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Problem-solving approaches in maintenance cost management: a literature review

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Abstract

Purpose – The purpose of this paper is to investigate the use of problem-solving approaches in maintenance cost management (MCM). In particular, the paper aims to examine characteristics of MCM models and to identify patterns for classification of problem-solving approaches.

Design/methodology/approach – This paper reflects an extensive and detailed literature survey of 68 (quantitative or qualitative) cost models within the scope of MCM published in the period from 1969 to 2013. The reviewed papers have been critically examined and classified based on implementing a morphological analysis which employs eight criteria and associated expressions. In addition, the survey identified two main perspectives of problem solving: first, synoptic/incremental and second, heuristics/meta-heuristics.

Findings – The literature survey revealed the patterns for classification of the MCM models, especially the characteristics of the models for problem-solving in association with the type of modeling, focus of purpose, extent and scope of application, and reaction and dynamics of parameters. Majority of the surveyed approaches is mathematical, respectively, synoptic. Incremental approaches are much less and only few are combined (i.e. synoptic and incremental). A set of features is identified for proper classification, selection, and coexistence of the two approaches.

Research limitations/implications – This paper provides a basis for further study of heuristic and meta-heuristic approaches to problem-solving. Especially the coexistence of heuristic, synoptic, and incremental approaches needs to be further investigated.

Practical implications – The detected dominance of synoptic approaches in literature – especially in the case of specific application areas – contrasts to some extent to the needs of maintenance managers in practice. Hence the findings of this paper particularly address the need for further investigation on combining problem-solving approaches for improving planning, monitoring, and controlling phases of MCM. Continuous improvement of MCM, especially problem-solving and decision-making activities, is tailored to the use of maintenance knowledge assets. In particular, maintenance management systems and processes are knowledge driven. Thus, combining problem-solving approaches with knowledge management methods is of interest, especially for continuous learning from past experiences in MCM.

Originality/value – This paper provides a unique study of 68 problem-solving approaches in MCM, based on a morphological analysis. Hence suitable criteria and their expressions are provided. The paper reveals the opportunities for further interdisciplinary research in the maintenance cost life cycle.

Keywords Problem-solving, (Meta-)Heuristic, Incremental, Maintenance cost management, Planning, Synoptic, Monitoring, Controlling

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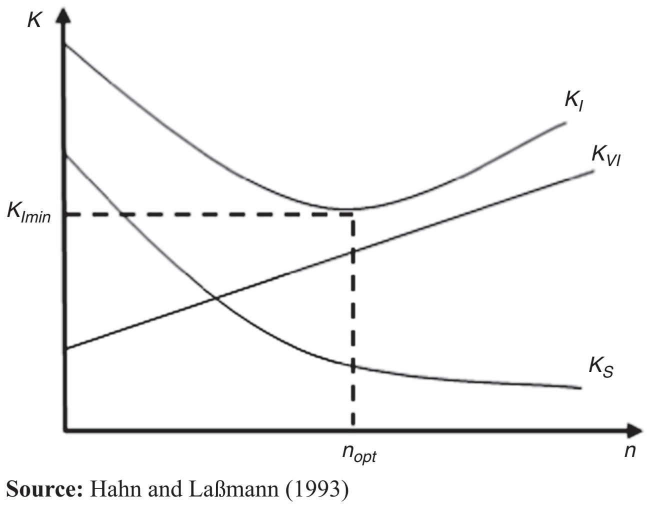
Introduction

In today's industry, maintenance is an integral part of the production strategy subject to periodic, predictive, and corrective maintenance of the machineries, equipment and physical assets. In typical manufacturing companies, maintenance costs are between 15 and 40 percent of the total cost of production (Wireman, 2014). The potential to reduce or optimize maintenance cost is about 10-20 percent; 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 and 16 percent, while keeping production costs the same, leads to an increase in pre-tax profits of between 2.8 and 14 percent (Wireman, 2014). Management (i.e. planning, monitoring, and controlling) of budget and expenditures is, therefore, essential for the overall success of companies.

Maintenance cost attributes are classified into two major categories: direct and indirect cost. The former is associated with costs of periodic inspection and preventive maintenance (PM), repair, overhaul, and servicing as well as the labor and material expenses needed to implement maintenance actions. The latter, indirect cost, is related to: loss of production due to primary equipment breakdown and unavailability of standby equipment; 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; and operating and maintaining standby equipment.

Besides, Hahn and Laßmann (1993) defined planned and unplanned cost as the major cost attributes. In this paradigm, the total maintenance cost is calculated as the summation of planned and unplanned maintenance cost (Hahn and Laßmann, 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 and Laßmann, 1993). Figure 1 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 PM activities in a certain period, that on the one hand influences the planned maintenance



Source: Hahn and Laßmann (1993)

Figure 1. The trade-off curve for the indication of planned and unplanned cost

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 PM activities (n_{opt}) for a single production machine in the certain planning period (e.g. per year). 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 1) is discussed underlying the framework of total productive maintenance, e.g. by Wireman (2004), Mobley (2008), and Stevenson (2012). The model is understood as 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).

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. The paradigm constituted by Hahn and Laßmann (1993) emphasizes the desired goal of maintenance cost management (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.

According to DIN (2010/2012), MCM should be seen from both operational and strategic perspectives. The focus of MCM is placed 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). Thus effective planning-monitoring and efficient controlling is required to increase the accuracy of planning, and detect improvement potentials for the forthcoming planning period. 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 and solve existing problems, 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, especially within problem-solving and decision-making activities.

Taking into account the challenge of planning-monitoring-controlling, this paper presents an extensive literature survey of 68 selected MCM models using a morphological approach. The primary objective of the survey is to identify the patterns for classification of the MCM models, especially the characteristics of the models for problem solving in association with the type of modeling, focus of purpose, extent and scope of application, and reaction and dynamics of parameters. Thus the paper holds a unique approach on classification of MCM models through collaborative consideration of multiple criteria for identification of general patterns in problem solving.

Survey design and methodology

The literature survey of MCM models has been conducted in 2013. The scope of the selection procedure was limited to the models that consider economic impacts of maintenance. Investigating the scientific databases and journals, such as databases of Emerald, Elsevier, IEEE, and Springer, 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. Finally, the research results in the qualification of 68 models. Of the selected models, 31 percent are from the articles published by the *IEEE Transactions*, namely articles which appeared in *IEEE Transactions* on: *Reliability*, *Engineering Management*, and *Energy Conversion*. The survey showed 16 percent to be from journals of operational research, 10 percent from maintenance engineering journals especially the articles appearing in the *Journal of Quality in Maintenance Engineering*, and also 10 percent 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 percent of the articles. Additionally, 9 percent of the articles belong to the conference publications (proceedings) of the European Operations Management Association, and other related peer-reviewed conferences on production and operations management. Last but not least, 4 percent of models come from articles published by *IIE Transactions* (IIE stands for Institute of Industrial Engineers).

In order to systematically analyze the papers and identify patterns for classification, we conducted a morphological study by defining eight criteria and associated expressions. We defined terminology of the criteria and associated expressions in Table I.

For a traceable classification of problem-solving characteristics of the surveyed MCM models either synoptic and incremental, or heuristics and meta-heuristics, an analysis scheme was used as depicted in Figure 2.

Survey results

Table II presents the results of the survey by sorting the reviewed models in the chronological order. Each column represents a criterion and associated expressions, based on Table I. Each row shows a model and its association with the criteria. In case of interdependency between models, they are mentioned in one row or indicated by means of footnote. The check-mark (✔) is used to indicate whether a model fulfills a certain expression or not. Finally the sum of counted check-marks is presented.

Discussion and conclusion

The literature survey is intended to extend and deepen the insight into problem-solving approaches in the literature of MCM. The survey revealed patterns for classification of the reviewed MCM models by implementing eight criteria and associated expressions.

Criteria	Characteristics of the associated expressions
C1: type of modeling	C1.1: 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) C1.2: 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 C1.3: 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)
C2: type of problem-solving	C2.1: 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" C2.2: 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)" C2.3: 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
C3: 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 and Scholl, 2011; Frankel, 2008) C3.1: 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 C3.2: explanation models provide hypothesis (or what-if relationship) to scientifically define a scope or structure of a system using the deductive-nomological model (Hempel-Oppenheim model) for defining conditions and associated consequences. Such models can be used for prognosis C3.3: 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
C4: extent of the model	C4.1: 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 C4.2: total models, in contrast, deal with the problem holistically i.e. considering all (organic or functional) relations and interdependencies between cost and benefits
C5: reaction of parameters	In the context of the mathematical models, the reaction of parameters/variables can be classified into three categories as follows: C5.1: deterministic behavior refers to non-random evolution of parameters (i.e. only in one way) C5.2: 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

Table I.
The criteria and associated expressions for morphological analysis

(*continued*)

Criteria	Characteristics of the associated expressions
	C5.3: 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
C.6: consideration of time	C6.1: static models represent the equations without considering the time variable C6.2: semi-static models, however, considers the behavior of a system over time instances (discontinuous), but they do not include a time-dependent variable explicitly C6.3: dynamic models directly represent the equations including time variable
C7: scope of application	C7.1: 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 C7.2: universally applicable models, in contrast, provide a generic reference model for solving a group of problems in one or different domain(s)
C8: heuristics	Heuristic approaches – using special methods, experiences or even trial-and-error – do not guarantee the solving of a problem in an optimal way. Meta-heuristic approaches provide a pattern for solving a wide range of problems In the morphological analysis, three expressions are considered for identifying the heuristic or meta-heuristic nature of the problem-solving as: C8.1: 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 a 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 C8.2: no (N) which indicates that author(s) has (have) explicitly refused to use any heuristic or meta-heuristic method C8.3: not available (na) 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

Source: Ansari (2014)

Table I.

The synoptic characteristic has been detected in most of the models which aim at minimizing the total cost of maintenance using straightforward methods instead of continuous approaches. The promising result indicates typology of models deploying incremental or synoptic approaches vs combined models (i.e. using synoptic and incremental approaches). As discussed earlier in Table I, incremental models consider "errors" in decision making and use a feedback and/or feed-forward loop to compensate errors, and learn for future decisions. In contrast, synoptic models pre-suppose comprehensive information for decision making and therefore are based on open control chains. For the incremental approaches it is difficult to identify 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. Therefore incremental approaches require using and analyzing MCM knowledge assets. 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 (Ansari, 2014).

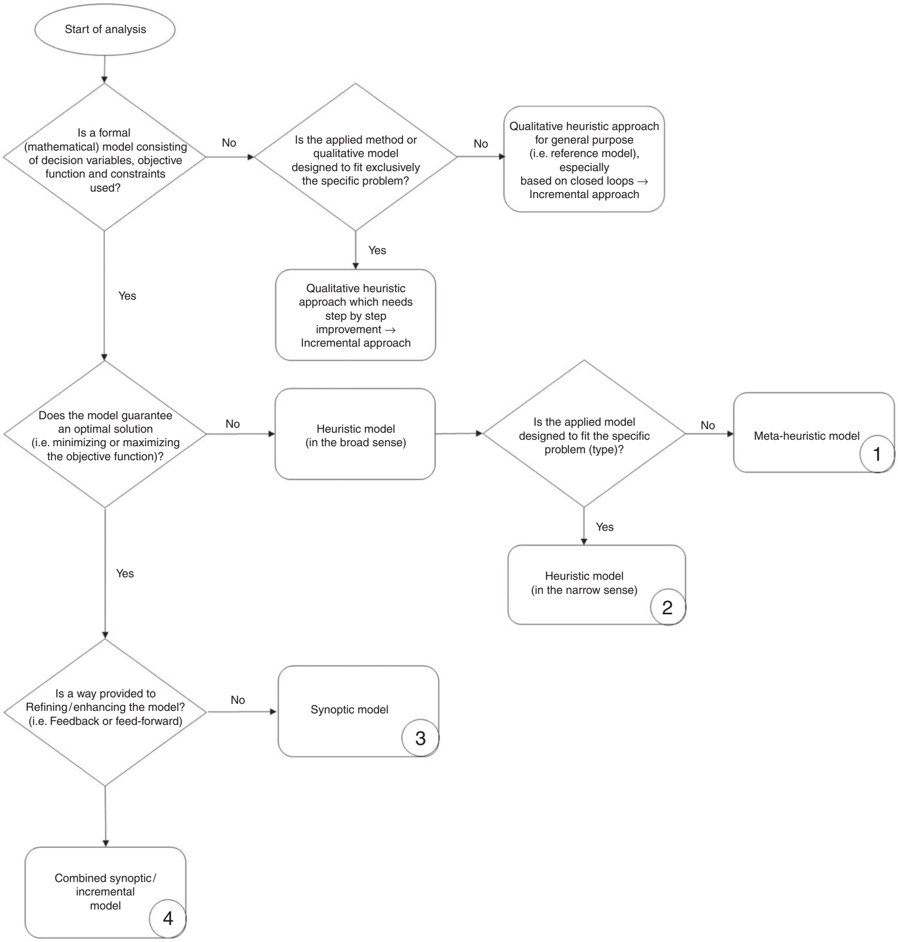


Figure 2.
Analysis scheme for classification of the surveyed MCM models

Furthermore, the analysis is extended for compounding the insight into the use of heuristic or meta-heuristic approaches in the context of MCM. Most of the authors (of the surveyed articles) have neither refused nor indicated using heuristic or meta-heuristic approaches in MCM (cf. Table II). 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 and Kusy (1985) and Sung and Cho (2000) directly stressed that their approaches are a 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. Within the literature survey, few models have been detected which can be classified either as heuristic or meta-heuristic.

Table II. Morphological analysis of the surveyed MCM models

Criteria	C.1			C.2			C.3			C.4		C.5			C.6			C.7		C.8
Expressions	C.1.1	C.1.2	C.1.3	C.2.1	C.2.2	C.2.3	C.3.1	C.3.2	C.3.3	C.4.1	C.4.2	C.5.1	C.5.2	C.5.3	C.6.1	C.6.2	C.6.3	C.7.1	C.7.2	C.8.1/2/3
Models																				
Nathan (1969)	✓				✓				✓		✓	✓			✓		✓	✓		na
McLeod (1973)			✓			✓			✓		✓	✓				✓			✓	na
Tempest (1976)			✓			✓			✓	✓		✓				✓			✓	na
Sule and Harmon (1979)	✓				✓				✓	✓		✓					✓		✓	na
Regulinski and Gupta (1983)	✓					✓			✓		✓		✓				✓		✓	na
Collins (1983)	✓					✓			✓		✓	✓	✓				✓	✓		na
Goyal and Kusy (1985)	✓				✓				✓	✓		✓					✓		✓	Y
Canfield (1986)	✓					✓			✓	✓			✓				✓		✓	na
Blohm and Lüder (1988)		✓		✓				✓	✓	✓		✓				✓			✓	Y
Seidenberg (1989)																				
Adam (1989)																				
Jayabalan and Chaudhuri (1992)	✓				✓				✓	✓		✓					✓	✓		na
Hahn and Laßmann (1993)	✓				✓				✓	✓		✓				✓			✓	na
Sheu and Krajewski (1994)			✓	✓					✓		✓	✓					✓		✓	na
van Gestel (1994)			✓			✓			✓	✓			✓				✓		✓	na
Al-Najjar (1996)		✓		✓					✓		✓	✓				✓			✓	na
Usher *et al.* (1998)	✓					✓			✓		✓	✓					✓	✓		Y[a]
Lim and Park (1999)	✓				✓			✓		✓			✓				✓	✓		na
Reineke *et al.* (1999a)	✓				✓				✓	✓			✓				✓	✓		na
Barlow and Hunter (1960)																				
Reineke *et al.* (1999b)	✓				✓				✓	✓			✓				✓	✓		na
Baron and Pate-Cornell (1999)			✓		✓				✓		✓		✓				✓	✓		na
Sung and Cho (2000)	✓				✓				✓		✓	✓				✓		✓		Y[b]
Yam *et al.* (2000)	✓		*[c]		✓				✓		✓	✓				✓		✓		na
Duffuaa *et al.* (2001)		✓		✓					✓	✓		✓				✓			✓	na
Dhillon (2002)	✓			✓					✓	✓			✓				✓		✓	na

(*continued*)

Table II.

Criteria	C.1			C.2			C.3			C.4		C.5			C.6			C.7		C.8
Expressions	C.1.1	C.1.2	C.1.3	C.2.1	C.2.2	C.2.3	C.3.1	C.3.2	C.3.3	C.4.1	C.4.2	C.5.1	C.5.2	C.5.3	C.6.1	C.6.2	C.6.3	C.7.1	C.7.2	C.8.1/2/3
Maillart and Pollock (2002)	✓				✓				✓	✓			✓				✓	✓		na
Grall *et al.* (2002)	✓				✓				✓	✓			✓				✓	✓		na
Chen and Jin (2003)	✓				✓				✓	✓		✓					✓		✓	na
Rhee and Ishii (2003)	✓			✓					✓	✓			✓				✓		✓	na
Elegbede *et al.* (2003)	✓					✓			✓	✓		✓			✓			✓		Y[d]
Dey (2004)	✓			✓					✓		✓	✓			✓			✓		na
Labib (2004)	✓			✓					✓		✓			✓		✓			✓	na
Shum and Gong (2004)	✓					✓			✓	✓		✓	✓				✓		✓	Y[e]
Haarman and Delahay (2004)			✓	✓					✓		✓	✓					✓		✓	na
Jardine and Tsang (2005)	✓				✓				✓	✓		✓				✓			✓	na
Yao *et al.* (2005)	✓				✓				✓	✓			✓				✓	✓		na
Selman and Schneider (2005)	✓			✓				✓		✓		✓				✓		✓		na
Rishel and Canel (2006)			✓	✓				✓			✓	✓				✓			✓	na
Lehtonen (2006)	✓				✓				✓	✓		✓	✓				✓	✓		na
Wang and Pham (2006)	✓				✓				✓	✓		✓					✓	✓		na
Kelly (2006)			✓	✓					✓		✓	✓				✓			✓	na
Vasiu and Stoica (2007)	✓				✓				✓	✓			✓				✓	✓		na
Nakagawa (1979)																				
Hagmark and Virtanen (2007)			✓			✓			✓	✓			✓			✓		✓		na
Nilsson and Bertling (2007)	✓				✓				✓		✓	✓			✓			✓		na[f]
Dersin *et al.* (2008)	✓				✓				✓	✓		✓	✓				✓	✓		na[g]
Zhou and Zhu (2008)[h]			✓			✓			✓	✓			✓				✓		✓	na
Huang and Fang (2008)[i]	✓				✓				✓		✓		✓			✓		✓		na
Kister (2008)	✓			✓					✓	✓			✓				✓		✓	na
Frenkel and Khvatskin (2009)	✓				✓				✓		✓		✓				✓	✓		na
Liu and Huang (2010)	✓					✓			✓	✓		✓	✓		✓		✓	✓		Y[j]
Chen (2010)	✓					✓			✓	✓			✓				✓	✓		na

(*continued*)

Table II.

Criteria	C.1			C.2			C.3			C.4		C.5			C.6			C.7		C.8
Expressions	C.1.1	C.1.2	C.1.3	C.2.1	C.2.2	C.2.3	C.3.1	C.3.2	C.3.3	C.4.1	C.4.2	C.5.1	C.5.2	C.5.3	C.6.1	C.6.2	C.6.3	C.7.1	C.7.2	C.8.1/2/3
Chea (2011)			✓	✓					✓		✓	✓				✓			✓	na
Destri *et al.* (2012)																				
Salonen and Deleryd (2011)	✓			✓					✓	✓		✓				✓			✓	na
Dandotiya and Lundberg (2012)	✓			✓					✓		✓		✓				✓	✓		na[k]
Almgren *et al.* (2012)	✓				✓			✓		✓		✓					✓	✓		na
van Horenbeek *et al.* (2012)	✓				✓			✓			✓	✓					✓	✓		na
Shafiei-Monfared and Jenab (2012)			✓	✓				✓		✓				✓	✓				✓	na
Tinga and Janssen (2012)			✓		✓				✓	✓		✓	✓			✓		✓		na
Rommens (2012)	✓			✓				✓		✓		✓			✓			✓		na
Ierace and Cavalieri (2013)	✓			✓					✓	✓		✓			✓				✓	na
Sum	42	3	13	19	26	13	0	8	51	37	21	36	26	2	8	18	34	31	27	

Notes: [a]Meta-heuristic approach using genetic algorithm; [b]the authors indicated that for future work it is best to use the model through a heuristic procedure; [c]the authors indicated the need for intelligent decision support systems (DSS); [d]meta-heuristic approach for approximation; [e]meta-heuristic approach using genetic algorithm; [f]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; [g]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; [h]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); [i]used the cost model of (Jayabalan and Chaudhuri (1992); [j]Meta-heuristic approach using genetic algorithm; [k]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

Meta-heuristic approaches are the ones using a genetic algorithm except for the model of ECAY (cf. Elegbede *et al.*, 2003).

The reviewed MCM models are mainly established based on a mathematical representation of the operational and economic variables using 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 in problem-solving and provide a kind of guideline and instruction for MCM. 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) such as the model of Hahn and Laßmann (cf. Figure 1). 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. This provides opportunity for integrating the principles of mathematical and qualitative modeling toward creating a novel reference model.

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.

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 (cf. Table II). The results confirm the importance of incorporating time factors due to the dynamic and evolutionary characteristics of MCM, i.e. developing semi-dynamic or dynamic models instead of static.

In addition, most of the surveyed models deal with supporting or assisting the maintenance manager for improving policy selection, trading-off between economic and operational variables, and decision making. Through the morphological analysis, no descriptive model has been detected. 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 in Table I, each decision model is built on a class of explanatory models. 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).

The survey reveals a polarization for concentration on part of the problem domain of MCM, in contrast to 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. Table II). 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.

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. Table II). 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.

Future

The general pattern, detected through morphological analysis identifies the major characteristics of the surveyed MCM models. 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. So a novel MCM model should be established based on new premises, i.e. ends (goals)-means (alternatives): 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 maintenance personnel) for reviewing the past events and planning future ones.

Taking into account the findings of the literature survey and the evolution of synoptic and incremental heuristic models/approaches over the past 45 years, it is not precise to question which one is "the best way of problem-solving in MCM?" Instead, it is recommended to reformulate to "when and how" these approaches could be used (cf. Table I). Coexistence and combination of the two basic approaches is generally discussed in the management literature and proposed by Fredrickson (1983), Toft (2000), Methe *et al.* (2000), Bresser (2010), and Seidenberg (2012). In addition, the advantages and drawbacks of synoptic/incremental models and the neighborhood of the incremental approaches to heuristic and meta-heuristic ones indicate the potential for coexistence of these approaches.

Hence we recommend directing the future research toward combining the principles of incremental and synoptic approaches. The synoptic models cannot bridge the planning-monitoring-controlling gap, because of their limitation with planning. In addition, the evolution of the model and its empowerment is achieved through a heuristic procedure of testing and upgrading, i.e. trial-and-error. Thus, continuous learning from past events leads to the improvement of the MCM process, especially assisting the maintenance manager 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 (cf. Figure 1). 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.

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