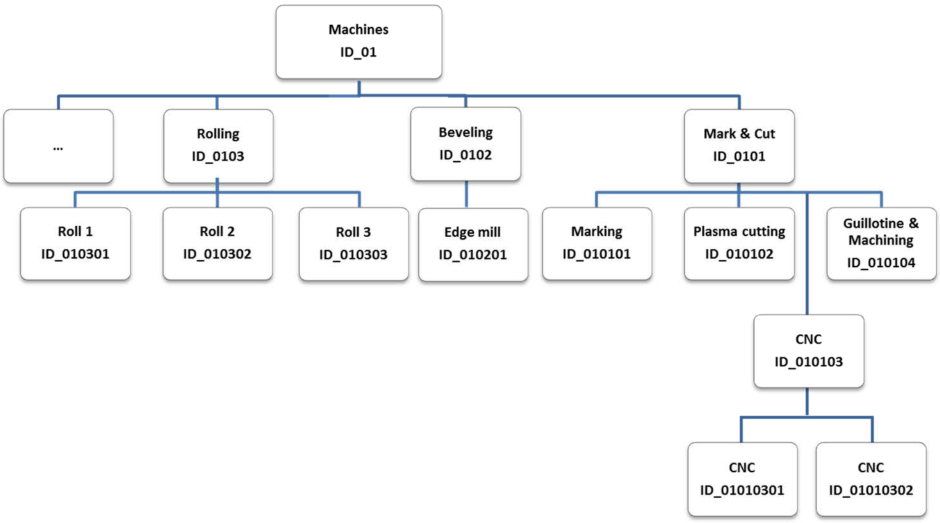

Fig.37. Class of **machines**- Adopted by the author from (Ansari, et al., 2014a).

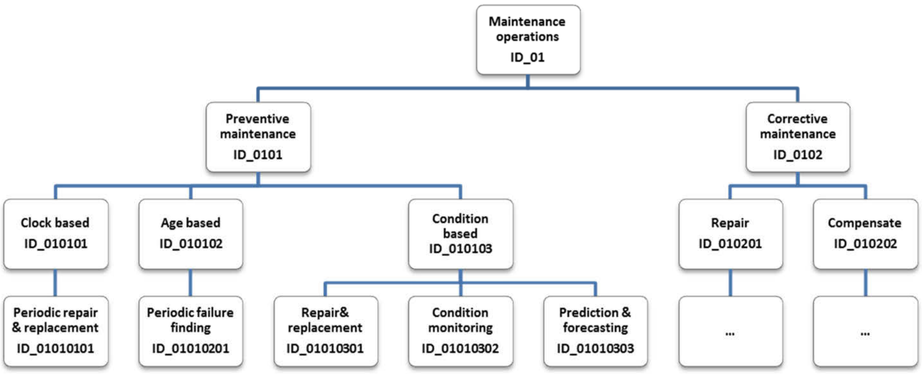

Fig.38. Class of **maintenance operations-**Adopted by the author from (Ansari, et al., 2014a).

The association measuring method, CIMAWA, examines the association and extracts meta-information from stored text documents in the CMMIS database. For calculating the CIMAWA values it is necessary to analyze the underlying text database properly. Especially statistical data about word frequencies and co-occurrence need to be gathered (Uhr, et al., 2013). By using the entities' structures, the entities of the classes and subclasses have to be identified in the text documents (cf. Figures 36, 37, and 38). For the identification of certain instances, an adapted version of the developed entity detection algorithm is applied (Uhr, et al., 2012). This algorithm analyses the texts and detects instances of classes, like certain machines or engineers. For example machines can be described in different ways in the text by ID number, explicit name or internal description, etc. Other problems can be caused in the misspelling of words. Regardless of this deficiency the algorithm solves the problem and detects the instances properly. A prototype is designed for supporting the CMO who is the software's end user. Compared to the human word association, the stimulus can be one of the three classes, a subclass, or instances of one or more classes. Accordingly, the CMO chooses firstly a class, subclass or entity of interest which he/she wants to investigate; the so called *association root* (cf. Figure 39). The relevant associations will be calculated according to the selection. In the application scenario the CMO selects the class of **machines**, subclass of **rolling**, and in that category of **roll 1 id_010301** and **roll 2 id_010302** (cf. Figure 39).

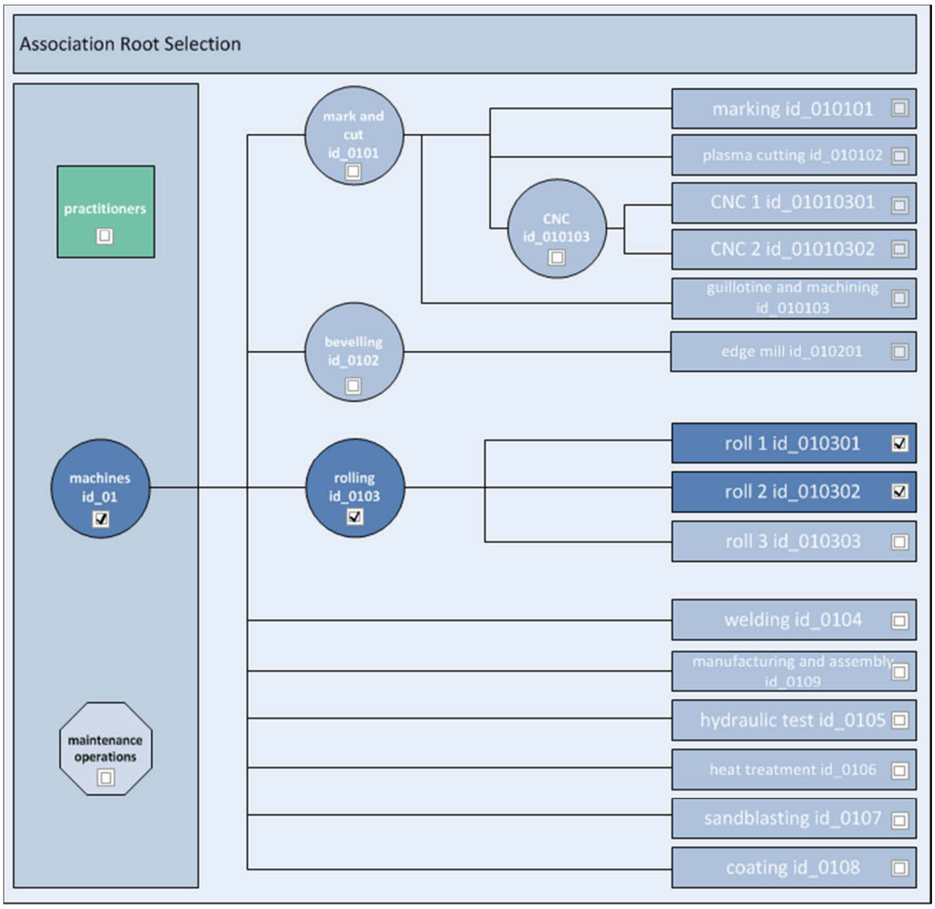

Fig.39. Selection of the association root (Ansari, et al., 2014a).

In the next step, the CMO should select the maintenance entities that he/she wants to investigate. Like the selection step of the association root, classes, subclasses, or a number of certain instances can be selected. As shown in Figure 40, the classes of **practitioners** and **maintenance operations** are selected. The **practitioners** are marked as one **chief engineer**, two **engineers**, one **technician**, and two **administrative** personnel. Under the **maintenance operations**, the subclass of **corrective maintenance** is selected with the instances of **repair** and **replacement, set-up, restart**, and **purchase new unit**. No instances of **machines** are a matter of interest in this example (cf. Figure 40).

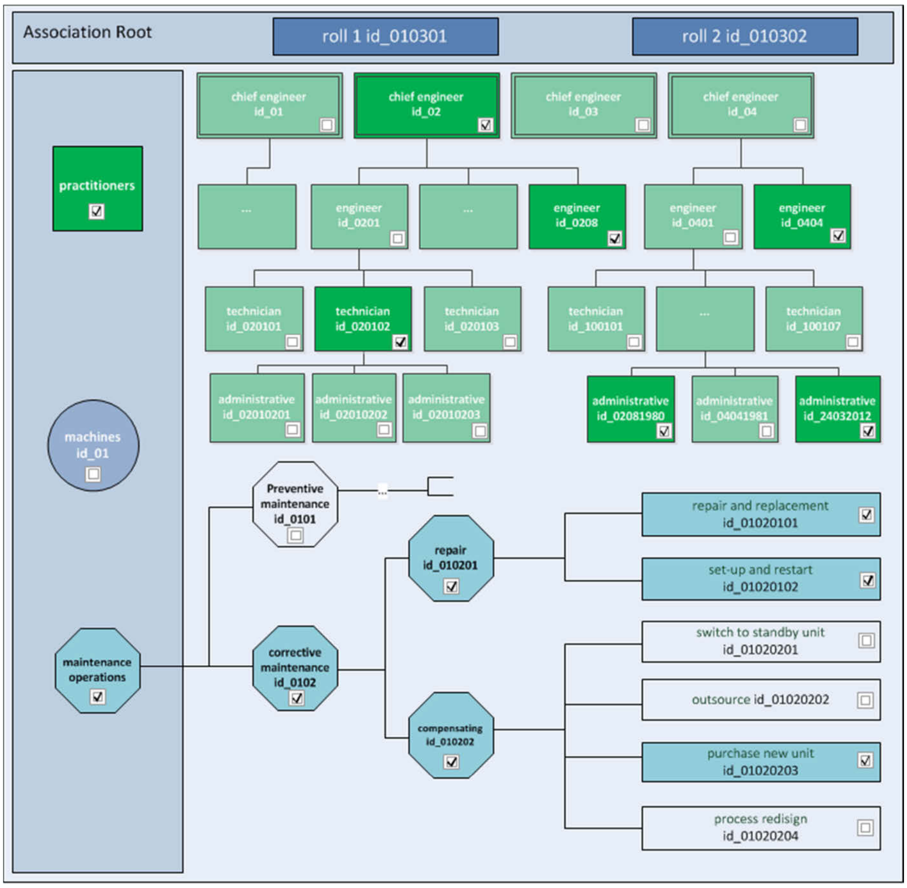

Fig.40. Selection of the maintenance entities for association mapping (Ansari, et al., 2014a).

After the selection process, the application starts calculating the requested associations, based on CIMAWA (Uhr, et al., 2013). A visualization of such an analysis is shown in Figure 41. In the application scenario, **roll 1 id_010301** and **roll 2 id_010302** are selected as the instances of **machines**. These instances are displayed in the center of the association map (cf. Figure 41). The association map visualizes all relevant associations to all instances corresponding to the selection of the CMO. As a result, the thicker the arrows appear, the stronger the association between the items.

The arrows and the distance between the items are a direct representation of the calculated CIMAWA values. In this example, five associated **practitioners** and three associated **maintenance operations** are selected. In turn, the most associated instances of **practitioners** are **engineer id_0404**. Based on the analysis, no association between the association root and **engineer id_0208** is detected, which might include a hint for the CMO about the experiences of this engineer with the rolling machines (i.e. **roll 1** and **roll 2**). Also the most associated maintenance operation is **purchase new unit id_01020203**.

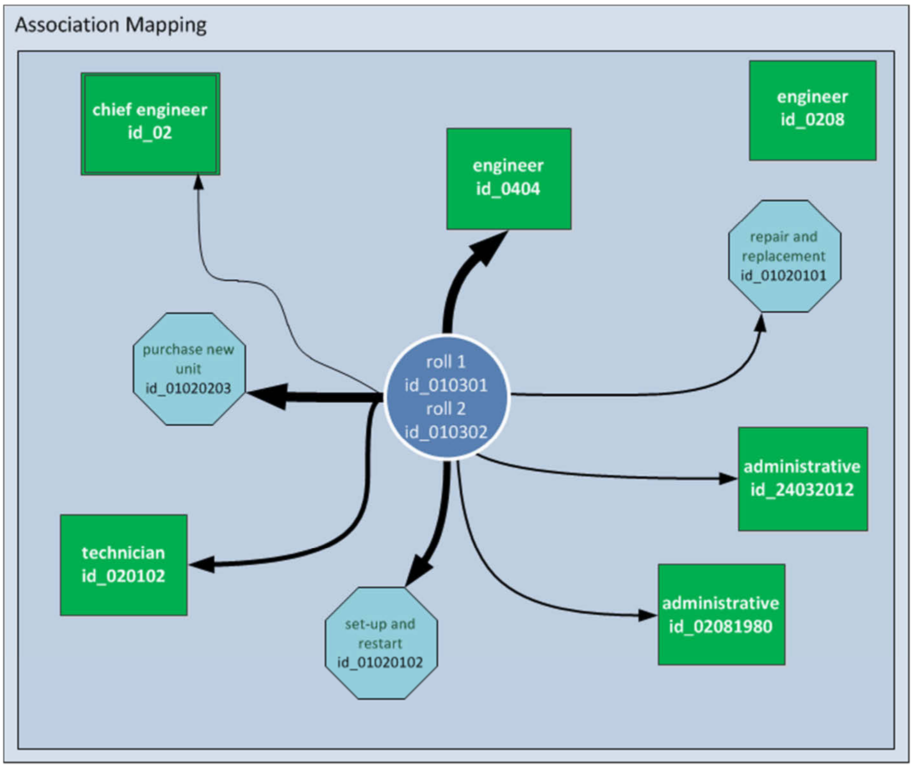

Fig.41. Association mapping feature for meta-analysis of text-based documents (Ansari, et al., 2014a).

Textual meta-analysis is not sufficient for handling planning, monitoring and controlling activities. However, it deepens and compounds the CMO's insight into the status/condition of machines, practitioners and operations underlying the stored documents. It also provides possibilities to learn from former experiences documented and stored in CMMIS databases. For instance, the CMO can realize that the rolling machines in Figure 41 are strongly associated with **engineer id_0404**. This is perhaps already known to the CMO, but the analysis can alert and lead him/her to discover hidden potentials, based on the reviewing of engineer's comments and his/her observation within maintenance intervals. Obviously the benefit of the association mapping is to automate utilization of knowledge assets, especially text documents, without human interference. Moreover, the CMO has a responsibility to control and conduct strategic and tactical maintenance activities corresponding to physical and human resources, budget and cost, technology, environmental factors, safety, etc. Therefore he/she needs to use all possibilities to capture the required information for establishing or updating new/running strategies.

The CMO needs to find out what is known and what is probably unknown. For the latter, textual meta-analysis is crucially helpful, such as to discover propositions and potential consequences of a certain event like a failure. For instance, the CMO starts the application and selects certain entities (cf. Figure 39 and 40). Accordingly the software provides a typical result, such as what is shown in Figure 41. With respect to the strength of the associations, the CMO can (1) define some work orders (tasks) in operational, tactical or strategic MaM /MCM, (2) acquire consequences of investigations, and (3) approve/correct the initial proposition. For example, the CMO can define the following tasks based on the results of Figure 41 as:

- **Task 1** to operational/tactical layer:
    - → **Proposition**:
        - *Association map shows that there is a strong relationship between "rolling machines" and "purchasing new unit".*
    - → **Consequences**:
        - *"Cost intensiveness of the machine"* OR
        - *"Human failure in usage"* OR
        - *"Process overload"* OR
        - *"Further elaborations required".*
- **Task 2** to tactical/strategic layer:
    - → **Proposition**:
        - *Association map shows that there is a weak relationship between "chief engineer" and "rolling machines".*
    - → **Consequences**:
        - *"Human failure"* OR
        - *"Overloaded with other machines"* OR
        - *"Lack of management structure and organization in the engineering department"* OR
        - *"Further elaborations required".*
- **Task 3**…

The mathematical meta-analysis of *Costprove* Toolbox is to some extent independent of textual meta-analysis. However, the prototype presented in sub-section 3.6.1 generates reports based on each instance of analysis by the CMO or CME. These reports include recommendations and hints for improving forthcoming planning period. In addition, the CMMIS regularly accumulates all reports of operators (administrative staff), technicians and service engineers. These reports can be analyzed with the *Costprove* prototype of textual meta-analysis presented in this sub-section.

As a result, the presented prototype is a tool for *alerting the CMO to hidden potentials which are reflected in the text documents but not directly recognizable in mathematical or statistical analyses*. So, the CMO has a gadget to establish new orders or tasks in the CMMIS and make further investigation for improving the maintenance management.

Besides, the software is flexibly designed with a capability to add new entities or subentities. In other words, there is no limitation in regard to any specific process or company, the entities (major classes) as well as their subclasses are expandable. One possibility for further development is to add **resources** as the fourth entity. In the current version, the **resources** (except human resources) which are required to fulfill a certain maintenance operation are divided and distributed under classes of **machines** and **maintenance operations**. For example, spare parts are directly associated with a certain machine. Tools or equipment for diagnosis relate to a certain maintenance activity. In addition, the subclasses can be expanded or customized based on industry needs. For instance, subclasses of **practitioners** can be enlarged by adding **external practitioners** (e.g. **vendors, customers**, etc.). The current structure only considers the internal practitioners[51].

3.6.3 Prototype III: Combining Mathematical and Textual Meta-Analysis Tools

The CMO deals with huge amounts of text documents and historical data for planning the next budgeting period. *Costprove* Toolbox is, therefore, developed using mathematical and textual meta-analysis of maintenance knowledge assets. One question still remains: *Is it possible to combine both approaches?* (i.e. developing an extra dashboard for combining mathematical and textual meta-analysis).

The findings of the textual meta-analysis can be interpreted in terms of cost-intensive items. There are standard tariff lists of maintenance activities, material and labor costs. Detected words inside of maintenance reports can be mapped with the tariff list and ultimately the total cost of these reports is estimated. Thus, the CMO has an additional tool for cost-based analysis of the reports. This supports him/her in the planning of forthcoming maintenance periods and the controlling of the past one.

Taking this approach into account, a software prototype is developed for cost-based analysis of maintenance reports. Firstly, standard lists of maintenance tasks and related cost-intensive items for materials and labor for each machine are created. Secondly, textual meta-analysis is applied for detection of cost-intensive items in maintenance reports, including maintenance activities and associated material and labor items. Thirdly, detected entities are mapped to the tariff list. Finally the cost of each category of maintenance activity, material, and labor are calculated, respectively. This

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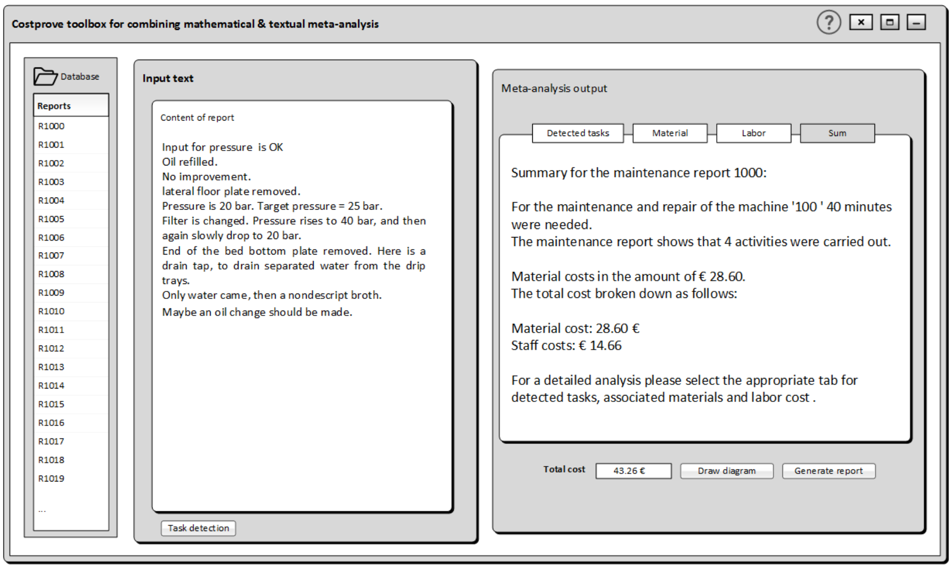
[51] In cooperation with industry partner a prototype of textual meta-analysis is realized as an add-on for the CMMIS. In this study, real datasets are used including text-based reports of maintenance staff. The study was co-supervised by the author. The results appeared in [5].

leads to the calculation of the total maintenance cost, i.e. estimated cost of a maintenance report. The prototype also supports drawing diagrams and generating reports of the cost administration.



Input for pressure is OK
Oil refilled.
No improvement.
lateral floor plate removed.
Pressure is 20 bar. Target pressure = 25 bar.
Filter is changed. Pressure rises to 40 bar, and then again slowly drop to 20 bar.
End of the bed bottom plate removed. Here is a drain tap, to drain separated water from the drip trays.
Only water came, then a nondescript broth.
Maybe an oil change should be made.

Summary for the maintenance report 1000:

For the maintenance and repair of the machine '100 ' 40 minutes were needed.
The maintenance report shows that 4 activities were carried out.

Material costs in the amount of € 28.60.
The total cost broken down as follows:

Material cost: 28.60 €
Staff costs: € 14.66

For a detailed analysis please select the appropriate tab for detected tasks, associated materials and labor cost .

Fig.42. Meta-analysis dashboard combining mathematical and textual methods -Screenshot is created by the author from the prototype developed in [6].

Figure 42 presents the screenshot of the software for the calculation of the total cost of a sample maintenance report[52].

3.7 Discussion

In this chapter, realization of the *Costprove* model and related results are presented. The characteristics of the *Costprove* model are discussed in Chapter 1 and 2. In order to develop an add-on for the CMMIS, first functionalities and sub-systems of the CMMIS are analyzed (cf. Section 3.2- Table 17). Second, the usage domain of the CMMIS inside the production system is revealed and classified (cf. Section 3.2- Table 18). Third, the constraints which fail implementation of the CMMIS are reviewed (cf. Section 3.2-Table 19). Fourth, the commercial CMMIS packages have been analyzed and the *black hole* is detected in three areas: (1) Cost planning-controlling, (2) Cost-based decision support, and (3) Analyzing the content of reports (text) for improving MCM (cf. Section 3.2-Table 20). In addition, the needs analysis with maintenance

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[52] This study was co-supervised by the author in cooperation with an industry partner. Details concerning design and development of the software appeared in [6].

professionals deepened the insight into practice-oriented requirements (cf. Section 3.3).

On the basis of aforementioned analyses, the *Costprove* Toolbox (software) is designed in two usage levels; operational and managerial (cf. Section 3.4). The method for meta-analysis of knowledge assets is discussed as the main approach to finding the strength of the relationship between maintenance variables (cf. Section 3.5).

Costprove deploys mathematical meta-analysis, using the mathematical reference model discussed in Chapter 2. Two prototypes for mathematical meta-analysis are presented in sub-section 3.6.1.

Besides, high potential is detected to support the CMO through meta-analysis of unstructured data (text) and extraction of knowledge from document repositories. In a joint work, association measuring is used to discover the strength of the relationship between maintenance entities in the CMMIS database. It supports the processing of text documents and generating new knowledge from former experiences. The prototype of textual meta-analysis is presented in sub-section 3.6.2.

The scope of study is extended to bridge mathematical and textual meta-analysis. A prototype for analyzing maintenance reports is developed. It estimates the cost of maintenance activities based on the detection of entities (e.g. tasks) inside reports (i.e. keyword detection) and mapping to the tariff list. This prototype is presented in sub-section 3.6.3. In fact the combination of the mathematical and textual meta-analysis should be further studied in future.

As a consequence, *Costprove* Toolbox is realized in three directions of meta-analysis, namely, mathematical, textual and combined. The presented prototypes are successfully developed in cooperation with industry partners, and therefore can be used as a proof of concept for the *Costprove* model.

4 Conclusion and Future Outlook

In this chapter, first key findings and results are summarized. Second, open issues for further contribution and potentials for future research are identified.

4.1 Key Findings and Implications

This dissertation establishes evidence for employing and managing knowledge assets towards continuous improvement of MCM. The domain of application is maintenance of production systems which includes various types of machines. In each planning period (t), the CMO defines cost figures (i.e. planned, unplanned or total cost) and correspondingly the operational factors such as number of maintenance activities. Attainment of the predefined goals is monitored and controlled during and after the planning period respectively. To identify figures of the forthcoming period ($t+1$), the CMO studies records of the past planning period (t), and examines the deviations. The result is the recognition or discovery of certain facts with regard of the state of MCM. The cost planning, monitoring and controlling process therefore exploits existing knowledge, and generates facts and artifacts that need to be further explored. In Figure 43 the above-mentioned process is schematically shown. Cost planning, monitoring, and controlling is an iterative process which is shown by green circles. Each green circle is surrounded by an orange circle referring to the learning process from the past event. The evolution occurs in certain increments ($1 \ldots n$) through planning and the monitoring instances ($t \ \ldots t+n$).

Fig.43.MCM continuous improvement, enhanced by learning from former experiences.

This work constitutes a novel model, *Costprove*, for continuous improvement of MCM through meta-analysis of existing knowledge assets and generating new knowledge from past instances of MCM. Meta-analysis refers to a set of methods for identifying the significant relation between features of cost planning, monitoring and controlling. Meta-analysis supports the CMO in detecting deviations in the actual and desired figures of past planning periods, and defining figures of forthcoming one. The primary focus of this work is on mathematical, and secondary on textual, meta-analysis of maintenance records. The former refers to the main target of *Costprove* for mathematical modeling of the cost functions, and the latter to incorporating analysis of text reports for enhancing MCM. Design, development and realization of *Costprove* are discussed and elaborated in previous chapters. Here, key findings and results are specified as:

Key Finding#1: *Costprove* model consists of mathematical and qualitative components. Mathematical component represents cost functions for planned, unplanned and total maintenance cost of single, non-associated and associated machines. Estimating the aforementioned costs leads to the planning of a number of maintenance activities. The process can incorporate historical data (history-based approach) or can be applied without them (zero-based approach). The qualitative component provides guidelines for dealing with the *Costprove* model and includes an algorithm for deploying *Costprove* in cost planning and monitoring (cf. Chapter 2- Figure 23). The evolution of the model occurs in planning iterations through learning from past experiences, detecting deviations between actual and desired values, and ultimately updating existing strategies for the forthcoming planning period (cf. Chapter 2- Table 12). More details about the use of mathematical model in several periods of application, and the process to use meta-analysis for supporting the CMO to define the adequate mathematical function and the values of its parameters, are discussed in Chapter 2 (cf. Table 12 and Figure 23).

Key Finding#2: The *Costprove* Toolbox (Software tool) assists the CMO in cost planning, monitoring and controlling. The *Costprove* Toolbox mainly deploys the *Costprove* model (cf. Key Finding#1) for meta-analysis of structured knowledge assets of maintenance. As an extension, textual meta-analysis is also integrated into the *Costprove* Toolbox for identifying the value of incorporating unstructured knowledge assets (i.e. text). Such analysis assists the CMO to explore the contents of the maintenance reports and discover hidden improvement potentials in MCM. It is pointed out that the combination of mathematical and textual meta-analysis aggregates findings of both types of analysis (cf. Chapter 3).

Key Finding#3: The foremost finding is the integration of meta-analysis as a kind of knowledge-based approach in MCM. The *Costprove* model establishes a new account on MCM, especially to meta-analyze knowledge assets, identify certain facts or artifacts (i.e. evidence) for improving cost planning and controlling process. The evidence is further explored to enhance MCM process. This work, therefore, constitutes a new knowledge-based approach, for continuous improvement of cost controlling.

The novelty of the *Costprove* model is principally related to Key Finding#3. The problem of *maintenance cost planning-monitoring-controlling*, thereby, is figured out with KM perspective. This dissertation firstly proves that the MCM process gains benefit from knowledge-based approaches such as meta-analysis, and secondly advances the scope of continuous improvement by "*learning from former experiences*".

As a consequence, the author believes that this research breaks through classic approaches in the field of MCM, begins the first step for the integration of knowledge-based approaches in MaM, and highlights new perspectives for sustaining maintenance cost life cycle.

4.2 Future Research: Open Issues and Potentials

Considering aforementioned key findings, *Costprove* model provides opportunities for further research. The open issues are discussed in relation to the key findings. Lastly, potentials for future research are indicated.

Open issue#1: *Costprove* uses an approach to estimate the cost of maintenance and accordingly define the number of maintenance activities. Another approach is to estimate probability of failure and calculate related costs. In this regard, advanced approaches exist (cf. Appendix 7.1 – Table 24). The algorithm for mathematical meta-analysis (cf. Chapter 2 – Figure 23) can be further developed to interact with the existing stochastic algorithms. Thus the meta-analysis is enabled to support predictive MCM and prognosis of causes. The concept for combing *Costprove* with Bayesian Networks has been presented in (Dienst, et al., 2014).

Open issue#2: The *Costprove* model does not consider entire economic aspects of maintenance life cycle. The model can be further developed by considering a total cost life cycle of maintenance, including investments and return on capital. So evidence is analyzed, not only on the basis of operation causes and effects, but also economic implications.

Open issue#3: In order to improve practical implication of the *Costprove* Toolbox (i.e. estimations and analysis), employing an artificial learning algorithm is crucial. This intends to upgrade the toolbox to an automatic assistance system. In addition, the toolbox should interoperate not only with the CMMIS but also enterprise (maintenance) management systems such as EAM or ERP. This issue needs to be taken into account for further developments. It depends on the requirements analysis of the application domain and can be handled by implementing application programming interfaces (APIs).

Open issue#4: *Costprove* toolbox supports meta-analysis of text reports. The prototype for textual meta-analysis and also its combination with mathematical meta-analysis is discussed in Chapter 3 (cf. Section 3.6). Such analysis provides extra information for the CMO based on maintenance reports. Despite the advantages, the presented prototypes of textual meta-analysis should be further developed and integrated with MCM. Thus the *Costprove* Toolbox becomes capable of examining numeric values and text reports simultaneously, and ultimately proposing the best matching solution for solving an existing problem in operation or cost management.

Considering the open issues, the scope of *Costprove* model can be extended to "evidence-cause" analysis in the future (cf. Figure 44). Meta-analysis tools developed in this dissertation identify evidence of problems and support the CMO in the detection of the causes. Beyond meta-analysis, *evidence-cause* analysis enables the CMO to identify the nature of a cause in the planning period (t) (i.e. diagnosis), and further, predict a cause in the forthcoming period ($t+1$), (i.e. prognosis). Evidence-cause analysis should be investigated, first from the management perspective, i.e. defining and selecting appropriate problem-solving approaches, and second as a domain specific study, i.e. defining the fields of application.

An ongoing research is to examine which type of synoptic, incremental or heuristic approaches to problem-solving exist for evidence-cause analysis and which one can cooperate with the meta-analysis tools of *Costprove* (Ansari, et al., 2013). This also requires further study on prioritization of evidences and causes, based on the risk of occurrence and consequential expenditures (economic effects) imposed on the entire cost planning and controlling process.

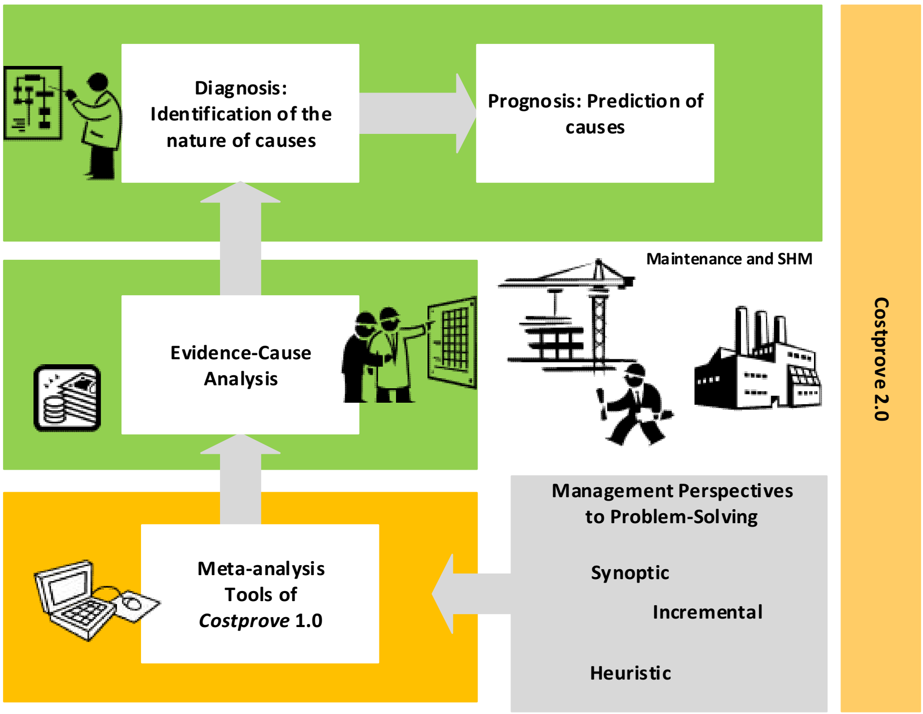

Fig.44.*Costprove 2.0*–Modular concept for future research.

Evidence-cause analysis is domain-specific, thereby; causes of a problem and its evidences are different in each problem domain. A progressive field of research to apply evidence-cause analysis is structural health monitoring (SHM). According to (Giurgiutiu, 2007) and (Balageas, et al., 2006), SHM “assesses the state of structural health continuously or periodically in an automated way via direct measurements and through appropriate data processing and interpretation in a diagnostic system” (Ansari, et al., 2014b). Maintenance and SHM of structures and infrastructure requires a substantial amount of cost. “Approximately one third of all bridges in the US national inventory need either be repaired or replaced” (Giurgiutiu, 2007), (Ansari, et al., 2014b). Between 2009 and 2011, the annual maintenance cost to upgrade and replace aging distribution infrastructure was estimated to be from \$3 to \$6 billion per year by Edison Electric Institute (EEI) (Harris Williams, 2010).

The synergistic use of the *Costprove* model and evidence-cause analysis in SHM may lead not only to the fostering of learning from past experiences in cost planning, but also to promoting early stage diagnosis and prediction of disturbances and hidden cost factors. The initial step to integrate knowledge-based approaches in SHM is studied in collaboration with SHM engineers (Ansari, et al., 2014b) and (Niu, et al., 2013). The studies have highlighted the potential for cost-based analysis of SHM records (Ansari, et al., 2014b).

Figure 44 presents the modular concept, *Costprove 2.0*, for future research in both management and technological perspectives. It utilizes meta-analysis tools of *Costprove* in evidence-cause analysis for identifying the nature of causes and prediction (i.e. diagnosis and prognosis). This concept considers the economic impact and the effects of the identified or predicted causes on MCM, especially SHM cost management.

5 Bibliography

Ackoff, R. L. 1989. From Data to Wisdom. *Journal of Applied Systems Analysis.* 1989, Vol. 16, pp. 3-9.

Adam, S. 1989. *Optimierung der Anlageninstandhaltung.* Berlin : Erich Schmidt Verlag GmbH, 1989.

Ahlmann, H. 1984. Maintenance effectiveness and economic models in therotechnology concept. *Maintenance Management International.* 1984, Vol. 4, pp. 131-139.

Ahuja, I. P. S. and Khamba, J. S. 2008. Total productive maintenance: literature review and directions. *International Journal of Quality & Reliability Management.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2008, Vol. 25, pp. 709-756.

Alavi, M. and Leidner, D. E. 2001. Review: Knowledge management and knowledge management systems: Conceptual foundations and research issues. *MIS Quarterly.* Minneapolis, MN, USA : Carlson School of Management, University of Minnesota, 2001, Vol. 25, pp. 107-136.

Alexander, S. M., Dillman, M. A., Usher, J.S. and Damodaran, B. 1995. Economic design of control charts using the Taguchi loss function. *Computers and Industrial Engineering.* Amsterdam, the Netherlands: Elsevier Science Ltd, 1995, Vol. 28, pp. 671-679.

Almgren, T., Andréasson, N., Palmgren, M., Patriksson, M., Strömberg, A. B., Wojciechowski, A. and Önnheim, M. 2012. Optimization models for improving periodic maintenance schedules by utilizing opportunities. *Proceedings of 4th World Conference on Production & Operations Management and the 19th International Annual EurOMA Conference.* Amsterdam, the Netherlands : University of Amsterdam, 2012.

Al-Najjar, B. 1996. Total quality maintenance: An approach for continuous reduction in costs of quality products. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England : MCB UP Ltd., Emerald Group Publishing Limited, 1996, Vol. 2, pp. 4-20.

Andrews, K. R. 1971. *The Concepts of Corporate Strategy.* New York : Dow Jones-Irwin, 1971.

Ansari, F., Uhr, P. and Fathi, M. 2014a. Textual Meta-analysis of Maintenance Management's Knowledge Assets. *International Journal of Services, Economics and Management.* Geneva, Switzerland: Inderscience Enterprises Ltd., 2014a, Vol. 6, pp. 14-37.

Ansari, F., Buethe, I., Niu, Y., Fritzen, C.P. and Fathi, M. 2014b. Integration of Knowledge-based Approach in SHM Systems. *IAENG Transactions on Engineering Technologies.* Berlin, Germany: Springer, 2014c, Book chapter No.: 55.

Ansari, F., Fathi, M. and Seidenberg, U. 2013. Combining Synoptic and Incremental Approaches for Improving Problem-Solving in Maintenance Planning, Monitoring and Controlling. *Proceedings of 9th Interdisciplinary Workshop on Intangibles, Intellectual Capital and Extra-Financial Information.* Copenhagen, Denmark : European Institute for Advanced Studies in Management (EIASM), 2013.

Ansari, F., Fathi, M. and Seidenberg, U. 2012a. Developing an Algebraic Model for Administrating Preventive Maintenance Cost of Production Machines. *Proceedings of 4th World Conference on Production & Operations Management and the 19th International Annual EurOMA Conference.* The Netherlands : University of Amsterdam, 2012a.

Ansari, F., Fathi, M. and Seidenberg, U. 2012b. Integration of Knowledge Management in Preventive Maintenance Cost Controlling Using Performance Quality Indicators. Chicago : CG-Publisher, 2012b. (Received Graduate Scholar Award).

Ansari, F., Dewa, R.A. and Fathi, M. 2012c. Drive System Assistance Tool for Meta-Analysis of Dimensioning. *Proceedings of the 38th Annual Conference of the IEEE Industrial Electronics Society (IEEE-IECON 2012).* Montreal, Canada : IEEE Press, 2012c.

Ansari, F., Fathi, M. and Seidenberg, U. 2011. Evolution of Intelligent Quality Management Process Based on Using Performance Quality Indicators. [ed.] Ronald Maier. *Professional Knowledge Management: From Knowledge to Action.* Bonn : Gesellschaft für Informatik, 2011, pp. 149-160.

Ansoff, H. I. 1991. Critique of Henry Mitzberg's The Design School: Reconsidering the basic premise of strategic management. *Strategic Management Journal.* New York : John Wiley & Sons, 1991, Vol. 12, pp. 449-461.

Ansoff, H. I. 1977. The state of practice in planning systems. *Sloan Management Review.* Massachusetts, USA : Massachusetts Institute of Technology, 1977, Vol. XVIII, pp. 1-24.

Attri, R., Grover, S., Dev, N. and Kumar, D. 2012. Analysis of barriers of total productive maintenance (TPM). *International Journal of System Assurance Engineering and Management* . Berlin, Germany: Springer , 2012, Vol. 4, pp. 365-377.

Baars, H. and Kemper, H.G. 2008. Management support with structured and unstructured data- An integrated Business Intelligence Framework. *Information Systems Management.* London, UK : Taylor& Francis Group, 2008, Vol. 25, pp. 132-148.

Baets, W.R.J., [ed.]. 2005. *Knowledge Management and Management Learning:Extending the Horizons of Knowledge-Based Management.* Berlin, Germany : Springer, 2005.

Bagadia, K. 2006. *Computerized maintenance management systems made easy.* New York : McGraw-Hill, 2006.

Balageas, D., Fritzen, C.P. and Güemes, A. 2006. *Structural Health Monitoring.* London, UK : ISTE Ltd., 2006.

Barlage, A. 2005. Instandhaltung, Verfügbarkeit und Wirtschaftlichkeit:Ergebnisse einer Studie zum Einfluss der Instandhaltung auf den Unternehmenserfolg. *Instandhaltung.* 2005, Vol. 4, pp. 14-16.

Barlow, R. and Hunter, L. 1960. Optimum Preventive Maintenance Policies. *Operations Research.* INFORMS, 1960, Vol. 8, pp. 90-100.

Baron, M. M. and Pate-Cornell, M. E. 1999. Designing Risk-Management Strategies for Critical Engineering Systems. *IEEE Transactions on Engineering Management.* IEEE Press, 1999, Vol. 46, pp. 87-100.

Beck, N. 2001. *Kontinuität des Wandels:Inkrementale Änderungen einer Organisation.* Wiesbaden : Westdeutscher Verlag, 2001.

Becker, T. 2008. *Prozesse in Produktion und Supply Chain optimieren.* 2nd. Berlin/ Heidelberg : Springer, 2008.

Beierle, C. and Kern-Isberner, G. 2008. *Methoden wissensbasierter Systeme* . 4th. Berlin, Germany : Springer, 2008.

Ben-Daya, M., Duffuaa, S. O., Raouf, A., Knezevic, J. and Ait-Kadi, D. [ed.]. 2009. *Handbook of Maintenance Management and Engineering.* Berlin, Germany : Springer, 2009.

Ben-Daya, M. 2000. You may need RCM to enhance TPM implementation. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England: MCB UP Ltd. - Emerald Group Publishing Limited, 2000, Vol. 6, pp. 82-85.

Berens, W., Delfmann, W. and Schmitting, W. 2004. *Quantitative Planung.* 4th. Stuttgart,Germany : Schäffer-Poeschel Verlag, 2004.

Blohm, H., Beer, T., Seidenberg, U. and Silber, H. 2008. *Produktionswirtschaft.* 4th. Herne, Germany : NWB Verlag, 2008.

Blohm, H. and Lüder, K. 1988. *Investition.* 6. Munich : Verlag Vahlen, 1988.

Blohm, H. 1977. *Organisation, Information und Überwachung.* Wiesbaden,Germany: Betriebswirtschaftlicher Verlag Gabler, 1977.

Bordag, S. 2008. A Comparison of Co-occurrence and Similarity Measures as Simulations of Context, Computational Linguistics and Intelligent Text Processing. *Lecture Notes in Computer Science.* Berlin, Germany: Springer, 2008, Vol. 4919, pp. 52-63.

Braybrooke, D. and Lindblom, C. E. 1963. *A strategy of decision: policy evaluation as a social process.* New York : Free Press, 1963.

Bresser, R. K. F. 2010. *Strategische Managementtheorie.* Stuttgart : Kohlhammer, 2010.

BS. 1991 (Confirmed on 2012). *BS 4778-3.1:1991 - Quality vocabulary. Availability, reliability and maintainability terms. Guide to concepts and related definitions.* London, UK : British Standards Institution, 1991 (Confirmed on 2012).

Canfield, R. V. 1986. Cost optimization of predictive preventive maintenance. *IEEE Transactions on Reliability.* IEEE Press, 1986, Vols. R-35.

Cavalier, M.P. and Knapp, G.M. 1996. Reducing preventive maintenance cost error caused by uncertainty. *Journal of Quality in Maintenance Engineering*, Bingley, West Yorkshire, England: Emerald Group Publishing Limited 1996, Vol. 2, pp. 21–36.

CEN. 2004. Part 4: Guidelines for Measuring KM. *European Guide to Good Practice in Knowledge Management (Ref. No.:CWA 14924-4:2004 E).* Brussels, Belgium : European Committee for Standardization , 2004.

Chea, A.C. 2011. Activity-Based Costing System in the Service Sector: A Strategic Approach for Enhancing Managerial Decision Making and Competitiveness. *International Journal of Business and Management.* Toronto : Canadian Center of Science and Education, 2011, Vol. 6, pp. 3-10.

Chen, H. 2010. An Optimal Synchronization Decision Model of Correlation Maintenance Task. *Proceedings of International Conference on Management and Service Science.* IEEE Press, 2010.

Chen, Y. and Jin, J. 2003. Cost-variability-sensitive Preventive Maintenance Considering Management Risk. *IIE Transactions.* Norcross, GA, USA : Institute of Industrial Engineers (IIE), 2003, Vol. 35.

Coakes, E. and Clarke, S., [ed.]. 2006. *Encyclopedia of communities of practice in information and knowledge management.* Hershey, PA, USA : Idea Group Inc., 2006.

Collins, D. E. 1983. Management of Logistic Support Costs in the Equipment Acquisition Phase. *IEEE Transactions on Reliability.* IEEE Press, 1983, Vol. 32, pp. 264-271.

Cooper, R. and Kaplan, R. S. 1991. Profit priorities from activity-based costing. *Harvard Business Review.* Boston, Massachusetts, USA : Harvard Business Publishing, 1991, pp. 130-137.

Cray, J. 2008. Maintenance Engineering Handbook. [ed.] R.K, Higgins, L.R. and Wikoff, D.J. Mobley. 7. New York : Mc Graw Hil, 2008.

Crellin, G. L., Mott, J. E. and Smith, A. M. 1988. *Defensive Strategies for Reducing Susceptibility to Common-Cause Failures.* California, USA : Electric Power Research Institute (EPRI), 1988.

Dagan, L., Lee, L. and Pereira, F. C. N. 1999. Similarity-Based Models of Word Co-occurrence Probabilities. *Machine Learning.* Dordrecht, the Netherlands : Kluwer Academic Publishers, 1999, Vol. 34, pp. 43-69.

Dalkir, K. 2005. *Knowledge management in theory and practice.* Amsterdam, the Netherlands : Elsevier, 2005.

Dandotiya, R. and Lundberg, J. 2012. Economic model for maintenance decision: a case study for mill liners. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England: Emerald Group Publishing Limited, 2012, Vol. 18, pp. 79-97.

Davenport, T. H. and Prusak, L. 1998. *Working knowledge:How Organizations Manage What They Know.* Boston, USA : Harvard Business School Press, 1998.

Davenport, T.H. and Probst, G.J.B. 2002. *Knowledge Management Case Book: Siemens Best Practices.* 2nd. Erlangen, Germany : Wiley/Publicis, 2002.

Dawson, R. 2005. *Developing Knowledge-Based Client Relationships: The Future of Professional Services.* 2nd. Boston, MA, USA : Elsevier , 2005.

Dawson, R. 2000. Knowledge capabilities as the focus of organizational development and strategy. *Journal of Knowledge Management.* Bingley, West Yorkshire, England : MCB University Press (Emerald Group Publishing Limited), 2000, Vol. 4, pp. 320-327.

Dersin, P., Peronne, A. and Arroum, C. 2008. Selecting Test and Maintenance Strategies to achieve Availability Target with lowest Life-Cycle Cost. *Reliability and Maintainability Symposium.* IEEE Press, 2008, pp. 301 – 306.

Destri, A.M.L., Picone, P.M. and Minà, A. 2012. Bringing Strategy Back into Financial Systems of Performance Measurement:Integrating EVA and

PBC. *Business Systems Review.* Business Systems Laboratory, 2012, Vol. 1, pp. 85-102.

Dey, P. K. 2004. Decision Support System for Inspection and Maintenance: A Case Study of Oil Pipelines. *IEEE Transactions on Engineering Management.* IEEE Press, 2004, Vol. 51, pp. 47-56.

Dhillon, B. S. 2002. *Engineering Maintenance-A Modern Approach.* Florida, USA : CRC Press LLC., 2002.

Dhillon, B. S. 1989. *Life Cycle Costing.* New York, USA : Gordon and Breach Science Publishers, 1989.

Dienst, S., Ansari, F. and Fathi, M. 2014. Integrated system for analyzing maintenance records in product improvement. *International Journal of Advanced Manufacturing Technology*. Springer, 2014.

Dienst, S., Uhr, P., Fathi, M., Klahold, A., Abramovici, M. and Lindner, A. 2012. Concept for Improving Industrial Goods via Contextual Knowledge Provision. *Proceedings of the 12th International Conference on Knowledge Management and Knowledge Technologies (I-Know).* Graz, Austria : ACM, 2012.

DIN. 2010-12. *Maintenance - Maintenance terminology, Trilingual version EN 13306:2010-2012 (Revised version of DIN 31051:1985-01 and EN 13306:2001-09).* Berlin, Germany : Deutsches Institut für Normung, Beuth Verlag GmbH, 2010-12.

Dror, Y. 1964. Muddling Through - "Science" or Inertia? *Public Administration Review.* Blackwell Publishing-American Society for Public Administration, 1964, Vol. 24, pp. 153-157.

Duffuaa, S.O., Ben-Daya, M., Al-Sultan, K.S. and Andijani, A.A. 2001. A generic conceptual simulation model for maintenance systems. *Journal of Quality in Maintenance Engineering*. Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2001, Vol. 7, pp. 207-219.

Duncan, A. J. 1956. The economic design of x-charts used to maintain current control of a process. *Journal of the American Statistical Association.* Alexandria, VA, USA : American Statistical Association, 1956, Vol. 51, pp. 228-242.

Elegbede, A. O. C., Chu, C., Adjallah, K. H. and Yalaoui, F. 2003. Reliability Allocation Through Cost Minimization. *IEEE Transactions on Reliability.* IEEE Press, 2003, Vol. 52, pp. 106-111.

Eppler, M.J. 2006. *Managing Information Quality: Increasing the Value of Information in Knowledge-intensive Products and Processes.* 2nd. Berlin, Germany : Springer, 2006.

Evans, J. R. and Lindsay, W. M. 2011. *The Management and Control of Quality.* 8th. Michigan, USA: South-Western,Cengage Learning, 2011.

Fathi, M., [ed.]. 2013. *Integration of Practice-Oriented Knowledge Technology: Trends and Prospectives.* Berlin, Germany : Springer, 2013.

Fei, R. 2008. Maintenance Engineering Handbook. [ed.] R.K, Higgins, L.R. and Wikoff, D.J. Mobley. 7. New York : Mc Graw Hil, 2008.

Franceschini, F., Galetto, M. and Maisano, D. 2007. *Management by Measurement: Designing Key Indicators and Performance Measurement Systems.* Berlin, Germany : Springer, 2007.

Frankel, E. G. 2008. *Quality Decision Management - The Heart of Effective Futures-Oriented Management.* Cambridge : Springer, 2008.

Fredrickson, J. W. 1983. Strategic Process Research: Questions and Recommendations. *The Academy of Management Review.* Academy of Management, 1983, Vol. 8, pp. 565-575.

Frenkel, I., Lisnianski, A. and Khvatskin, L. 2009. Corrective Maintenance and Reliability Associated Cost Estimation of Aging Multi-State Systems. *Journal of Computer Modelling and New Technologies.* 2009, Vol. 13.

Gigerenzer, G. and Gaissmaier, W. 2011. Heuristic Decision Making. *Annual Review of Psychology.* California, USA : Annual Reviews , 2011, Vol. 62, pp. 451-482.

Gigerenzer, G. 2008. Why heuristics work. *Perspectives on Psychological Science.* Washington, D.C., USA : Association for Psychological Science, 2008, Vol. 3, pp. 20-29.

Giurgiutiu, V. 2007. *Structural Health Monitoring with Piezoelectric Wafer Active Sensors.* Amsterdam, the Netherlands : Elsevier , 2007.

Glass, G. 1977. Integrating findings: The meta-analysis of research. *Review of Research in Education.* Washington, D.C., USA : American Educational Research Association, 1977, Vol. 5, pp. 351-379.

Goffin, K. and Mitchell, R. 2010. *Innovation Management.* 2nd. New York : Palgrave Macmillan, 2010.

Gottschalk, P. 2004. *Strategic Knowledge Management Technology.* Hershey, PA, USA : Idea Group Publishing, 2004.

Goyal, S.K. and Kusy, M.I. 1985. Determining Economic Maintenance Frequency for a Family of Machines. Journal of Operational Research Society, 1985, Vol. 36, pp. 1125-1128.

Grall, A. and Dieulle, L., Bérenguer, C., Roussignol, M. 2002. Continuous-Time Predictive-Maintenance Scheduling for a Deteriorating System. *IEEE Transactions on Reliability.* IEEE Press, 2002, Vol. 51, pp. 141-150.

Gronau, N. and Weber, E. 2004. Management of Knowledge-Intensive Business Processes. *Lecture Notes in Computer Science.* Berlin, Germany : Springer, 2004, Vol. 3080, pp. 163-178.

Gross, J.M. 2006. *Fundamentals of Preventive Maintenance.* AMACOM (division of American Management Association), 2006.

Gunasekaran, A. and Sarhadi, M. 1998. Implementation of activity-based costing in manufacturing. *International Journal of Production Economics.* Amsterdam, the Netherlands : Elsevier Science B.V., 1998, Vols. 56-57, pp. 231-242.

Haarman, M. and Delahay, G. 2004. *Value Driven Maintenance – new faith in maintenance.* Dordrecht, : Mainnovation, 2004.

Hagmark, P.E. and Virtanen, S. 2007. Simulation and calculation of reliability performance and maintenance cost. *Reliability and Maintainability Symposium.* IEEE Press, 2007, pp. 34-40.

Hahn, D. and Laßmann, G. 1993. *Produktionswirtschaft- Controlling industrieller Produktion.* Heildelberg : Physica-Verlag, 1993, Vol. 3.1, p. 353.

Harris Williams, & Co. 2010. *Transmission & Distribution Infrastructure.* Virginia,USA : Harris Williams & Co., 2010.

Hartung, J., Knapp, G. and Sinha, B. K. 2008. *Statistical Meta-Analysis with Applications* . New York : John Wiley & Sons Inc., 2008.

Hastings, N. A. J. 2010. Maintenance Organization and Budget. *Physical Asset Management.* London, UK : Springer , 2010, pp. 255-278.

Heyer, G., Quasthoff, U. and Wittig, T. 2012. *Text Mining: Wissensrohstoff Text.* Dortmund, Germany : W3L-Verlag, 2012.

Hilgers,D.2008. *Performance Management.* Wiesbaden, Germany: Betriebswirtschaftlicher Verlag / GWV Fachverlage GmbH, 2008.

Hipkina, I. B. and De Cock, C. 2000. TQM and BPR: lessons for maintenance management. *Omega: The International Journal of Management Science.* Amsterdam, the Netherlands: Elsevier Science Ltd., 2000, Vol. 28, pp. 277-292.

Hoffmann, M., Goesmann, T. and Kienle, A. 2002. Analyse und Unterstützung von Wissensprozessen als Voraussetzung für erfolgreiches Wissensmanagement. *Geschäftsprozessorientiertes Wissensmanagement.* Berlin, Germany : Springer, 2002, pp. 159-184.

Hotho, A., Maedche, A. and Staab, S. 2002. Text Clustering Based on Good Aggregations. *Künstliche Intelligenz (KI).* Bonn, Germany : Gesellschaft für Informatik e.V. - Springer, 2002, Vol. 16, pp. 48-54.

Huang, Y. S. and Fang, C. C. 2008. A Cost Sharing Warranty Policy for Products with Deterioration. *IEEE Transactions on Engineering Management.* IEEE Press, 2008, Vol. 55, pp. 617-627.

IEC. 1990. *International Electrotechnical Vocabulary - Chapter 191- Dependability and Quality of Service.* Geneva, Switzerland: International Electrotechnical Commission (IEC), 1990.

Ierace, S. and Cavalieri, S. 2013. An Analytic Hierarchy Process Based Model for the Selection of Decision Categories in Maintenance Systems. *Management and Production Engineering Review.* Opole, Poland : Production Engineering Committee of the Polish Academy of Sciences, 2013, Vol. 4, pp. 37-49.

Imai, M. 2002. *Kaizen.* 2nd. Munich : Econ Ullstein List Verlag, 2002.

Jardine, A.K.S. and Tsang, A.H.C. 2005. *Maintenance, Replacement, and Reliability: Theory and Applications.* USA : CRC Press, 2005.

Jayabalan, V. and Chaudhuri, D. 1992. Cost Optimization of Maintenance Scheduling for a System with Assured Reliability. *IEEE Transactions on Reliability.* IEEE Press, 1992, Vol. 41, pp. 21-25.

Jennex, M. E. 2007. *Knowledge Management in Modern Organizations.* Hershey, PA, USA: Idea Group Publishing, 2007.

Jennex, M.E. and Croashell, D. 2005. Knoweledge Management: are we a discipline? *International Journal of Knowledge Management.* Hershey, PA, USA : IGI Global, 2005, Vol. 1, pp. i-v.

Johnson, G. 1988. Rethinking Incrementalism. *Strategic Management Journal.* New York : John Wiley & Sons, 1988, Vol. 9, pp. 75-91.

Kans, M. 2008. An approach for determining the requirements of computerized maintenance management systems. *Computers in Industry.* Amsterdam, the Netherlands : Elsevier Science Publishers B. V., 2008, Vol. 59, pp. 32-40.

Kans, M. 2009. The advancement of maintenance information technology: A literature review. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2009, Vol. 15, pp. 5-16.

Käschel, J. and Teich, T. 2001. Reihenfolgeplanung in Produktionsnetzwerken. [ed.] Jahnke, B. and Wall, F. *IT-gestützte betriebswirtschaftliche Entscheidungsprozesse.* Wiesbaden: Gabler Verlag, 2001, pp. 239-259.

Kelly, A. 2006. *Managing Maintenance Resources.* Burlington, MA, USA : Elsevier Ltd., 2006.

Kijima, M. 1989. Some results for repairable systems with general repair. *Journal of Applied Probability.* Applied Probability Trust, JSTOR, 1989, Vol. 26, pp. 89-102.

Kijima, M., Morimura, H. and Suzuki, Y. 1988. Periodical replacement problem without assuming minimal repair. *European Journal of Operational Research.* Amsterdam, the Netherlands : Elsevier B.V., 1988, Vol. 37, pp. 194-203.

Kister, T. 2008. Estimating Repair and Maintenance Costs. [ed.] Mobley, R.K, Higgins, L.R. and Wikoff, D.J. *Maintenance Engineering Handbook.* 7th. New York, USA : Mc Graw Hil, 2008, 5, pp. 3.107-3.120.

Klahold, A. , Uhr, P., Ansari, F. and Fathi, M. 2013. A Framework to utilize the Human Ability of Word Association for detecting Multi Topic Structures in Text Documents. *IEEE Intelligent Systems.* IEEE Press, Vol. PP/99, 2013.

Klein, R. and Scholl, A. 2004. *Planung und Entscheidung.* Munich, Germany : Verlag Franz Vahlen GmbH , 2004.

Koen, B. V. 2002. *Discussion of the method:Conducting the Engineer's Approach to Problem Solving.* Oxford : Oxford University Press, 2002.

Koen, B. V. 1984. Toward a definition of the engineering method. *Engineering Education.* 1984, Vol. 75, pp. 151-155.

Koen, B. V. 1985. *Definition of the engineering method.* Washington : American Society for Education, 1985.

Labib, A. W. 2004. A Decision Analysis Model for Maintenance Policy Selection Using a CMMS. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2004, Vol. 10.

Labib, A. W. 1998. World-class maintenance using a computerized maintenance management system. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 1998, Vol. 4, pp. 66-75.

Lamb, R. G. 2009. *Maintenance Reinvented and Business Success: Everything is about business.* Houston, TX, USA : Cost Control Systems, LLC, 2009.

Lationo, C. J. 1999. *Hidden treasure: Eliminating chronic failures can cut maintenance costs up to 60%.* Hopewell, Virginia : Reliability Center, 1999.

Leavitt, P., [ed.]. 2003. *Using Knowledge Management to Drive Innovation.* Houston, TX, USA : American Productivity & Quality Center (APQC) , 2003.

Lee, J. and Wang, B., [ed.]. 1999. *Computer-Aided Maintenance Methodologies and Practices.* Berlin, Germany : Springer, 1999.

Lehtonen, M. 2006. On the optimal strategies of condition monitoring and maintenance allocation in distribution systems. *Proceedings of 9th International Conference on Probabilistic Methods Applied to Power Systems.* Stockholm, Sweden: PMAPS, 2006, pp. 1-5.

Leistner, F. 2010. *Mastering Organizational Knowledge Flow: How to Make Knowledge Sharing Work.* Hoboken, New Jersey, USA : John Wiley & Sons, Inc., 2010.

Levitt, J. 2009. *Handbook of Maintenance Management.* 2nd. USA : Industrial Press Inc., 2009. ISBN-10: 0831133899.

Lim, J.H. and Park, D.H. 1999. Evaluation of Average Maintenance Cost for Imperfect-Repair Model. *IEEE Transactions on Reliability.* IEEE Press, 1999, Vol. 48, pp. 199-204.

Lindblom, C.E. 1959. The science of "muddling through". *Public Administration Review.* American Society for Public Administration, 1959, Vol. XIX, pp. 79-88.

Linderman, K., McKone-Sweet, K.E. and Anderson, J.C. 2005. An integrated systems approach to process control and maintenance. *European Journal of Operational Research.* Amsterdam, the Netherlands : Elsevier B.V., 2005, Vol. 164, pp. 324-340.

Liu, L. and Huang, H.Z. 2010. Optimal Selective Maintenance Strategy for Multi-State Systems Under Imperfect Maintenance. *IEEE Transactions on Reliability.* IEEE Press, 2010, Vol. 59, pp. 356 – 367.

Lorange, P. 1980. *Corporate planning: An executive viewpoint.* New Jersey: Prentice Hall, 1980.

Luke, S. 2009-2012 . *Essentials of Metaheuristics.* 1st (Online Version 1.3, 2012). Virginia, USA: Department of Computer Science, George Mason University, 2009-2012 .

Lyons, L.C. 2000 (Last revised: 30.01.2003). *Meta-Analysis: Methods of Accumulating Results Across Research Domains.* Manassas, USA : s.n., 2000 (Last revised: 30.01.2003).

Xu, W., Sun, Y., Turban, E., Wang, S. and Liu, O. 2012. An Ontology-Based Text-Mining Method to Cluster Proposals for Research Project Selection. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans.* IEEE Press, 2012, Vol. 42, pp. 784-790.

Maier, R. 2007. *Knowledge Management Systems, Information and Communication Technologies for Knowledge Management.* 3rd. Berlin, Germany : Springer, 2007.

Maillart, L. M. and Pollock, S. M. 2002. Cost-Optimal Condition-Monitoring for Predictive Maintenance of 2-Phase Systems. *IEEE Transactions on Reliability.* IEEE Press, 2002, Vol. 51, pp. 322 - 330.

Manning, C. and Schütze, H. 1999. *On Foundations of Statistical Natural Language Processing.* Massachusetts, USA: The MIT Press, 1999.

Márquez, A. C. and Herguedas, A. C. 2004. Learning about failure root causes through maintenance. *Journal of Quality in Maintenance Engineering.*

Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2004, Vol. 10, pp. 254-262.

Martens, I. and Riehm, S. 2005. Nachhaltigkeit in der Anlagenwirtschaft. *Generalisierungsaspekte zur Integrierten Instandhaltung, Ergebnisbericht des INST-Arbeitskreises, Kap.2.17.* Hamburg, Germany : Die Forschungsgemeinschaft für Logistik e.V. (FGL e.V.), Technische Universität Hamburg-Harburg, 2005.

Marwala, T. 2012. *Condition Monitoring Using Computational Intelligence Methods: Applications in Mechanical and Electrical Systems.* Berlin, Germany : Springer, 2012.

Mather, D. 2003. *CMMS : a time saving implementation process.* Florida, USA: CRC Press LLC, 2003.

Matsukawa, T. 1993. Hypothesizing word association from untagged text. *Proceedings of the workshop on Human Language Technology.* Stroudsburg, USA : Association for Computational Linguistics, 1993.

McKenna, T. and Oliverson, R. 1997. *Glossary of Reliability and Maintenance Terms.* Houston, Texas, USA : Gulf Publishing Co., 1997.

McLeod, R. B. 1973. Requirements of an Economic Approach to Maintenance. *IEEE Transactions on Engineering Management.* IEEE Press, 1973, Vol. 20, pp. 75-80.

Mentzas, G., Apostolou, D., Abecker, A. and Young, R. 2003. *Knowledge Asset Management: Beyond the Process-centred and Product-centred Approaches.* London, UK : Springer, 2003.

Mesarovic, M. D., Macko, D. and Takahara, Y. 1970. *Theory of Hierarchical, Multilevel, Systems.* New York, USA : Academic Press, 1970.

Methe, D. T., Wilson, D. and Perry, J. L. 2000. A Review of Research on Incremental Approaches to Strategy. [ed.] Rabin, J., Miller, G. J. and Hildreth, W. B. *Handbook of Strategic Management.* 2nd. New York: Marcel Dekker, Inc., 2000.

Miller, D. 2011. Some Hard Questions for Critical Rationalism. Coventry : University of Warwick, 2011.

Mintzberg, H. 1973. Strategy Making in Three Modes. *California Management Review.* Oakland, California, USA : University of California Press, 1973, Vol. 16.

Mintzberg, H. 1990. The Design School: Reconsidering the Basic Premises of Strategic Management. *Strategic Management Journal.* New York : John Wiley & Sons, 1990, Vol. 11, pp. 171-195.

Mirghani, M. A. 2009. Guidelines for Budgeting and Costing Planned Maintenance Services. [ed.] M. Ben-Daya, et al. *Handbook of Maintenance Management and Engineering.* 1st. Berlin, Germany : Springer, 2009, pp. 115-132.

Mitchell, J.S. 2006. Metrics/Measures of Performance. [ed.] Hickman, J.E., Amadi-Echendu, J.E., Barringer, H.P. and Bond, T.H.. *Physical Asset Management Handbook.* 4. Clarion Technical Pub, 2006.

Mobley, R.K. 2008. *Maintenance Engineering Handbook.* [ed.] Mobley, R.K, Higgins, L.R. and Wikoff, D.J. 7th. New York : Mc Graw Hill, 2008.

Montana, J.C. 2000. The legal system and knowledge management. *The Information Management Journal.* 2000, Vol. July, pp. 54-57.

Murphy, K. R., [ed.]. 2013. *Validity Generalization: A Critical Review.* 1st. New York : Psychology Press, Taylor & Francis Group, 2013.

Nakagawa, T. 1979. Optimum policies when preventive maintenance is imperfect. *IEEE Transactions on Reliability.* IEEE Press, 1979, Vol. R-28, pp. 331-332.

Nakajima, S. 1988. *Introduction to TPM: Total Productive Maintenance.* Cambridge, MA, USA : Productivity Press, 1988.

Nasiri, S., Ansari, F. and Fathi, M. 2013. Dynamics of Knowledge Assets and Change Management Perspectives. *Proceedings of 2013 IEEE International Conference on Electro/Information Technology (IEEE- EIT 2013).* Rapid City, SD, USA : IEEE Press, 2013, pp. 1-6.

Nathan, I. 1969. Management Decision Utilizing Cost Effectiveness Modeling. *IEEE Transactions on Reliability.* IEEE Press, 1969, Vol. R-18, pp. 54-63.

Newbrough, E.T. 1967. *Effective Maintenance Management.* New York : McGraw-Hill Education, 1967. p. 61.

Nicholas, J. 2011. *Lean Production for Competitive Advantage: A Comprehensive Guide to Lean Methodologies and Management Practices.* New York : CRC Press, 2011.

Nicolai, C. 2010. Konzepte für den organisatorischen Wandel. *WISU - Das Wirtschaftsstudium.* Dusseldorf : Lange Verlag GmbH & Co. KG, 2010, Vol. 39.

Niebel, B.W. 1994. *Engineering Maintenance Management.* New York, USA : Marcel Dekker, 1994.

Nilsson, J. and Bertling, L. 2007. Maintenance Management of Wind Power Systems Using Condition Monitoring Systems—Life Cycle Cost Analysis for Two Case Studies. *IEEE Transactions on Energy Conversion.* IEEE Press, 2007, Vol. 22, pp. 223-229 .

Niu, Y., Buethe, I., Ansari, F., Fathi, M. and Fritzen, C.P. 2013. Towards Integration of a Knowledge-Based Approach into SHM. *Proceedings of 5th European-American Workshop on Reliability of NDE.* Berlin, Germany : The German Society for Non-Destructive Testing (DGZfP), 2013.

Nonaka, I. 1994. A dynamic theory of organizational knowledge creation. *Organization Science.* INFORMS, 1994, Vol. 5, pp. 14-37.

Nonaka, I. and Takeuchi, H. 1995. The knowledge-creating company-How Japanese companies create the dynamics of innovation. Oxford, England : Oxford University Press, 1995.

Nonaka, I., Toyama, R. and Konno, N. 2000. SECI, Ba and leadership: A unified model of dynamic knowledge creation. *Long Range Planning.* Amsterdam, the Netherlands : Elsevier B.V., 2000, Vol. 33, pp. 5-34.

Nowlan, F.S. and Heap, H. 1978. *Reliability-centered maintenance.* Springfield, Virginia, USA : National Technical Information Service,US Department of Commerce, 1978.

Ólafsson, S. 2006. Metaheuristics. [ed.] Henderson, S.G. and Nelson, B.L. *Handbook on Simulation,Handbooks in Operations Research and Management Science VII.* Amsterdam, the Netherlands : Elsevier, 2006, 23, pp. 633-654.

Paramenter, D. 2010. Key Performance Indicators:Developing,Implementing and Using Winning KPIs. 2nd. New York : John Wiley & Sons, Inc., 2010.

Pawellek, G. 2013. *Integrierte Instandhaltung und Ersatzteillogistik: Vorgehensweisen, Methoden, Tools.* Berlin, Germany : Springer, 2013.

Pfeifer, T. 2002. *Quality Management: Strategies, Methods and Techniques.* Munich, Germany: Carl Hanser Verlag, 2002.

Picot, A. and Lange, B. 1978. *Strategische Planung: synoptisch oder Inkremental?* Hannover : Leibniz Universität Hannover, 1978.

Polanyi, M. 1964. *Personal knowledge: Toward a post-critical philosophy.* New York, USA : Harper Torchbooks, 1964.

Polanyi, M. 1967. *The tacit dimension.* London, England : Routledge and Keoan Paul, 1967.

Popper, K. R. 2003. *Das Elend des Historizismus (The Poverty of Historicism).* 7th. Tübingen: Mohr, 2003.

Prajapati, A., Bechtel, J. and Ganesan, S. 2012. Condition-based maintenance: a survey. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2012, Vol. 18, pp. 384-400.

Quinn, J. B. 1980. *Strategies for change: logical incrementalism.* Richard D. Irwin, 1980.

Rapp, R. and Wettler, M. 1991. Prediction of free word associations based on Hebbian Learning. *Proceedings of the IEEE International Joint Conference on Neural Networks.* Singapore : IEEE Press, 1991.

Rapp, R. 2002. The Computation of word Associations. Comparing Syntagmatic and Paradigmatic Approaches. *Proceedings of the 19th International Conference on Computational Linguistics.* Stroudsburg, USA : Association for Computational Linguistics, 2002, Vol. 1.

Rausand, M. and Høyland, A. 2003. *System Reliability Theory: Models, Statistical Methods, and Applications.* 2nd . USA : John Wiley & Sons, Inc., 2003.

Regulinski, T.L. and Gupta, Y. P. 1983. Reliability Cost Estimation: Managerial Perspectives. *IEEE Transactions on Reliability.* IEEE Press, 1983, Vol. 32, pp. 276-281.

Reineke, D. M., Murdock, W.P.,Pohl, E.A. and Rehmert, I. 1999a. Improving Availability and Cost Performance for Complex Systems with Preventive Maintenance. *Proceedings of Annual Reliability and Maintainability Symposium.* IEEE Press, 1999a, pp. 383-388.

Reineke, D. M., Pohl, E. A. and Murdock, W. P. 1999b. Maintenance-Policy Cost-Analysis for a Series System with Highly-Censored Data. *IEEE Transactions on Reliability.* IEEE Press, 1999b, Vol. 48, pp. 413-420.

Reiner, J., Koch, J., Krebs, I., Schnabel, S. and Siech, T. 2005. Knowledge Management Issues For Maintenance of Automated Production Systems. *Integrating Human Aspects in Production Management, IFIP International Federation for Information Processing.* Berlin, Germany : Springer, 2005, Vol. 160.

Rhee, S. J. and Ishii, K. 2003. Using cost-based FMEA to enhance reliability and serviceability. *Journal of Advanced Engineering Informatics.* Amsterdam, the Netherlands : Elsevier B.V., 2003, Vol. 17, pp. 179-188.

Rishel, T.D. and Canel, C. 2006. Using a Maintenance Contribution Model to Predict the Impact of Maintenance on Profitability. *Journal of Information* *and Optimization Sciences.* New Delhi India : Taru Publications, 2006, Vol. 27.

Röben, D. 1998. Einsatz der Lebenszyklusrechnung in der Instandhaltung. *Generalisierungsaspekte zur Integrierten Instandhaltung, Ergebnisbericht des INST-Arbeitskreises, Kap.2.11.* Hamburg, Germany : Die Forschungsgemeinschaft für Logistik e.V. (FGL e.V.), Technische Universität Hamburg-Harburg, 1998.

Röben, D. 1997. Neue Konzepte der Instandhaltung. In: Generalisierungsaspekte zur Integrierten. *Generalisierungsaspekte zur Integrierten Instandhaltung, Ergebnisbericht des INST-Arbeitskreises, Kap.1.6.* Hamburg, Germany : Die Forschungsgemeinschaft für Logistik e.V. (FGL e.V.)., Technische Universität Hamburg-Harburg, 1997.

Rommens, S. 2012. Measuring the Right Level of Maintenance Costs in a Cement Plant. *Proceedings of 2012 IEEE-IAS/PCA Cement Industry Technical Conference.* Texas, USA : IEEE Press, 2012.

Ruiz, P.P., Foguem, B. K. and Grabot, B. 2014. Generating knowledge in maintenance from Experience Feedback. *Knowledge-Based Systems.* Amsterdam, the Netherlands : Elsevier B.V., 2014, Vol. 57.

Russell, S. and Norvig, P. 2010. *Artificial Intelligence: A Modern Approach.* USA : Prentice Hall, 2010.

Russell, W. A. 1970. *The complete German language norms for responses to 100 words from the Kent-Rosanoff word association test.* New York, USA : Academic Press, 1970.

Saaty, T. L. 2009. *Mathematical Principles of Decision Making: Generalization of the Analytic Network Process to Neural Firing and Synthesis.* Pittsburgh, USA : RWS Publications, 2009.

Saaty, T. L. 1983. Priority setting in complex problems. *IEEE Transactions on Engineering Management.* IEEE Press, 1983, Vols. EM-30, pp. 140-155.

Saaty, T. L. 1980. *The Analytic Hierarchy Process.* New York, USA : McGraw-Hill, 1980.

Salgado, J. F., Anderson, N., Moscoso, S., Bertua, C., College, G., de Fruyt, F. and Rolland, J. P. 2003. A Meta-Analytic Study of General Mental Ability Validity for Different Occupations in the European Community. *Journal of Applied Psychology.* Washington, D.C., USA : American Psychological Association, 2003, Vol. 88, pp. 1068-1081.

Salonen, A. and Deleryd, M. 2011. Cost of poor maintenance: A concept for maintenance performance improvement. *Journal of Quality in Maintenance.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2011, Vol. 17, pp. 63-73.

Schiuma, G. and Moustaghfir, K. 2010. Knowledge assets and value creation dynamics, Managing knowledge assets and business value creation in organizations. [ed.] Schiuma, G.. USA : Business Science Reference, 2010, pp. 30-49.

Schmelzer, H. J. and Sesselmann, W. 2010. Geschäftsprozessmanagement in der Praxis. 7th. Munich : Hanser Verlag, 2010.

Schwartz, D., [ed.]. 2006. *Encyclopedia of knowledge management.* Hershey, PA, USA: Idea Group Inc., 2006.

Seidenberg, U. 1989. *Auslöseinformationen im organisatorischen Gestaltungsprozeß - Voraussetzung einer flexiblen Organisation.* Frankfurt am Main, Germany : Verlag Peter Lang , 1989.

Seidenberg, U. 2012. *Ausprägungen und Einsatzbedingungen inkrementaler Managementansätze.* Siegen : University of Siegen, 2012.

Selman, J.R. and Schneider, R. 2005. The Impact of Life-cycle Cost Management on Portfolio Strategies. *Journal of Facility Management.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2005, Vol. 3, pp. 173-183.

Shafiei-Monfared, S. and Jenab, K. 2012. Fuzzy Complexity Model for Enterprise Maintenance Projects. *IEEE Transactions on Engineering Management.* IEEE Press, 2012, Vol. 59, pp. 293-298.

Sheu, C. and Krajewski, L.J. 1994. A Decision Model for Corrective Maintenance Management. *International Journal of Production Research.* Taylor & Francis, 1994, Vol. 32, pp. 1365-1382.

Shum, Y.S. and Gong, D.C. 2004. Development of a Preventive Maintenance Analytical Model. Australia : Fifth Asia Pacific Industrial Engineering and Management Systems Conference, 2004, pp. 38.5.1-38.5.12.

Simon, H. A. 1997 (1957:1st). *Administrative Behavior.* 4th. Free Press, 1997 (1957:1st).

Smith, D.J. and Babb, A.H. 1973. *Maintainability Engineering.* New York, USA : John Wiley & Sons, 1973.

Smith, Karl A. 2002. Teamwork and Project Management. New York : McGraw-Hill, 2002.

Staab, S., Studer, R., Schnurr, H. P. and Sure, Y. 2001. Knowledge Processes and Ontologies. *IEEE Intelligent Systems* . IEEE Press, 2001, Vol. 16, pp. 26-34.

Staab, S., Studer, R. and Sure, Y. 2003. Knowledge Processes and Meta Processes in Ontology-based Knowledge Management. [ed.] Holsapple, C. W. *Handbook on Knowledge Management.* Berlin, Germany : Springer, 2003, Vol. 2, pp. 47-67.

Starfield, A.M., Smith, K.A. and Bleloch, A.L. 1994. *How to model it: Problem solving for the computer age.* Edina, MN, USA : Burgess International Group, 1994.

Steiner, G. A. 1979. *Strategic Planning.* New York : Free Press, 1979.

Stevenson, W. J. 2012. *Operations Management: Theory and Practice.* 11th. New York : McGraw-Hill Irwin, 2012.

Strunz, M. 2012. *Instandhaltung: Grundlagen – Strategien – Werkstätten.* Berlin, Germany : Springer, 2012.

Sturm, A. and Mehldau, J. 2001. Einsparungspotenziale in der Instandhaltung. *In: Tagungshandbuch zum 9. Workshop „Integrierte Instandhaltung und Ersatzteillogistik“* . Hamburg, Germany : Die Forschungsgemeinschaft für Logistik e.V. (FGL e.V.), Technische Universität Hamburg-Harburg, 2001, pp. 5.1–5.7.

Sturm, A. 2001. *Wissen basierte Betriebsführung und Instandhaltung.* Essen : VGB PowerTech Service GmbH, 2001.

Sule, D. R. and Harmon, B. 1979. Determination of Coordinated Maintenance Scheduling Frequencies for a Group of Machines. Norcross, Georgia, USA : (American) Institute of Industrial Engineers, AIIE Transactions, 1979, Vol. 11, pp. 48-53.

Sung, C.S. and Cho, Y. K. 2000. Reliability optimization of a series system with multiple-choice and budget constraints. *European Journal of Operational Research.* Amsterdam, the Netherlands : Elsevier Science B.V., 2000, Vol. 127, pp. 159-171.

Suzuki, T. 1992b. *New Directions for TPM.* Cambridge, MA, USA : Productivity Press, 1992b.

Suzuki, T. 1992a. New Directions for TPM in Japan. *Proceedings of Total Productive Maintenance Conference.* Brussels, Belgium : s.n., 1992a.

Taguchi, G., Elsayed, E. A. and Hsiang, T. 1989. *Quality Engineering in Production Systems.* New York, USA : McGraw-Hill, 1989.

Tar, H. H. and Nyunt, T. T. S. 2011. Ontology-Based Concept Weighting for Text Documents. *Proceedings of the 2011 International Conference on Information Communication and Management, IPCSIT.* Singapore : IACSIT Press, 2011, Vol. 16.

Tempest, P.A. 1976. A Model of Industrial Maintenance Control. *Journal of Production Engineer.* IEEE Press, 1976, Vol. 55.

Thompson, G. The reduction of plant maintenance costs using creative problem-solving principles. *Journal of Process Mechanical Engineering, Proceedings of the Institution of Mechanical Engineers (Part E).* London,UK : Institution of Mechanical Engineers-SAGE Publications, Vol. 215, pp. 185-195.

Thyssen, J., Israelsen, P. and Jørgensen, B. 2006. Activity-based costing as a method for assessing the economics of modularization—A case study and beyond. *International Journal of Production Economics.* Amsterdam, the Netherlands : Elsevier B.V., 2006, Vol. 103, pp. 252-270.

Tinga, T. and Janssen, R.H.P. 2012. Modeling the Effects of Usage Variations on the Optimal Maintenance Intervals for Military Systems. *Proceedings of 4th World Conference on Production & Operations Management and the 19th International Annual EurOMA Conference.* The Netherlands : University of Amsterdam, 2012.

Toft, G. S. 2000. Synoptic (One Best Way) Approaches of Strategic Management. [ed.] Rabin, J., Miller, G. J. and Hildreth, W. B. *Handbook of Strategic Management.* 2nd. New York : Marcel Dekker, Inc., 2000.

Uhr, P., Dienst, S., Klahold, A. and Fathi, M. 2012. Kontextbasierte Bereitstellung von Textdokumenten im Produktverbesserungsprozess. *wt Werkstatts-technik online.* Düsseldorf, Germany: Springer-VDI-Verlag, 2012, Vol. 102.

Uhr, P., Klahold, A. and Fathi, M. 2013. Imitation of the Human Ability of Word Association . *International Journal of Soft Computing and Software Engineering (JSCSE).* Advanced Academic Publisher, 2013.

Usher, J. S., Kamal, A. H. and Syed, W. H. 1998. Cost optimal preventive maintenance and replacement scheduling. *IIE (Institute of Industrial*

Engineers) Transactions. Taylor & Francis Group, 1998, Vol. 30, pp. 1121-1128.

van Gestel, P.J. 1994. KEMA Maintenance Optimization Support System. Delft, the Netherlands : Heron Journal, 1994, Vol. 39, pp. 85-96.

van Horenbeek, A., van Ostaeyen, J., Duflou, J. R. and Pintelon, L. 2012. Prognostic maintenance scheduling for offshore wind turbine farms. *Proceedings of 4th World Conference on Production & Operations Management and the 19th International Annual EurOMA Conference.* Amsterdam, the Netherlands : University of Amsterdam, 2012.

Vargas, L. G. 1990. An overview of the analytic hierarchy process and its applications. *European Journal of Operation Research.* 1990, Vol. 48, pp. 2–8 .

Vasiu, T. and Stoica, D. 2007. Mathematical Model of Preventive Maintenance Based on Cost Minimization. *Machines, Technologies, Materials International Journal.* 2007, Vol. 2, pp. 32-34.

VDW. 2012. *The German Machine Tool Industry in 2011.* Frankfurt am Main, Germany : Economy and Statistics Division, German Machine Tool Builders' Association, 2012.

Veldman, J., Klingenberg, W. and Wortmann, H. 2011a. Managing condition-based maintenance technology: A multiple case study in the process industry. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2011a, Vol. 17, pp. 40-62.

Veldman, J., Wortmann, H. and Klingenberg, W. 2011b. Typology of condition-based maintenance. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2011b, Vol. 17, pp. 183-202.

Wang, H. and Pham, H. 2006. *Reliability and Optimal Maintenance, Springer Series in Reliability Engineering.* Berlin, Germany : Springer, 2006. pp. 91-109.

Washtel, J. and Markert, K. 2009. A Comparison of Windowless and Window-Based Computational Association Measures as Predictors of Syntagmatic Human Associations. *Proceedings of the 2009 Conference on Empirical Methods in Natural Language Processing.* Singapore : ACL and AF, 2009, pp. 628-637 .

Watson, I. 2003. *Applying Knowledge Management: Techniques for Building Corporate Memories.* San Francisco, CA, USA : Morgan Kaufmann Publishers, Elsevier Science, 2003.

Westerkamp, T.A. 1997. *Maintenance Manager's Standard Manual.* New Jersey, USA : Prentice-Hall, Paramus, 1997.

Wettler, M., Rapp, R. and Sedlmeier, P. 2005. Free Word Associations Correspond to Contiguities Between Words in Texts. *Journal of Quantitative Linguistics.* Taylor & Francis Group, 2005, Vol. 12, pp. 111-122.

Wijnhoven, F. 2006. Knowledge Management: More than a Buzzword. [ed.] A. Jetter, et al. *Knowledge Integration: The practice of Knowledge Management in small and medium enterprises.* Heidelberg, Germany: Physica Verlag-Springer, 2006, pp. 1-16.

Wireman, T. 2014. *Benchmarking Best Practices for Maintenance and Reliability.* 3rd. South Norwalk, CT, USA : Industrial Press Inc., 2014.

Wireman, T. 2008. *Successfully utilizing CMMS/EAM systems.* South Norwalk, CT, USA : Industrial Press, 2008.

Wireman, T.2004. *Total Productive Maintenance.* 2nd. South Norwalk, CT, USA : Industrial Press, 2004.

Yam, R. C. M., Tse, P., Ling, L. and Fung, F. 2000. Enhancement of maintenance management through benchmarking. *Journal of Quality in Maintenance Engineering.* Bingley, West Yorkshire, England : Emerald Group Publishing Limited, 2000, Vol. 6, pp. 224-240.

Yang, X., Guo, D. Cao, X. and Zhou, J. Y. 2008. Research on Ontology-based Text Clustering. *Third International Workshop on Semantic Media Adaptation and Personalization.* Prague, Czech Republic : IEEE Press, 2008, pp. 141-146.

Yao, X., Xie, X., Fu, M.C. and Marcus, S.I. 2005. Optimal Joint Preventive Maintenance and Production Policies. New York: Wiley InterScience, 2005, pp. 668-681. http://www.interscience.wiley.com.

Zhou, W.H. and Zhu, G.L. 2008. Economic Design of Integrated Model of Control Chart and Maintenance Management. *Journal of Mathematical and Computer Modeling.* Amsterdam, the Netherlands : Elsevier, 2008, Vol. 47.

Zizka, J., Sredl, M. and Bourek, A. 2003. Searching for Significant Word Associations in Text Documents Using Genetic Algorithms. *Lecture Notes in Computer Science.* Berlin, Germany : Springer, 2003, Vol. 2588, pp. 584-587.

Zwicky, F. 1969. *Discovery, Invention, Research through the morphological approach.* Toronto,Canada : Macmillan, 1969.

Zwicky, F. 1989. *Morphologische Forschung.* 2nd. Glarus, Switzerland : Baeschlin, 1989.

6 Bibliography of Prototypes

The present list includes selected master/bachelor theses and student research projects (co)supervised by the author. These selected works are cited in Chapter 3 for implementation of *Costprove* Toolbox.

[1] **Sosilo, A. (2013),** *Design and Prototypical Implementation of Maintenance Management Toolbox (CostBox)*, Master Thesis, Fathi, M. and Ansari, F. (Supervisors). Department of Electrical Engineering and Computer Science, Institute of Knowledge-Based Systems, University of Siegen, Summer Semester 2013.

[2] **Sosilo, A. (2012-13),** *Design and Implementation of Maintenance Cost Management Assistance System*, Student research project, Fathi, M. and Ansari, F. (Supervisors). Department of Electrical Engineering and Computer Science, Institute of Knowledge-Based Systems, University of Siegen, Winter Semester 2012-13.

[3] **Dewa, R. A. (2011),** *Developing Prototype of Drive System Designer Assistance Tools: MainDriveASSIST*, Student research project, Fathi, M. and Ansari, F. (Supervisors). Department of Electrical Engineering and Computer Science, Institute of Knowledge-Based Systems, University of Siegen, Summer Semester 2011.

[4] **Hallatu, P. O. (2012-13),** *Design and Implementation of Condition Monitoring Module of MainDriveASSIST*, Student research project, Fathi, M. and Ansari, F. (Supervisors). Department of Electrical Engineering and Computer Science, Institute of Knowledge-Based Systems, University of Siegen, Winter Semester 2012-13.

[5] **Beck, F. (2013),** *Meta-analysis of Maintenance Text Documents using Association Measuring in the use-case scenario of Thomas Magnete GmbH*, Diploma Thesis, Fathi, M. and Schüll, A. (Examiners), Uhr, P. and Ansari, F. (Supervisors), Department of Electrical Engineering and Computer Science, Institute of Knowledge-Based Systems, University of Siegen, Summer Semester 2013.

[6] **Hölzemann, A. (2013),** *Conception and Prototypical Realization of a Text Mining Application for Cost Administration in SMS Siemag AG*, Bachelor Thesis, Fathi, M. and Klaus, F.(Examiners), Ansari, F. and Uhr, P. (Supervisors), Department of Electrical Engineering and Computer Science, Institute of Knowledge-Based Systems, University of Siegen, Summer Semester 2013.

7 Appendix

7.1 Summary of Surveyed MCM Models

To enable the reader to understand the results of the morphological analysis, this section presents the extensive literature survey (cf. Chapter 1- Section 1.3 and 1.4). The author reviewed and summarized the models in Table 24. For each model, information of its author(s) and an abstract is given. The abstract is written by the author based on the review of the original sources. The models are further studied in the morphological analysis (cf. Chapter 1- Section 1.4- Table 6).

Table 24. Summary of the surveyed MCM models in chronological order

(*Note: This table runs over pages 135 to 150.*)

(Author(s), Year)	Abstract
(Nathan, 1969)	Nathan addressed the problem of cost-effective selection of subsystems and developed a single Figure of Merit, as a management decision tool. He declared that "for the subsystem whose performance does not limit the productivity of the primary system (achieves minimum productivity) the measure of effectiveness for a constant force size is [the] lowest life cycle cost". The model was established on the premises that a cost-effective system has already been chosen by means of certain criteria (which are known to the managers), and the resources for suitable procurement are available. In this context, the productivity function was mathematically developed to represent the productivity of the subsystem during the mission. The productivity was defined as the function of "equipment state at mission start (including "under repair" states), mission dependability, and subsystem performance by equipment state". The study confirmed the hypothesis that the lowest life cycle cost is achieved only through reaching the minimum productivity. Therefore the management choice was identified for properly (i.e. cost-effective) selection of a subsystem from an array of subsystems (alternatives) i.e. "meeting minimum productivity requirements and the lowest life cycle cost".
(McLeod, 1973)	McLeod analyzed economic implication of planning maintenance activities during and after the design phase. The aim was to develop a model for applying economic principles to minimize life cycle cost of a product or system development, and in turn for maximizing the return on investment. Specifically, he considered the economic impact of reliability, maintainability and availability during and after the design phase. He developed the index for calculating the income as a function of availability ("for a system which is desired to be productive 100 percent of the time"), and associated costs for improving maintainability or reliability. Maintainability was defined as "the time interval between failure and correction of [the] failure of the part, assembly, or system under consideration", and reliability as "the time interval between failures of the part, assembly, or system under consideration". Thus the income was calculated as the summation of all financial gains correlated with availability minus the marginal costs of improving maintainability and reliability. The index was used in cost/benefit trade-off model to

(Author(s), Year)	Abstract
	achieve the optimum maintainable design of the product or system. He extended the study into quantitative and qualitative determination of maintenance resource requirements considering the deployment phase. Finally, he integrated a feedback mechanism into the trading-off model, i.e. gathering feedback data not only for improving the cost/benefit ratio, but also for improving performance of the maintenance organization including management and engineering.
(Tempest, 1976)	Tempest presented a model of the feedback processes and communication required to control the maintenance costing. He used the visualization model, similar to the model of Hahn and Laßmann (1993) that specifically represents the relation between direct maintenance cost, down time loss and total cost. Tempest indicated that the “minimal expenditure on maintenance will result in large downtime costs; [while] minimal downtime cost will be achieved only at the expense of large maintenance expenditure. **Between these two extremes lies the optimum situation**”. He focused on developing a conceptual feedback-control system (instead of mathematical modeling of costs) for gathering required information to continually regulating actions and costs towards attaining an optimum solution.
(Sule, et al., 1979)	Sule and Harmon developed an economic model of maintenance planning. They defined the operating cost as a function of time for a single/group of machines. They distinguished between fixed and variable cost (i.e. function of time) within maintenance cycles, and calculated the value close to minimum of total cost of production and maintenance. In this way, they determined the frequency of maintenance and time between two consecutive overhauls for each machine. They have also pointed out that maintenance of a group of machines leads to save the fixed cost associated with separate overhauls.
(Regulinski, et al., 1983)	Regulinski and Gupta studied the uncertainties (e.g. requirements and cost estimating uncertainties) associated with reliability related life cycle costs. They used probability distribution (i.e. Beta distributions) in the estimation process of life cycle cost. The assumed life cycle cost model “consists of four major categories as […], acquisition of **hardware cost, retrofit cost, spares-replacement cost** for i^{th} year of operation, **maintenance cost** for i^{th} year of operation”. Each of the categories can be broken down into subcategories. The hardware cost was calculated by the analyst or obtained from bidders or vendors. It is most likely the highest cost in comparison with the other categories. Retrofit cost is calculated as the summation of engineering, drafting, installation, inspection, and testing cost. The spares-replacement cost “is a function of […] system usage, number of units, unit cost, unit mean time to failure, and the fraction of units which cannot be repaired […]”. The maintenance cost was modeled based on the relation between the cost factors such as: owner's and manufacturer's material costs per maintenance action, unit cost, mean man-hours expended/expressed by owners/manufacturer for corrective maintenance (i.e. repair), owner's and manufacturer's mean labor rates in $/man-hours, as well as the expected operating hours per year, the mean operating time between maintenance actions. At last, they concluded that the life cycle cost can be predicted as a stochastic summation of the four cost categories, the Beta cumulative distribution function of which can be computed based on estimation of, the most likely, lowest and highest cost associated with these four categories respectively.

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(Collins, 1983)	Collins also focused on the maintainability related life cycle costs, and developed a probabilistic based control tool. The model consists of three modules, maintenance cost model, cost estimator and risk assessment. The maintenance cost was modeled, based on summation of three cost elements (1) the cost of initial repair spare items, (2) the cost of on-equipment maintenance (i.e. "total mean number of failures × average on-equipment repair cost/failure"), and (3) cost of off-equipment maintenance (i.e. "total mean number of off-equipment repairs × average cost per off-equipment repair"). In the same classification, the target cost was estimated using operational test data and statistical analysis, and the variance between the modeled and estimated cost was determined. At the end, the associated risk was assessed using the well-known probabilistic method of Monte Carlo. In this way, the maintenance managers can be supported, especially in the proper estimation/adaptation of life cycle cost and defining tangible goals in contracting.
(Goyal, et al., 1985)	As a continual work of (Sule, et al., 1979), Goyal and Kusy developed a total cost model for a family of machines considering a fixed cost independent of the machines was being repaired, and a variable cost dependent on the machines being repaired in a maintenance cycle. They have determined the maintenance frequency of each machine and in turn calculated the minimum of the associated costs per unit of time. The model is used to trade-off between the maintenance policy and operation costs. The authors pointed out that the developed model is heuristic (i.e. providing a solution, without guarantee, for solving the problem).
(Canfield, 1986)	Canfield developed a hazard function for cost optimization of preventive maintenance intervention intervals by determining the average cost-rate of system operation. The main proposition, here, is that the operation causes system degradation and "hence an increase in the level of the hazard function with time". He revealed that "the hazard function under PM [Preventive Maintenance] is approximately a 2-parameter Weibull with shape parameter 2 for systems with strictly increasing hazard without PM". The hazard model consists of cost optimization function (i.e. optimizing the cost of preventive maintenance intervals). The cost function encompasses cost rate of system operation, based on the cost of preventive maintenance per occurrence, system cost, time interval between preventive maintenance interventions, and time to failure with and without preventive maintenance. Notably, this work considers that the hazard function with PM is known. When the hazard function without PM is unknown (i.e. not the case of this paper) the optimum value can be found through an iterative process which seems to be destructive and expensive.
(Blohm, et al., 1988) (Seidenberg, 1989) (Adam, 1989)	Blohm and Lüder established the two-level control system with a sub-loop for learning process (Blohm, et al., 1988). This model provides a plausible heuristic structure for controlling a production related process, based on the indication of management and engineering responsibilities as well as their interconnections, and effects of external environmental factors (Blohm, et al., 1988). Seidenberg refined and upgraded this model by adding a feed-forward loop which provides information from operational level and external sources for top management (Seidenberg, 1989). Adam also introduced a control model for optimization of maintenance strategies (Adam, 1989), which uses the fundaments of the model of Blohm and Lüder. He created a loop model for acquisition of cost and availability data towards optimization of mainte-

(Author(s), Year)	**Abstract**
	nance strategy (Adam, 1989).
(Jayabalan, et al., 1992)	To overcome maintenance problems, one can either consider decreasing intervals and constant cost, or decreasing costs and constant intervals. In this extend, Jayabalan and Chaudhuri have established an algorithm that assumes the cost/maintenance is constant and successive simple-maintenance intervals as decreasing. Any increasing maintenance cost function could be incorporated. The proposed cost model represents the accumulative relation between the acquisition cost of each system (i.e. initial system and its degraded state) as a function of the annual rate of increase in acquisition cost of the system, time of preventive maintenance, and period of operation of the system. The accumulative representation causes to calculate total cost of maintenance within the planning period and based on the number of maintenance activities. Finally "the optimum solutions depend on the: constant improvement factor, first simple-maintenance point, rate of increase in acquisition cost, maintenance cost factor, and planning period". In this context, they used Branch-and-Bound, the well-known optimization method, to find the optimal maintenance schedule.
(Hahn, et al., 1993)	The paradigm of Hahn and Laßmann (discussed earlier) is a basic, ideal and an intended quantitative model for MCM. It is in fact an incomplete mathematical model, because the parameters are not concretely defined and represented in mathematical formulations. This model has been discussed earlier in **Section 1.2.**
(Sheu, et al., 1994)	Sheu and Krajewski proposed a decision model for comparative evaluation of alternatives in the selection of corrective maintenance policies. The decision model consists of input data, such as training, capital costs, and machine life. The simulation model includes two parts. The first is a planning module, particularly for Manufacturing Resource Planning (MRP), and also generating draft of work orders to be checked and confirmed by the manager. The second is work order module to assign the orders to the work stations based on availability of resources. The simulator provides the possibility to monitor cost components "such as wages, material, inventory carrying, and backlog penalties". It can also consider "uncertainties in demands, vendor lead times, scrap losses, rework, equipment failures and inventory record errors". The financial impact of the corrective maintenance is then calculated through monitoring "the net changes in cash flows or the difference between revenues and costs". In this context, Sheu and Krajewski have defined and simulated two corrective maintenance policies, (1) *worker flexibility* policy: "the number of operations each worker can perform" and (2) *machine redundancy*: "the same type of machine will be purchased again when the first wears out". The net present value of these two policies has been computed over an infinite horizon. The result was revealed the policies as a function of the cost of capital. At the crossing point, where both policies are indifferent in terms of net values, the training cost of skillful workers was calculated. In practice, the combination of these two policies provides a variety of possibilities for managing the cost of corrective maintenance. In addition, they have modeled "optimal corrective maintenance decision as a function of the cost of capital and the service life of the equipment". The entire economic analysis and decision model provides the alternatives and identifies management choice in corrective maintenance.

(Author(s), Year)	**Abstract**
(van Gestel, 1994)	Van Gestel introduced five probabilistic models to control inspections and maintenance intervals. The first and second models deal with optimization of maintenance intervals respectively, based on revealed and unrevealed (unknown) failure of the production components. The third model optimizes the conservation intervals of a component and predicts replacement events. The fourth model is an approach to condition-based maintenance, which optimizes the inspection intervals and accordingly predicts the replacement events. The fifth model harmonizes different computed maintenance intervals and produces an optimal maintenance plan, including associated costs for a whole system. In the general framework of these models limited cost portions are considered such as corrective costs, replacement costs, preventive costs, conservation costs per unit of time, test costs, downtime process costs per time period, consequence costs of the process due to a failure, and inspection costs.
(Al-Najjar, 1996)	Al-Najjar developed the concept of a model of Total Quality Maintenance, *TQMain*. TQMain encompasses the principle of TQM, TPM and RCM. The objective is to continuously improve the technical and economic aspect of maintenance, especially in terms of condition-based maintenance. He defined the model as “a means for monitoring and controlling deviations in a process condition and product quality, and for detecting failure causes and potential failures in order to interfere when it is possible to arrest or reduce the machine deterioration rate before the product characteristics are intolerably affected, and to perform the required action to restore the machine/process or a particular part of it to good as new”. The model is an integrated approach for using feedback mechanism and capturing data (including, but not limited to, cost) from different maintenance strategies for optimizing condition-based and predictive maintenance.
(Usher, et al., 1998)	Usher et al. proposed a method for predicting a cost-optimal maintenance policy for a repairable system with an increasing rate of occurrence of failure, also called as deterioration. The model is closely related to that of (Jayabalan, et al., 1992). The method predicts three possible actions as: (1) maintain the system, (2) replace the system, or (3) do nothing. The cost of preventive maintenance activities is calculated by considering different combinations of three associated factors as failure, replacement and maintenance cost as a function of time over different planning periods. To find the optimal solution (including the minimum total net present worth (value) for all future costs) a numerical analysis is presented and three methods of optimization are compared, namely, random search, genetic algorithm and branch-and-bound approach are employed. The evaluation revealed that the genetic algorithm is dominant than the other methods, particularly for analyzing a wide range of problem types.
(Lim, et al., 1999)	Lim and Park developed a model for evaluating the average cost of maintenance per unit time over an infinite time span. The model is used for imperfect repair by assuming fixed amount of cost for perfect and minimal repairs when an item failed. They employed a probability based approach using the exponential and Weibull distributions for calculation of expected costs and cost-rates.
(Reineke, et al., 1999a)	Reineke et al. emphasized on the importance of considering the availability and cost performance as critical system characteristics. In this context, they presented a methodology to “trade-off between availability and cost to be evaluated for a classic bridge reliability structure

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(Barlow, et al., 1960)	consisting of five independent sub-systems". They employed a cost function of (Barlow, et al., 1960) which represents the expected cost per unit time for the system. In the end, they extended the classic age replacement policy model by "trade-off between limiting availability and expected cost rate at the system level" through "minimizing cost over an infinite time horizon and maximizing limiting system availability".
(Reineke, et al., 1999b)	In addition, Reineke et al. studied maintenance policy and analyzed associated costs for estimating "the optimal age replacement time of series arrangement of functional sub-systems" without redundant components. They examined incorporating system-level data and component-level data, and used various statistical and estimation methods (Kaplan-Meier Estimator, the Piecewise Exponential Estimator and the Maximum Likelihood Estimator) for estimating the optimal age replacement time. Monte Carlo analysis is also employed "to estimate average optimal age replacement times determined using total time on test (TTT) transforms" based on the mentioned estimation methods. The estimations result "is used to compare the relative long-run cost per unit time for each method". The captured data "subject to high level of random censoring on the right" i.e. the censoring (partially known) and failure time is independent and the majority of data have values greater than the minimum of censoring and failure time. The comparative study of the methods revealed that "for a correctly specified model and for large sample sizes (about 2500), the age replacement times provided by the [Maximum Likelihood Estimator] are more accurate than those provided [by the others], especially under high levels of censoring". In the end, they detected some factors which affect optimal replacement time, particularly the ratio of replacement cost to failure cost. Other influential factors are the amount of censoring, component arrangements, method of estimation and logistics of the maintenance procedure, e.g. timing and personnel.
(Baron, et al., 1999)	Baron and Pate-Cornell presented a decision support model to design optimal strategies in the use-case of the maintenance of a corporate airplane (e.g. to balance long term maintenance costs). The model encompasses probabilistic and dynamic risk analysis tools, "linking different aspects of risk-management to the specific characteristics of the physical system". They used the probabilistic modeling of system performance using "Markov process [for modeling dynamic system evolution], with transitions occurring first among maintenance states, then among states of planned operation (including the possibility of unplanned shutdowns)". Therefore the total associated cost was modeled as the summation of the state occupancy and state transition costs during the i^{th} cycle. The cost function of each state was modeled using a probabilistic representation/distribution "of beginning the cycle in each of the possible system states". They have calculated the minimized cost, as a management choice to trade-off between "productivity and safety over the life of the system". In this way they optimized the total cost in each cycle using the root mean square (RMS) method. Finally the total RMS of RMSx (in each cycle) should be calculated which represents the minimized value through the lifetime cost.
(Sung, et al., 2000)	Sung and Cho derived a branch-and-bound algorithm to search the optimal solution for maximum reliability of a series system with multiple-choice (i.e. subject to each subsystem) and budget constraints. The research was an initial step and opened the door to several studies, especially to utilize the proposed algorithm in a variety of application systems, including mixed systems with series and parallel subsystems. Also the method can be further developed using resource constraints, and be tested through a heuristic procedure. The latter issues, however, were

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	only highlighted and not elaborated by Sung and Cho.
(Yam, et al., 2000)	Yam et al. studied the enhancement of the policy selection in MaM through benchmarking “to improve the overall effectiveness of the operations and maintenance of the plant”. They studied and analyzed good/best practices in order to adopt the best solution for improving the overall effectiveness of the operations and maintenance of a large-scale power plant. Particularly, they classified MaM approaches as planned (i.e. time based and condition-based maintenance) and unplanned (i.e. failure-driven maintenance). In this context, they have used mathematical models for analyzing “productivity and service level of maintenance activities in the plant”. The productivity level was measured using average equipment maintenance cost for five years (AEMC). AEMC is a weighted average of four variables, (1) total plant maintenance cost per year, minus (2) total pollution control cost per year, (3) total technical support cost per year, and (4) total cost for disaster and rehabilitation per year. The maintenance service level was measured using average equivalent forced outage rate for five years (AEFOR), average equivalent availability for five years (AEA), and average forced outage maintenance rate for five years (AFOMR). AEFOR is a function of equivalent forced outage rate, and service hour. AEA and AFOMR are a weighted average of the values for equivalent availability and forced outage maintenance rate, respectively. They have normalized benchmarking data and compared the benchmarked plant with 72 power plants. Thus the best performers were indicated “with the lowest equipment maintenance cost per MW [Megawatt] on productivity level and the highest maintenance service level”.
(Duffuaa, et al., 2001)	Duffuaa et al. developed a generic conceptual model for maintenance systems which consists seven modules as input specification, modeling maintenance load, planning and scheduling, material and spare parts supply, equipment availability, quality control, and finally performance measures. They specified that “such a conceptual model lays the ground for developing a realistic simulation model”. The maintenance load associated with the model is classified as planned/unplanned maintenance.
(Dhillon, 2002)	Dhillon discussed the use of statistical project control methods in maintenance management, e.g. Program/Project Evaluation and Review Technique (PERT) and Critical Path Method (CPM) (Dhillon, 2002). In this context, he introduced fifteen specific indexes for cost controlling (Dhillon, 2002). Kister declared that estimating and controlling maintenance costs necessitate the past and present data (Kister, 2008). In this way the two areas of information are used to “estimate the cost, namely (1) the end use of the estimate and (2) the available information about the job” (Kister, 2008). He introduced a structure for using various estimation and project management techniques (e.g. CPM and PERT discussed earlier by Dhillon) for labor, material and overhead costs (Kister, 2008). In addition, the concept of BCM proposed by Kelly (discussed earlier) includes a loop model for MaM consisting of a module for workload-based budget forecast and maintenance policy control using KPIs (Kelly, 2006). Cf. (Salonen, et al., 2011) and (Rommens, 2012).

(Author(s), Year)	**Abstract**
(Maillart, et al., 2002)	Maillart and Pollock developed a probability based solution for 2-phase systems (new/worn) based on decomposition of “the expected cost per unit time into, first expected cost due to maintenance actions, and second the expected cost due to monitoring actions”. The goal is to minimize expected cost-rate, and to find the associated optimal sequence of monitoring intervals. They confirmed that the decomposition supports “evaluating the policy trade-offs in many situations, including those with constrained or unconstrained monitoring resources, multiple or single systems, and fixed or non-fixed monitoring intervals”.
(Grall, et al., 2002)	Grall et al. proposed a predictive maintenance structure for a deteriorating single unit system with continuous time and state. In this structure, they have developed “a mathematical model for the maintained system cost using regenerative and semi-regenerative process theory”. The mathematical model assesses the performance of the proposed structure, especially replacement threshold and inspection schedule based on system state. They concluded that “expected maintenance cost rate on an infinite horizon can be minimized by a joint optimization of the replacement threshold and the periodic inspection times”.
(Chen, et al., 2003)	Chen and Jin proposed a general analytical framework of the preventive maintenance decision-making. They argued traditional preventive maintenance policies such as “age replacement, periodic replacement under minimal repair and replacement policy N [i.e. performs minimal repairs for the first $N-1$ failures and replaces the N^{th} failure]”. They developed the model for calculation of average cost and cost variation, and represented the long-run variance of cost. Specifically, they analyzed the effect of maintenance policies on planned cost. They defined long-run variance of the cost under a maintenance policy, as the limit of the weighted average of total deviation of “cost spent at time unit t under [a] maintenance policy”, and “the long-run average cost per unit time under [the] policy”, when the time approaches to infinity. Then they have formulated and solved the problem of variability-sensitive optimization. They resolved the problem for the three preventive maintenance policies (i.e. reinvestigation of age replacement, periodic replacement under minimal repair, and replacement policy N), and proposed general management concept for optimal policy selection. Using numerical examples for modeling the “average cost and cost variation for different replacement intervals”, they have illustrated the results by means of MATLAB®. The entire process supports cost-effective (i.e. optimal) selection of preventive maintenance policies, and avoids the risk of unexpected higher cost. In sum, “the greater the cost-variability-sensitivity, […] the more conservative [choice] will be the optimal variability sensitive policy”. The method can be extended for condition-based maintenance policy through consideration of other factors “such as inspection and the failure detection capability [within the] complex structure of the cost stream”.
(Rhee, et al., 2003)	Rhee and Ishii proposed a methodology, Life Cost-Based Failure Modes and Effects Analysis (FMEA), which measures risk in terms of cost. The method is useful “for comparing and selecting design alternatives that can reduce the overall life cycle cost of a particular system”. They employed Monte Carlo simulation and took into account the uncertainties, especially for optimal policy selection complex scenarios, for example, “detection time, fixing time, occurrence, delay time, down time”. They studied the model for a use-case of a large scale particle accelerator. Finally, they illustrated “the advantages of the proposed approach in predicting life cycle failure cost, measuring risk and planning

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	preventive, scheduled maintenance and ultimately improving uptime”.
(Elegbede, et al., 2003)	Elegbede et al. developed an algorithm, ECAY, which produces the lowest reliability cost for a given reliability target in a parallel-series system. They employed a cost function which represents the relation between reliability and the sum of the cost of a system’s components (i.e. accumulation of number of series subsystems, parallel components in a subsystem, and components in a subsystem). They compared the method with Levenberg–Marquardt (LM) algorithm, a numerical algorithm for minimizing a function, and proved the dominancy of their approach for reliability allocation through minimizing cost.
(Dey, 2004)	Dey developed a “risk-based decision support system which uses a [well-known method of] multiple attribute [criteria] decision-making techniques, Analytic Hierarchy Process (AHP)”. The system was designed to solve the cost optimization problem in the inspection and maintenance of oil pipelines. It can support managers for preventive maintenance policy making, especially when the optimized cost depends on proper selection of a specific inspection method, identification and prioritization of the segment for inspection and maintenance, allocated budget, labor cost, emergency maintenance, and insurance. Cf. (Labib, 2004).
(Labib, 2004)	Labib also proposed a hybrid approach of using rule based analytics and AHP for multiple criteria decision-making in the maintenance management system (Labib, 2004). The developed algorithm is used to improve life cycle profit and reduce the life cycle cost (Labib, 2004). He has reported the successful test of the algorithm in several automotive industries (Labib, 2004). In the context of maintenance, the AHP - (Saaty, 1980), (Saaty, 1983), (Vargas, 1990), (Saaty, 2009) - provides managers with a rational basis for decision-making, and support interaction of the CMO within the policy selection process (Dey, 2004), (Labib, 2004). The general AHP is principally based on decomposition and analysis of criteria (e.g. high, medium, low values of downtime or frequency of downtime), comparative judgment, and synthesis of priorities (Dey, 2004), (Labib, 2004). In addition, the combination of the AHP and fuzzy rules provides “features of both fixed rules and flexible strategies” in maintenance-related policy selection activities (Labib, 2004). For example, the managers might need to select an optimal (cost-effective) strategy between “run to failure, upgrade operator skills, maintain on a fixed time basis, or design out the causes of failures” (Labib, 2004). Thus the AHP can break down the problem (decision) based on the desired criteria, which are important for the production (e.g. downtime), and asset management (e.g. frequency of downtime), prioritize and map the values, and finally derive alternatives. The fuzzy rules are in turn used for adapting “maintenance plans through the performance, in a consistent manner, of trade-off comparisons”, and ultimately in reasoning (Labib, 2004). The similar approach is also seen in the recent publication by Ierace and Cavalieri for prioritizing maintenance criteria and preferences for selection of maintenance strategies (Ierace, et al., 2013).
(Shum, et al., 2004)	Shum and Gong extended the mathematical model of (Goyal, et al., 1985) by considering maintenance frequency, purchasing strategy, and

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	size of the maintenance workforce. They also added part cost and maintenance labor cost to the model of Goyal and Kusy. So the adopted model is a "non-linear mixed integer programming model". It computes total cost through calculation of the following cost items within the planning time as (1) The machine maintenance cost of unit, (2) The replacement part purchasing cost of unit time, (3) The maintenance labor cost of unit time, (4) The cumulative operation cost of each machine, (5) The cumulative operation cost of the total machine, (6) The average holding cost of each replacement part, (7) The average holding cost of the total replacement parts, and (8) The purchasing cost of the total replacement parts. They employed genetic algorithm to find the optimum (minimum) of the total cost which is ultimately used to decide on maintenance frequency, purchasing quantity and basic maintenance cycle interval.
(Haarman, et al., 2004)	Haarman and Delahay proposed a model of Value Driven Maintenance (VDM). The model was invented based on the principles of TPM and RCM (Rausand, et al., 2003), (Wireman, 2004), (Haarman, et al., 2004).VDM was developed based on the premise that "*value* is the sum of all future free cash flows, discounted to today". They stressed that "VDM provides answers by identifying the value potential of the four value drivers in maintenance and enabling you to manage by those drivers". The four drivers are (1) asset utilization, (2) cost control, (3) resource allocation (i.e. to use the right technicians, spare parts, knowledge and contractors), and (4) laws and regulations concerning safety, health and environment (SHE). In this context, the present value of maintenance is calculated as the summation of future free cash flow in year *t* (cash flow) divided by the discount rate $(1 + \mathrm{r})^{\mathrm{t}}$. The cash flow is also calculated as the sum of all future free cash flows in year *t* corresponding to asset utilization, cost control, resource allocation, SHE, and multiplied by the SHE factor in year *t* (i.e. % of compliance with SHE regulations). They claimed that VDM concept integrates principles of well-known maintenance methodologies and management models like TPM, RCM, risk-based maintenance, condition monitoring, overall equipment effectiveness, and asset based budgeting. Despite the advantages and broad usage of the methodology in CMMIS systems such as Maximo® (IBM® software for asset management), the focus of VDM is mainly on values as a function of cash flow and discount rate whereas balancing and optimizing maintenance cost and influencing on cost/benefit ratio.
(Jardine, et al., 2005)	Jardine and Tsang studied several maintenance control and mathematical models. They concluded that using a mathematical model is required "to determine the optimal frequency of overhauling a piece of (production) plant by balancing the input (maintenance cost) of the maintenance policy against its output (reduction in downtime)". They developed a visualization model which uses the principles of Hahn and Laßmann (1993). However, it is customized by defining the cost of maintenance policy (e.g. frequency of overhauls) and cost of time lost due to breakdowns instead of planned and unplanned cost.
(Yao, et al., 2005)	Yao et al. designed a "joint preventive maintenance and production policy for an unreliable production-inventory system in which maintenance/repair times are non-negligible and stochastic". In this frame, the decision on whether performing preventive maintenance or not, and related effects on production are examined using several influential factors. Particularly cost factors are considered such as one time set-up cost for performing corrective maintenance, one time set-up cost for performing preventive maintenance, and unit inventory holding cost, and

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	unit backlog penalty cost per period. Considering the random and stochastic nature of the parameters, the Markov decision process is used for formulating the problem.
(Selman, et al., 2005)	Selman and Schneider studied the impact of life cycle cost management on portfolio management (mainly financial assets like cash). They used a simple, cost model for calculation of the life cycle cost, which is represented as a summation of: the initial construction cost + operational maintenance requirements (over maximum lifetime) + preventive and recurring maintenance (over maximum lifetime) + recapitalization costs (over maximum lifetime) ± final disposal/salvage + deferred (postponed) maintenance. The empirical studies have highlighted the importance of integrated asset management. They also demonstrated that "life cycle operation and maintenance, and recapitalization costs are surprisingly higher than construction costs" of physical infrastructures.
(Rishel, et al., 2006) (Ahlmann, 1984)	Rishel and Canel developed a financial maintenance contribution to the conceptual DuPont model for analyzing significant impact of maintenance on the firm's profitability. The DuPont model was established by (Ahlmann, 1984) to study and determine "the impact of [a] maintenance function on ROC [Return on Capital]". Rishel and Canel used numerical experiments to measure effectiveness of maintenance activities. They revealed that "variations in maintenance policies can impact on capital and profitability of a business, especially a company can increase its production and revenue through higher level of availability". In the end, they recommended reducing maintenance cost, when capacities are restricted, through reducing disruptions to the production process.
(Lehtonen, 2006)	Lehtonen introduced a method for "optimal condition monitoring and maintenance strategies for both component and system levels" in the power systems. The method is based on "the statistical analysis of component's condition data and probabilistic optimization of the overall cost function" using Markov decision models.
(Wang, et al., 2006)	Wang and Pham studied "availability measures, maintenance cost modeling and optimal maintenance policies of series systems whose components are subject to imperfect repair as well as correlated failure and repair". They have modeled the maintenance costs based on a proposition that no more than one failure occurs at the same time. The first model computes cost per unit of time for each component and the second calculates repair cost in a lump sum. The former is based on a premise that cost is calculated per unit of downtime for each component. It is composed of "loss cost per unit of the system and all components down time because the system is not available, and the repair cost per unit of time for each component". The latter is developed based on the distinction of cost into the cost of perfect repair and service interruptions "regardless of the time to complete repair", and imperfect ones for each failure. They have also extended the model to optimize availability and minimize maintenance cost rate (i.e. differential minimization), based on identification of number of repairs for each component with its period of service.
(Kelly, 2006)	Cf. (Dhillon, 2002).

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(Vasiu, et al., 2007) (Nakagawa, 1979)	Vasiu and Stoica presented a mathematical model of preventive maintenance, which “takes into account several stochastic factors that influence the failure rate and working life of an entity”. They assumed that “preventive maintenance is done through imperfections: it is not reduced only the proper operation, but the failure probability as well as much as the number of maintenance works is increased”. They employed the model of (Nakagawa, 1979) for calculation of the average cost of an entity, and used the Weibull distribution of the failure rate. The model incorporates corrective maintenance cost; preventive maintenance cost, and overhaul's cost (entity replacement) to calculate an average cost of the entity.
(Hagmark, et al., 2007)	Hagmark and Virtanen demonstrated a probabilistic approach for simulating and calculating reliability, performance, and maintenance cost of a product (system, function, equipment, mechanism, part, etc.), as a step in product requirement analysis prior to design. The model uses the stochastic failure logic and semi-Markov-like processes. They considered cost factors such as cost of availability, total maintenance costs caused by failures or scheduled procedures, and maintenance resource costs. The model does not explicitly provide a cost function, but considers the maintenance cost as a design factor. So the cost is calculated as a consequence of the failure and reliability analysis.
(Nilsson, et al., 2007)	Nilsson and Bertling presented a life cycle cost model and extracted improvement potentials for planning, maintenance activities for a use-case of wind turbine. The model consists of three discrete cost factors for (1) preventive maintenance: cost of a condition monitoring system plus scheduled maintenance, (2) corrective maintenance: cost of unscheduled service plus the cost for replacing major components, and (3) production loss. They analyzed six predefined strategies for optimizing the total maintenance cost and analyzing life cycle cost, and successfully tested the propositions in the two selected use-case scenarios in wind power systems.
(Dersin, et al., 2008)	Dersin et al. provided a guideline for reaching availability targets at the lowest life cycle cost. Employing Markov modeling, they assumed constant failure rate and perfect maintenance. In addition, they considered the maintenance-related aging. In this context, they used the model of (Kijima, 1989) for imperfect maintenance. “In order to contemplate the non-constant failure rate case, as well as the deterministic aspect of scheduled maintenance inspections, simulations are then run with Petri nets. Imperfect maintenance models are also considered so that the impact of maintenance-related aging can be taken into account”. In this research relative factors are considered such as: unit costs of investment, corrective and preventive maintenance, and sensitivity analyses of system availability with respect to failure rate, test coverage rate as well as percentage of perfect maintenance. The distinction of perfect/imperfect maintenance is based on special indicators such as mean time

(Author(s), Year)	**Abstract**
	to system failure, and the cost of failure, corrective maintenance and inspection. Finally the model provides simple, cost models based on the four predefined maintenance strategies, i.e. (1) wait until system down, (2) constant monitoring and (deferred) corrective maintenance, (3) purely preventive maintenance, and (4) combination of corrective and preventive maintenance.
(Zhou, et al., 2008)[53]	Zhou and Zhu discussed the integration of Statistical Process Control (SPC) and MaM consisting monitoring and control modules for planned, reactive and compensatory maintenance. They reinforced the integrated model of (Linderman, et al., 2005) which incorporates control charts for process control and maintenance. The control chart is used “to monitor the equipment and to provide signals that indicate equipment deterioration, while planned maintenance is scheduled at regular intervals to preempt equipment failure”. The integrated model has two states of in-control and out-of-control. The out-of-control state results on reactive maintenance, which raises unplanned costs. Therefore a Process Failure Mechanism was employing a Weibull distribution to analyze the economic behavior of the integrated model. Using the cost model of (Alexander, et al., 1995), they investigated “an optimal design for determining the four policy variables”, and then employed grid-search approach (also called as Hyperparameter optimization) to find the optimal values of maintenance policy particularly to minimize the hourly cost. The optimal values are, therefore, the interval between sampling, the number of samples taken before planned maintenance, sample size, and width of control limit in units of standard deviation. The model of (Alexander, et al., 1995) added details to Duncan's cost model (Duncan, 1956) with Taguchi's loss function (Taguchi, et al., 1989). Duncan applied “a penalty cost for operating out of control, but he [did] not show how this cost can be obtained or quantified” (Alexander, et al., 1995). Hence the embellished model of (Alexander, et al., 1995) incorporated “losses that result from both inherent variability due to assignable causes” (Alexander, et al., 1995).
(Huang, et al., 2008)	Huang and Fang analyzed warranty policy for products with deterioration. They incorporated and adopted the cost model of (Jayabalan, et al., 1992), and proposed a Bayesian decision model, especially for maximizing expected profit within the period of a preventive maintenance program. The model incorporates maintenance cost factors such as average repair cost for each repair, the cost of performing preventive maintenance activity, and annual increasing rate of maintenance activities.
(Kister, 2008)	Cf. (Dhillon, 2002).

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[53] Extension of (Linderman, et al., 2005) which is also based on: (Alexander, et al., 1995). The latter work was merging the work of : (Duncan, 1956) and (Taguchi, et al., 1989).

(Author(s), Year)	**Abstract**
(Frenkel, et al., 2009)	Frenkel et al. studied corrective maintenance and associated reliability's cost (i.e. income reward from system using, system operating cost in its lifetime, repair cost, penalty cost) for aging multi-state systems, "based on the Markov reward model for a non-homogeneous Poisson process". The reward method leads to "find the best maintenance contract level that provides a maximum of reliability associated costs during [the] system lifetime".
(Liu, et al., 2010)	Liu and Huang extended the study of 2-state systems (e.g. Maillart and Pollock) to multi-state systems consisting of binary state elements. They have established a "cost-maintenance quality relationship which considers the age reduction factor as a function in terms of maintenance" for applying selective maintenance (i.e. selection of the optimal strategy with desired quality). The total cost was modeled as a function of preventive and corrective maintenance cost. They employed a genetic algorithm for optimizing problem including both multi-state systems, and imperfect maintenance models. The proposed method is tested with a use-case of a power station coal transportation system. They made a comparative analysis which confirms the dominance of incorporating imperfect maintenance quality of (Kijima, et al., 1988) and (Kijima, 1989) into selective maintenance.
(Chen, 2010)	Chen established a model for "minimizing the maintenance/breakdown cost per unit of time". The model is designed based on the premise that the full consideration of all maintenance information is a requirement to minimize the cost. Therefore, it uses "the equipment's technological status, the equipment system running time, big and small maintenance constraints, maintenance time and maintenance/breakdown cost under various maintenance modes". The model includes an optimal synchronization decision tree of a correlation maintenance task, particularly to manage maintenance-related decisions of "components in a subsystem that are running a serious deterioration". In this context, condition monitoring data provide information regarding the maintenance status of the components and accordingly the deteriorating components will be detected. The maintenance time is statistically calculated. The residual life of the components is calculated using Weibull distribution. Afterwards the decision tree provides all possible alternatives based on maintenance schemes (i.e. combination of maintenance of the deteriorating components), time and cost. At last, the minimum expected maintenance/breakdown cost per unit of time will be selected. The cost model is a function of (1) risk factor: probability of a random breakdown situation, (2) cost: "expected sum of maintenance and breakdown cost when a random breakdown situation happens under each alternative", and (3) time: cumulative time from the last shutdown maintenance to the completion of this maintenance decision.
(Chea, 2011) (Destri, et al., 2012)	Chea discussed the application of Activity-Based Costing (ABC) - (Thyssen, et al., 2006), (Gunasekaran, et al., 1998) , (Cooper, et al., 1991) - in service sectors (Chea, 2011). ABC is basically initiated to support manufacturing sector, especially decision-makers and managers, for solving the problem of traditional cost management systems for identifying the true costs of processes (Cooper, et al., 1991). ABC takes into account direct and indirect cost allocation and activity cost drivers (e.g. cost of set-up) (Chea, 2011). Chea described ABC's capabilities to be applied in non-manufacturing sectors and emphasized that its principles are potentially customizable in the service sector (Chea, 2011). He further discussed the integration of ABC and economic value added (EVA) (Chea, 2011). He determined that integration of both concepts can

(Author(s), Year)	**Abstract**
	lead to compensate the lack of ABC that partially reflects to capital cost (Chea, 2011). Destri et al. elaborated the integration and emphasized on the integration of process-based costing (PBC) and EVA (Destri, et al., 2012). The proposed concept of PBC-EVA is, in fact, an integrated team concept for improving financial performance measures (Destri, et al., 2012).
(Salonen, et al., 2011)	In practice, there are several examples of applying or developing maintenance cost indexes (i.e. KPIs). Salonen and Deleryd studied "well-known measures from the area of quality development", and proposed a financial measure for maintenance. The measure is used to find out "which parts of the maintenance costs are justified and which costs relate to poorly performed maintenance". They argued that the measure provides "a more balanced view of the financial contribution of maintenance activities may be achieved, even at board level of the company".
(Dandotiya, et al., 2012)	Dandotiya and Lundberg proposed a decision model considering variations in process and maintenance parameters for improving cost-effective maintenance decision in the use-case of mill liners. Their aim was to consider the variations in process parameters and maintenance time and cost. They combined the lifetime model and a replacement interval model "to determine the optimum replacement interval for the mill liners which considers process parameters of multiple ore types". They applied experiments in cooperation with industrial experts and used weighting approach and simulation to evaluate the proposed model. Finally, they declared that "the finding of the combined model results leads to a significant improvement in mill profit".
(Almgren, et al., 2012)	Almgren et al. presented a mathematical model for "finding optimal opportunistic maintenance schedules [i.e. periodic maintenance] for systems [e.g. Aircraft Engine], in which components are assigned maximum replacement intervals". The model supports solving optimization problems to "find a replacement schedule that minimizes the total maintenance costs over the planning period". In this way, they used the mathematical modeling of cost associated items for a single module and system of several modules. The former refers to "costs related to spare parts and maintenance occasions only". The latter represents "costs related also to (dis)assembly and repair work".
(van Horenbeek, et al., 2012)	Van Horenbeek et al. employed a prognostic maintenance policy considering the interdependencies between components and systems for an offshore wind turbine farm. In this context, there are several reasons for grouping maintenance actions such as "difficulty to reach the offshore wind turbines, the specialized equipment necessary and dependence on external factors like weather conditions". Therefore, they developed a mathematical model for optimizing the maintenance cost by ensuring high availability. The model groups maintenance activities in a multi-component and multi-system environment. The grouping maintenance cost is calculated for a grouping structure which includes groups of maintenance actions. For each group the maintenance cost is calculated based on the saving of each group plus "additional cost of shifting a maintenance activity from the individual optimal time to the optimal group maintenance time". Thus the prognostic model incorporates "both the advantages of grouping maintenance activities and incorporating degradation information in the form of remaining useful life of components", and provides opportunities for minimization of costs and maximization of profits.

(Author(s), Year)	**Abstract**
(Shafiei-Monfared, et al., 2012)	Shafiei-Monfared and Jenab proposed a “fuzzy graph-based model to measure the relative complexity” of maintenance projects. The model considers both technical and managerial complexities and uses “an aggregation operator to mitigate the conflict of experts’ opinion on a complexity, relation”. The model can relatively identify the complexity of the projects in a scaled Cartesian diagram which can support decision-makers in policy selection, particularly for estimating and allocation of resources. The proposed model does not include any cost function, but it “may improve budget and resource allocation” of maintenance projects.
(Tinga, et al., 2012)	Tinga and Janssen studied the effects of usage variations on the optimal maintenance intervals. The aim was to optimize the maintenance process, and in turn to minimize total cost. They defined a cost function by classification of cost attributes to the preventive and corrective cost per activity, cost per period, and fix cost. The assumption was made to calculate the preventive cost as a fraction of the corrective cost. In addition, they defined number of corrective, preventive and intermediate maintenance periods as variables. Using different ratios between corrective and preventive maintenance costs, the total maintenance cost for various numbers of intervals was calculated and simulated through employing a stochastic process (i.e Markov process). The results revealed that the total maintenance cost is increased for any chosen interval when the fraction is higher (i.e. cost of preventive maintenance is increased). The optimal value for any chosen number of intervals is in turn achieved in the intersection (meeting point) of all curves, which corresponds to the lowest total cost. For the values lower than the optimal point “preventive maintenance is so cost-effective that a policy with many short intervals is preferable”. For higher values than the optimal “the higher costs of preventive actions make it more attractive to wait until the subsystems fail, which yields a policy with long intervals to be the most attractive”. They concluded that “[…] a remarkable transition exists from preventive to corrective maintenance at some ratio between corrective and preventive maintenance costs. This transition is not gradual (steadily decreasing values of [number of intervals]), but very abrupt”. In this study the fundaments of the concept of (Hahn, et al., 1993)were considered, especially the definition of a number of maintenance activities and associated costs.
(Rommens, 2012)	Rommens studied maintenance cost in a cement plant and empirically developed a tool for estimating the right level of maintenance cost. He gathered data from “a large number of plants in the company and considered all influential factors such as plant specifics and environment”. Finally, he created a maintenance cost index (i.e. KPI), which represents a division of maintenance cost of one plant by the reference level of maintenance cost of the plant. Within the study of the cement manufacturing company, they standardized the index, as a management tool, after twenty years of existence.
(Ierace, et al., 2013)	Cf. (Labib, 2004).

7.2 List of the Surveyed CMMIS Software Packages

Table 25 presents additional information corresponding to the analysis of CMMIS software packages (cf. Section 3.2 – Table 20).

Table 25. List of the surveyed CMMIS software

Name of CMMIS package	**Developer**	**Link / Date of last visit**
Advanced Maintenance Management System (AMMS)	MicroWest Software Systems USA	www.microwestsoftware.com/products/amms.stm Last visit: 16.11.2013
MP-Software	Tecnica Aplicada Internacional Mexico	www.mpsoftware.com.mx Last visit: 16.11.2013
BENCHMATE	Benchmate Systems USA	www.benchmate.com Last visit: 16.11.2013
Computerized Maintenance Management System PROACTIVE (CMMS PRO)	NAGSOFT Solutions India	www.cmmspro.com Last visit:16.11.2013
Ivara Asset Performance Management	Ivara Canada	www.ivara.com Last visit:16.11.2013
IBM-Maximo® [54]	IBM® (Earlier offered by MRO)	www-03.ibm.com/software/products/en/maximoassetmanagement/ Last visit:16.11.2013

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[54] IBM-Maximo® is comprehensive asset life cycle and maintenance management. This is a product of IBM® for enterprise asset management (EAM).

Name of CMMIS package	**Developer**	**Link / Date of last visit**
SAP® Enterprise Asset Management	SAP®	www.sap.com/solutions/bp/enterprise-asset-management/solutions-overview.epx Last visit:16.11.2013
Oracle® Enterprise Asset Management (eAM)	Oracle®	www.oracle.com/us/products/applications/060286.html Last visit:16.11.2013
MaintiMizer™	Aschom Technologies USA	www.ashcomtech.com Last visit:16.11.2013
CHAMPS CMMS	CHAMPS Software USA	www.champscmms.com Last visit:16.11.2013
Infor Enterprise Asset Management (Infor-EAM)	Infor USA	www.infor.com/solutions/eam Last visit:16.11.2013