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Classification of articles and journals on project control and earned value management

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Abstract

This paper presents an overview of the existing literature on project control and earned value management (EVM), aiming at fulfilling three ambitions. First, the journal selection procedure allows to discern between high-quality journals and more popular business magazines. Second, the collected papers on project control and EVM, published in the selected journals, are classified based on a framework consisting of six distinct classes. Third, the classification framework indicates current trends and potential areas for future research, which can be summarized as follows: (i) increased attention to the stochastic nature of projects, (ii) enhanced validation of the proposed methodology using a large historical dataset or a simulation experiment, (iii) expansion of integrated control models, focusing on time and cost as well as other factors such as quality and sustainability, and (iv) development and validation of corrective action procedures.

Keywords: Project management; Classification; Project control; Earned value management

1. Introduction

Project control aims at measuring and evaluating the actual progress of projects by applying techniques such as earned value management (EVM) in order to finish the project on time and within budget. Focusing on time and cost control, the baseline schedule or planned value (PV) serves as a starting point to evaluate the actual performance of the project. Typically, the development of planned and actual values is assumed to follow an S-curve pattern. This implies that more work is done in the middle stage of a project compared to the early and late stages. At the project start, a preliminary estimate of the planned duration and cost is made. While the focus of EVM was initially mainly on cost, it gradually shifted from cost control to time control, partly initiated by the article by Lipke (2003), which introduced the earned schedule (ES) concept. In order to track project progress during execution, the planned value (PV), earned value (EV) and actual cost (AC) curves are plotted in the time–cost space. To detect deviations from the schedule, the cost performance index (CPI), schedule performance index (SPI) and its ES-variant SPI(t) are calculated and evaluated. For a concise overview of the EVM metrics we refer the reader to the paper by Anbari (2003). Incorporating this new information, the time and cost estimates at completion are updated. When deviations occur, the project manager should decide whether corrective actions should be taken to bring the project back on schedule.

These concepts have been brought to attention by books on project management and control in general (Archibald and Villoria, 1967; Cleland and King, 1988; Kerzner, 2013) and EVM in particular (Fleming and Koppelman, 2005; Vanhoucke, 2010a). Moreover, a comprehensive bibliography on the earned value literature has been constructed by Christensen (2015). In

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2008, the first comparison between various time control methods using EVM has been published in the International Journal of Project Management (Vandevoorde and Vanhoucke, 2006) and resulted in an IPMA awarded research study by Vanhoucke (2010a). Besides cost and time, some research effort has been done to incorporate quality as a performance objective. However, most research has focused on managing quality in projects (Atkinson, 1999; Basu, 2014; Gardiner and Stewart, 2000), and integrating time, cost and quality in the scheduling phase (Babu and Suresh, 1996; Khang and Myint, 1999; Kim et al., 2012). Only few studies explicitly monitor and control quality during project execution.

The contributions of this paper are threefold. Our first ambition is to collect the academic work on time and cost control, focusing only on papers published in well-recognized and high-ranked journals. Selection of the relevant papers entails a clear definition of the scope, which will be provided in Section 2.1. Subsequently, Section 2.2 will address the journal selection procedure, applied to discriminate between high-quality journals and the more popular business magazines. Second, the collected papers will be classified according to a framework consisting of six classes, all representing a typical and fundamental aspect of a research paper. In particular, Section 3 will elaborate on the research problem, contribution, methodology, analysis, validation and application of the papers. The third and final objective of this paper is to identify trends in current research and to determine gaps in the literature that exhibit room for improvement. These trends and gaps should motivate researchers to make contributions to this interesting research field where its added value would be the highest. The main findings of this literature review and directions for future research are highlighted in Section 4.

2. Article and journal selection methodology

This study was initiated by an explorative search on EVM using the databases Web of Science, ScienceDirect and Google Scholar. The search terms mainly consisted of combinations of the keywords: earned, value, project and control. We used the topic of the paper (Section 2.1) and the journal in which it was published (Section 2.2) to delineate the scope of this review paper. The latter constraint cleared approximately 20% of the papers listed in Christensen's bibliography for inclusion in the classification framework. The literature search finally resulted in a collection of 187 academic research papers on EVM and project control, which will be classified along the following classes: (i) research problem, (ii) contribution, (iii) methodology, (iv) analysis, (v) validation and (vi) application. The specifics of this classification framework will be addressed in Section 3, followed by a discussion of the current research trends and possible areas for future research in Section 4. Fig. 1 presents a graphical summary overview of the upcoming sections.

2.1. Article selection

The literature on integrated project management and control (IPM&C) (Vanhoucke, 2014) can be broken down into three broad categories, that is, baseline scheduling, risk analysis and project control (Fig. 1). The focus of this review paper lies on the latter, and more precisely on the quantitative mechanisms used to monitor a project in progress, to measure its time and cost performance and to generate warning signals that act as triggers for action when the project tends to run out of control. In order to restrict the scope of this review paper, only articles on time and cost control will be included. Although a range of other objective functions, such as quality, safety and sustainability exist, they are only added when combined with time and/or cost control.

The earned value management methodology is undoubtedly one of the most straightforward and most widely disseminated techniques for monitoring and controlling projects, and we have therefore used this technique as a general theme. However, this does not mean that all papers in our review explicitly mention EVM as a project control tool. Instead, some of the papers that have been incorporated into the classification rely on a very similar quantitative approach without explicitly mentioning EVM as a technique. Thus, papers on time and/or cost forecasting methods, performance evaluation techniques and measuring systems applied to trigger corrective actions are included. Regarding cost and time forecasting, however, only papers explicitly dealing with forecasts during project progress were withheld. Furthermore, papers that do not cover any of the above-mentioned topics but exclusively deal with factors affecting cost, time, performance, success or failure are neglected in this overview paper since they have no direct link to the project control theme.

2.2. Journal selection

The literature on project control and EVM is rich and diverse, and is spread over various journals. Most of the academic journals are ranked in the Journal Citation Reports (JCR) of the Web of Science and are able to report an impact factor. This index reflects the relative importance of a journal, measured by the number of citations to recent articles in the journal. On the other hand, numerous articles on EVM are published in journals that provide a reliable source of information for a wide audience and report relevant results or ideas that are interesting and of public concern. Quite often, however, these articles lack a methodological ground and test of logic and can therefore not always be readily used for research purposes. Despite the relevance and necessity of both classes of journals, it is hard to draw the lines between these types of journals when it comes to judging the quality of the articles from an academic point of view and their relevance for future (academic) research purposes. Nevertheless, we believe we have followed an approach that objectively ranks all journals that published at least one article on the topic of this paper.

2.2.1. Minimum threshold

During the search process, we kept track of all journals and magazines in which the relevant articles that we encountered were published. This resulted in a collection of 663 items, such as articles, books, technical reports and dissertations. A first condition for an article to be accepted in the classification

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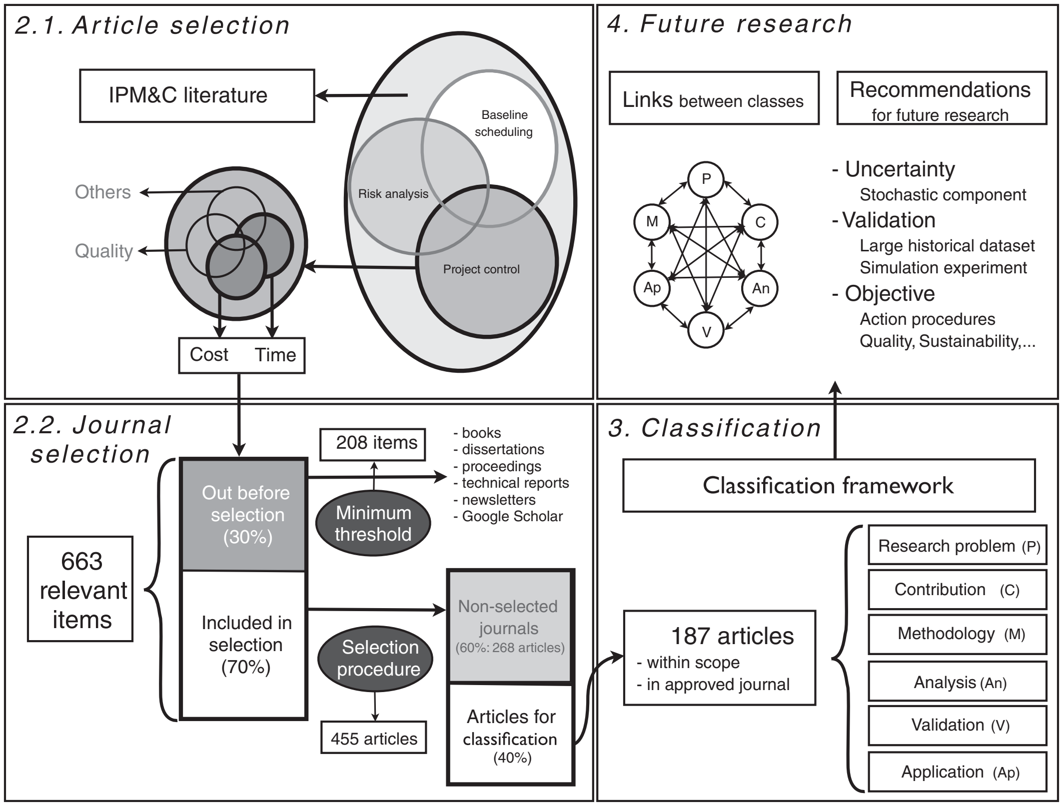


Fig. 1. Graphical representation of the methodology (scope definition and journal selection) that resulted in the classification framework presented in Section 3 and the research trends and areas for future research that will be discussed in Section 4.

framework was the publication in a *journal* recognized by the Google Scholar search engine. Because of this minimum threshold, items such as books, master and PhD dissertations, technical reports, newsletters and unpublished articles were discarded. As a result, approximately 70% of the dataset or 455 articles, published in 94 different journals, were subject to the selection procedure described next. The other 208 items were discarded.

2.2.2. Selection procedure

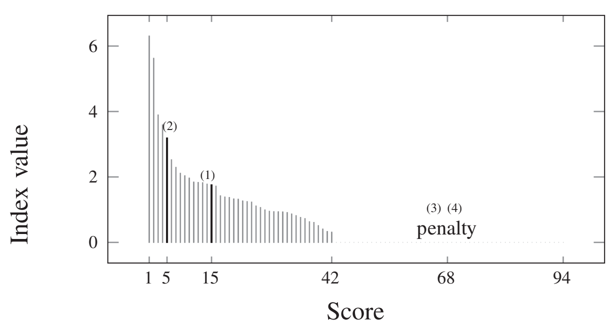
In order to rank the 94 journals satisfying the minimum threshold, we collected nine citation-based indices originating from three databases for each journal.

(i) The Web of Science database, published by Thomson Scientific in the Journal Citation Reports of 2013 (Reuters, 2014) provides (a) the Journal Impact Factor of 2013 and (b) the 5-year Journal Impact Factor.
(ii) The Scopus database, owned by Elsevier, is evaluated by the “SCImago Journal & Country Rank” portal (SCImago, 2007) by composing (a) the SRJ-indicator of 2013 and (b) the h-index of the journal.
(iii) The Google Scholar database, was analyzed using the software “Publish or Perish” (Harzing, 2007) based on (a) the h-index, (b) the g-index, (c) the contemporary h-index, (d) the individual h-index and (e) the average annual increase in individual h-index.

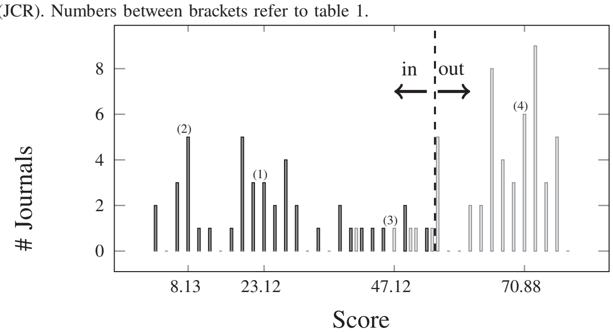
After collecting all index values, we ranked each journal relative to the other journals in the dataset based on their value for each index. Table 1 shows the indices and their ranks for four example journals: the journal containing the largest number of papers in the classification (Fig. 2(c)), a very high ranked journal, a journal not included in the Web of Science database, but included in the classification and a journal not included in the Web of Science database and not in the classification either. Fig. 2(a) summarizes the results for the Journal Impact Factor of 2013, which is index (i)(a) in Table 1. The first and the second journal in this table have an index value of 1.76 and 3.19 respectively, which corresponds to places 15 and 5 in the ranking of all journals based on this index. Since journals (3) and (4) are not indexed in the Web of Science, they receive a penalty score for this index. This penalty is calculated based on the total number of journals (94) and the number of journals with an index value above zero (42 for this index). In order to fairly favor journals that are indexed in a particular database, the penalty was set equidistant from these values. For the first index, the penalty is thus calculated as: $42 + \frac{94-42}{2} = 68$. Similar computations for the other indices resulted in the individual ranks or penalty scores for all journals.

Table 1
Example score calculation for four example journals.

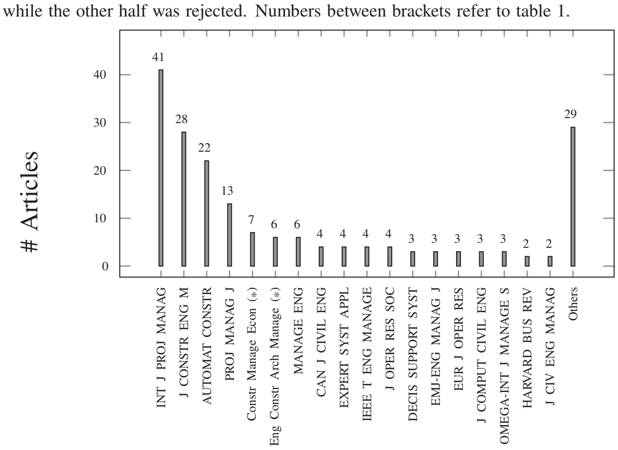
			WoS		Scopus		Google Scholar					
		Index weight	(i)(a)	(i)(b)	(ii)(a)	(ii)(b)	(iii)(a)	(iii)(b)	(iii)(c)	(iii)(d)	(iii)(e)	Total
			0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.2	
(1)	INT J PROJ MANAG	Index	1.76	–	1.09	67	2.94	127	189	74	91	**23.12**
		Rank	15	67.5	19	14	8	13	13	12	12	
(2)	OMEGA-INT J MANAGE S	Index	3.19	3.63	3.62	75	1.66	136	242	83	101	**8.13**
		Rank	5	6	3	10	24	9	9	10	10	
(3)	Eng Constr Arch Manag	Index	–	–	0.47	20	1.43	48	66	25	30	**47.12**
		Rank	68	67.5	37	39	29	34	41	36	38	
(4)	Measurable News	Index	–	–	–	–	0.32	11	21	9	10	**70.88**
		Rank	68	67.5	76	77	71	73	65	63	70	



(a) Example penalty score calculation for Journal Impact Factor of 2013 (JCR). Numbers between brackets refer to table 1.



(b) Total scores of the journals with (black) and without (gray) an impact factor for 2013 (JCR). The best scoring half was accepted in the classification while the other half was rejected. Numbers between brackets refer to table 1.



(c) Journals (JCR abbreviation Reuters (2014)) and number of articles in classification. Journals indicated with (∗) are not included in the Web of Science database.

Fig. 2. Journal selection procedure.

Subsequently, one overall score is calculated for each journal by weighting the separate scores based on the number of indices that were taken into account per database, such that each database is of equal importance to the final score. Thus, the score for the impact factors of the Web of Science and the indices corresponding to the Scopus database got a weight of 0.5, since for each database two indices were taken into account, whereas the indices calculated based on the Google Scholar database are assigned a weight of 0.2. The final score of the first journal in Table 1 is thus calculated as follows: $\frac{0.5\times(15+67.5)+0.5\times(19+14)+0.2\times(8+13+13+12+12)}{3}=23.12$.

Finally, a histogram (Fig. 2(b)) was created in order to decide which journals to incorporate into the classification framework and which ones not. The two distinct groups in Fig. 2(b) confirm the premise that indexation in the Web of Science is a good indicator of academic quality. We used the median of the scores as a cut-off value, such that journals that score well but are not indexed in the Web of Science will still be included in the classification. The third journal in Table 1, for instance, was not present in the Web of Science database. Nevertheless, because its overall score was lower than the median, it was included in the classification after all. This procedure has resulted in the decision to include all journals indexed in the Web of Science and five journals that were not. With respect to the collected articles, 40% of the updated dataset, or 187 papers, were retained for classification, which means that 268 of the 455 articles were discarded (Fig. 1). An overview of all accepted journals and corresponding number of papers included in the classification is available in Appendix B.

Fig. 2(c) indicates the selected journals with at least two publications in our review. The journals with only one publication are grouped in the category “Others”. The figure clearly shows that the International Journal of Project Management is the leading journal in the project control domain with 41 publications in our overview. Turner (2010) provides an overview of the topics covered in this journal. Furthermore, the table indicates that many other international journals have published articles in this research field.

Although we only considered the best-ranked journals in our classification, references to articles in other journals are given throughout the text when appropriate and/or necessary. The literature search has finally resulted in 187 papers, each of

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which is classified according to the six classes that will be discussed in Section 3.

3. Classification framework

The second objective of this literature review is to classify the relevant papers according to some suitable classes. After collecting and processing all articles within the defined scope (Section 2.1) and satisfying the journal constraint (Section 2.2), we developed a classification framework (Fig. 1) in collaboration with a team of PhD students and practitioners. This framework is based on the following six classes: (i) the research problem, (ii) the contribution, (iii) the methodology, (iv) the analysis, (v) the validation and (vi) the application of the paper. As illustrated below, each class represents a typical aspect of an academic research paper.

(i) *Research problem*: The problem for which the paper will attempt to provide an answer. This class divides journals based on issues related to the assumptions underlying EVM, the problems encountered during project progress and the practical problems and difficulties in managing (multiple) projects.

(ii) *Contribution*: The contribution or goal constitutes the main research topic of the paper. This class distinguishes between five categories: general project control, performance evaluation, forecasting, triggers for action and project control tools.

(iii) *Methodology*: The methodology indicates the techniques used to achieve the proposed goal or contribution of the paper. Since different methodologies are often compared to accomplish a given research goal, the paper can be allocated to one or more of the following subclasses: observational analysis, extended EVM analysis, statistical analysis, artificial intelligence and computerized analysis.

(iv) *Analysis*: The analysis represents the degree of uncertainty that is incorporated into the methodology, ranging from purely deterministic techniques to highly stochastic procedures. In this review, we will distinguish between deterministic, fuzzy and stochastic techniques.

(v) *Validation*: In order to validate the proposed methodology, data needs to be collected. This information can be gathered from historical case studies, or generated using Monte-Carlo simulations. Alternatively, qualitative data, such as questionnaires or surveys, can validate a statement.

(vi) *Application*: The application represents the area in which the author has claimed that the method can reliably be applied. The literature most often deals with construction projects and to a lesser extent with transportation and IT projects. The variety of application areas is partitioned into the private sector, the public domain and general projects.

The following sections each discuss one class and elaborate on the details of the subclasses. These subclasses are further divided into items, the abbreviations of which are indicated in the text as (*Abbr*). The same abbreviations will be used in the summary table in Appendix A. The general structure of the classes, subclasses and items, including abbreviations, is illustrated in Fig. 2. For example, "WBSdet" is the first item of the subclass "EVM assumptions" in the "Research problem" class.

In the text, references are included to invigorate a statement or to illustrate a remark, but we refer to Appendix A for a complete list of relevant articles. This table provides an overview of all retained papers, as described in Section 2, and their corresponding items for each class. Whenever deemed necessary, multiple items within the same class are provided. Moreover, this table indicates whether a paper was published in the Web of Science database or not, by the use of upper and lower case letters for the respective journal. That is, the JCR abbreviations (Reuters, 2014), in upper case letters, are applied for journals indexed in the Web of Science database, while similar lower case abbreviations are used for journals which are not.

The objective of this classification framework is to categorize all papers, withheld from the journal selection procedure, in comprehensive categories on three levels. The first level is the point of view from which the classification is interpreted. We consider six classes, which are segmented in subclasses at the second, more detailed level. These subclasses are broad research categories, which are further subdivided in items at the third and most specific level. The relations between these items within their (sub)class and across (sub)classes will be the subject of Section 4.

3.1. Research problem

The main goal of project management and project control in particular is to finish a project within budget and before a specified deadline, while fulfilling customer requirements. The earned value management methodology was developed with the ambition to integrate cost, time and scope in order to effectively and efficiently monitor and control a project during execution. However, both researchers and practitioners have been experiencing issues concerning its underlying assumptions and its practicability. These obstacles have resulted in the application of new approaches and adapted techniques originating from other research areas, such as Bayesian statistics and artificial intelligence techniques. They all attempt to enhance one or multiple aspects in the project control cycle and assist the project manager in his/her control tasks. As Fig. 3 illustrates, these endeavors can be subdivided in the following categories: (i) EVM assumptions and issued in the preparatory phase, (ii) impediments during project progress, and (iii) challenges managing (multiple) projects.

3.1.1. EVM assumptions and issues in the preparatory phase

3.1.1.1. Work breakdown structure. Before project initiation, a work breakdown structure (WBS) should be constructed, decomposing the project in manageable work packages. The threshold at which this partitioning process comes to an end is rather ambiguous and largely based on rules of thumb, advocating for logical and clear-cut units which can easily be assessed (WBSdet). In realistic projects, however, it is virtually

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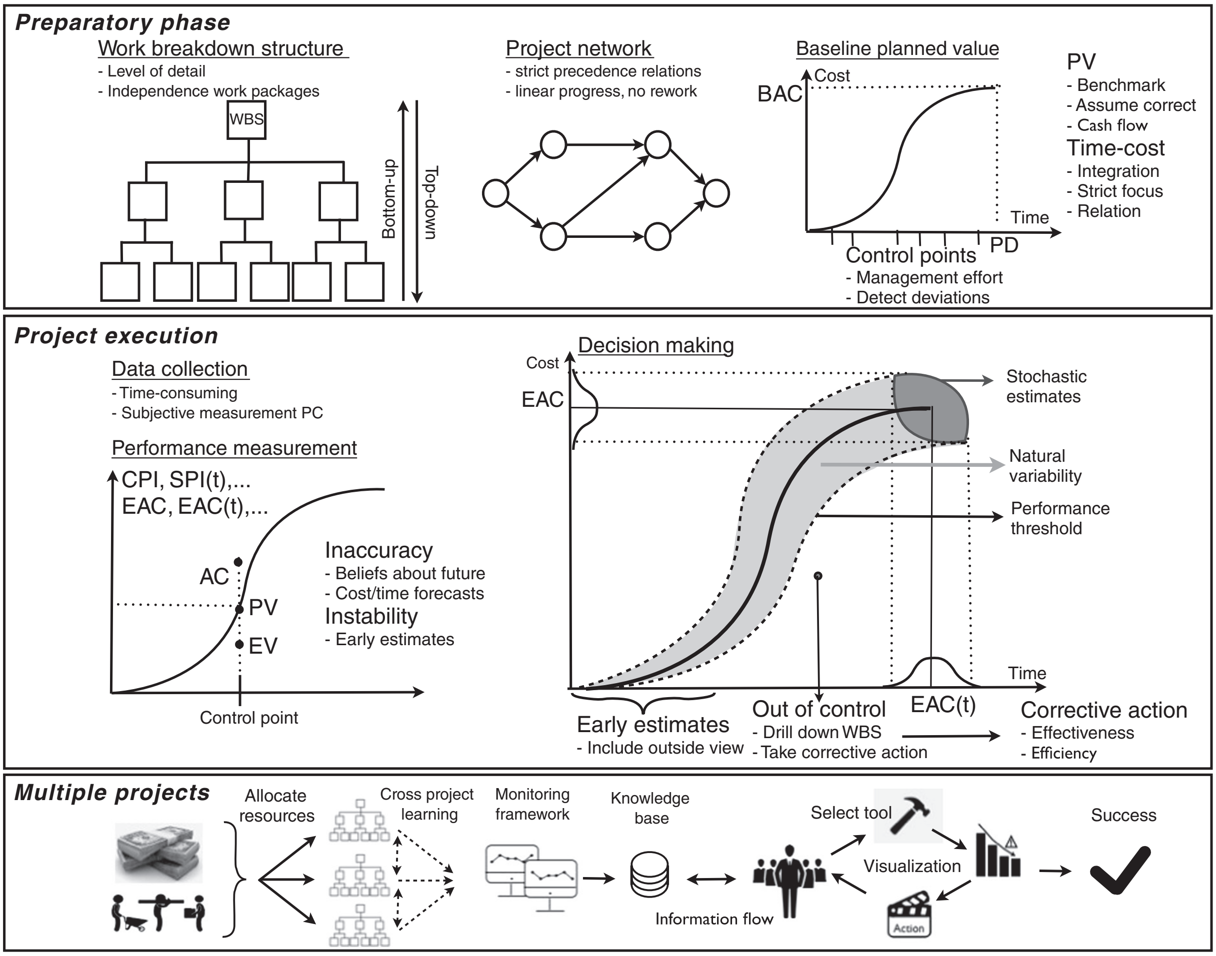

Fig. 3. Graphical presentation of the main aspects of the planning and execution phases of a project and the management of multiple projects.

impossible to define work packages such that they are all fully independent of each other. Although not incorporating these correlations could ensue considerable estimating errors, this cumbersome task is often neglected in literature (WBSind).

Based on the WBS, two opposing methods can be applied with the aim of controlling a project during execution: a top-down and a bottom-up approach (Vanhoucke, 2011). The EVM methodology is based on the former, as it defines performance measures on the project level and only suggests to drill down into the WBS when indicators signal poor performance. The latter approach defines tolerance limits on the activity level, which can be considered more accurate at the expense of additional effort for the project manager, especially in a multi-project environment. Consequently, a trade-off between accurate problem detection and control effort should be established for the project at hand (WBStd).

3.1.1.2. Project network. After organizing the WBS, a project network can be composed, linking the work packages by means of precedence relations (Netw). Most project control techniques, EVM included, assume strict precedence relations between the work packages or activities. This practice emanates linear progress in project execution. In reality, however, techniques such as fast-tracking are used to shorten the project duration in response to early warning signals. The idea behind this approach is to reschedule activities in parallel instead of in series, overlapping activities that were previously connected by precedence relations. This inevitably comes at the risk of rework because of the disrespected dependencies between the activities. Recursive cycles in project execution can accommodate for this issue.

3.1.1.3. Baseline planned value. A third step in preparation of project execution is the establishment of a baseline schedule or planned value (PV). This planned value is primarily used as a benchmark for actual performance, assuming that no scope changes occur during execution. Reality has learned, though, that this assumption does not hold in a considerable amount of cases. Causes, consequences and solutions have been discussed in the literature (PVchang). Besides acting as a benchmark, the planned value can give an indication of the expected cash flow balance during execution (PVcash). Indeed, negative cash flow statements regularly occur in practice due to misalignment of costs to be paid and revenues to be received. In order to anticipate these cash shortages, expected cash flow curves have been constructed based on historical data and information on the project itself. Additionally, fostering contractor–client relations by integrating cost and payment mechanisms can ensure a steady cash flow balance (Client).

The EVM framework is often praised for its ability to integrate time, cost and scope (TCint), yet a number of other parameters contribute to the success of a project, such as quality, sustainability and net present value (TCfocus). With respect to quality, EVM does implicitly incorporate this aspect as the progress of a project, though only allowing for linear quality accrual. As a response to the critique on the strict time–cost focus of EVM, Kim et al. (2014a) and Paquin et al. (2000), among others, integrate time and cost control with sustainability and quality control respectively. Furthermore, the use of cost as a proxy to measure time performance has raised concerns (Khamooshi and Golafshani, 2014), resulting in attempts to disentangle both factors while preserving the integrated character of the EVM concept (TCrel). During project progress, the EVM methodology dictates that the project should be monitored on a regular basis. Research on the optimal timing of control points (CP), however, indicated that appropriately allocated control points along the duration of the project can increase management effectiveness and efficiency. In this respect, the trade-off between management effort and deviation detection is crucial to making an informed decision.

3.1.1.4. Practical issues. Summarizing, a number of issues have been raised concerning the practical applicability of the EVM methodology and alternatives have been presented. Case studies on project control have supported these implementation issues, but also show the benefits of the EVM approach (EVMissue).

3.1.2. Impediments during project progress

3.1.2.1. Data collection. During the execution phase, data needs to be gathered in order to assess current performance (Data). As this process is generally very time-consuming and error-prone, the trend to employ automated techniques is increasing, especially in large construction sites. For tracking purposes, radio-frequency identification (RFID) and ultra-wide band (UWB) are common technologies to readily collect and process information regarding the use of resources (Azimi et al., 2011). Actual progress measurement, on the contrary, is a difficult and rather subjective task and is regularly assisted by advanced sensing and imaging technologies (Golparvar-Fard et al., 2009) or fuzzy sets (Moslemi Naeni and Salehipour, 2011).

3.1.2.2. Performance measurement. Using the data gathered, the current performance can be measured and compared to the baseline schedule. Planned and earned values and actual costs are updated at each control point and performance measures, such as SPI(t) and CPI, are computed. When unexpected events during execution occur, performance measures should timely warn the project manager. Recovering from disruptions and delays generally does not go without effort, though, and according to Brook's law, any attempt can even make the (software) project later (Cioffi, 2006a). Because of this anomaly, expectations about future performance are often unrealistic and arbitrary. Yet, efforts have been done to estimate the probability that a project will be delivered on time and within budget (Future) and to increase accuracy of time and/or cost forecasts (ACCfor). These endeavors will be covered in Section 3.2. Besides being inaccurate, forecasts are usually also unstable (Stabil). In their research, Christensen and Heise (1993) and Zwikael et al. (2000) investigated the instability of EVM indicators early in the project life. Although they produce diverging results, it is clear that the traditional EVM performance indicators, CPI, SPI and SPI(t), cannot be used to produce reliable forecasts in what is often referred to as the most important stage of the project. One of the main reasons for the instability of early forecasts is the fact that EVM assumes that past data on the current project is the best available information (ACCearly). As a result, the method only relies on historical and objective information, even though this kind of information is hardly available in the early phases of the project (Gardoni et al., 2007). To alleviate this problem, the outside view, comprising more subjective data, such as expert opinions or data on other similar projects, could be incorporated. Techniques to deal with this and other problems are discussed in Section 3.3.

3.1.2.3. Decision making. Although the EVM performance measures indicate whether a project experiences cost overruns or delays, they do not inform the project manager about whether or not these deviations are within the limits of the project's expected variability (Pajares and López-Paredes, 2011). Indeed, EVM deterministically forecasts time and cost at completion and represents both inputs and outputs by point estimates (Det). The discrepancy between deterministic and probabilistic techniques will be clarified in Section 3.4. An assessment of the actual performance against the probability distribution of time and cost might consider the project's natural variability more appropriately than a deterministic approach. That is, only when a threshold on acceptable performance is defined, out-of-control (OOC) performance can be detected at some confidence level. When early warnings have been issued, it is the project manager's task to take contingent actions in an attempt to bring the project back on track (Action).

3.1.3. Challenges managing (multiple) projects

Ordinarily, a project manager, or his/her team, is responsible for multiple projects being executed in parallel, in which case a range of additional issues arise. Scarce resources should be allocated to the projects (Res) and an efficient information flow to all relevant parties is even more important to effective decision making (Flow). Notwithstanding the efforts done to reorganize projects by introducing for example agile and scrum development, project failures are common, especially in the IT sector (IT). As a result, the effectiveness (PMeff) and practical applicability (PMapp) of project management tools and techniques have been scrutinized in order to facilitate the selection of appropriate methods.

Besides successful project completion, the overall objective of the project manager (team) is to build a knowledge base in the organization (Know) in order to share expertise across departments and indulge in cross-project learning (Learn). An automated monitoring framework (Auto), integrating an information system with database technology and automated sensing techniques, as well as visualization techniques (Visual), such as control charts and other graphical presentations, can assist in the project manager's decision process.

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3.2. Contribution

The papers taken into consideration cover a wide range of different research topics and contributions to the EVM community. Every research paper attempts to fill a gap in the literature and provide added value to the targeted research domain. To this purpose, the research territory is to be determined first. In this overview, all papers are operating in the project control field. Subsequently, a need is established in this domain, representing the niche in which the author will operate. We consider five distinct niches in the project control domain: (i) general project control, (ii) performance evaluation, (iii) forecasting techniques, (iv) triggers for action and (v) project control tools. The researcher ultimately attempts to fill the selected gap or niche by presenting his/her original research idea.

Whereas Section 3.1 addressed the problems that gave rise to new researches, this section will discuss the contributions to literature that have attempted to deal with those issues. For instance, the deterministic nature of EVM (research problem) has been approached from different angles. On the level of performance evaluation, improvements to the traditional indices (contribution) have been proposed by introducing fuzzy indices (methodology). With respect to forecasting (contribution), stochastic S-curves (methodology) have been developed in order to take into account uncertainty while predicting time and cost at completion. The most common links between the different classes will be discussed in Section 4.

3.2.1. General project control

As already indicated in Section 3.1, a variety of issues regarding the implementation and practical applicability of the EVM methodology and other project management techniques have been investigated (Gen).

3.2.2. Performance evaluation

With respect to performance evaluation, improvements to the traditional EVM indices, CPI, SPI and SPI(t), have been proposed. Although most papers on such measurement and control systems (Measur) deal with time and cost only, some do also explicitly incorporate quality as an objective that needs monitoring. The literature on this topic is still scarce though, and additional effort should be done to effectively make quality a third control variable. Until now, research on quality integration has mainly focused on the scheduling phase. Index-based improvements (Index) represent enhancements to the traditional deterministic approach of EVM and are predominantly established by creating fuzzy indices, incorporating risk measures or adjusting the indices to a specific context.

3.2.3. Forecasting

In order to keep a project under control, its progress should be monitored closely. This involves estimating the future progress and making cost and time forecasts before the project is finished. Regression analysis and growth models are frequently applied to estimate the shape of the S-curve and plan cash in and outflows (Cash). Extrapolating the S-shape toward the project completion point, results in an estimate for time and cost at completion. However, intrinsically different approaches, such as Bayesian forecasting, the Kalman filter and neural networks, serve the same goal without any prior assumptions about the shape of the underlying progress curve (Cost, Time). More information on these techniques is provided in Section 3.3. In addition to cost, time and cash flow forecasting, two extensions that aim to assist the project manager in his/her control tasks have been covered. They include determining and enhancing the forecast accuracy (Acc) and predicting project success during progress (Succ). The latter category mainly includes papers calculating the performance necessary during the remainder of the project to finish it successfully.

3.2.4. Trigger for action

As indicated in Section 3.1, control intervals do not necessarily need to be equidistant from each other, but can be front or end loaded instead to increase efficiency of management effort (CP). EVM is commonly used to detect cost and schedule deviations during project progress and to forecast time and cost at completion. However, it falls short in distinguishing natural variability from systemic deviations from the project plan. Indeed, the natural variability inherent in each project is not taken into account in the EVM methodology. Alerting the project manager when actual deviations occur should, however, be subject to the expected behavior of the project. The applied thresholds, or the minimum deviation from the plan at which an early warning signal is to be issued, should thus be based on a distribution around the expected progress rather than a point estimate. Whenever performance falls outside the thresholds, a warning signal notifies the project manager of possible problems (EW), upon which the manager can decide on corrective actions (Action).

3.2.5. Tools

A number of tools to apply EVM and other project control mechanisms in practice have been suggested (Tool). These mostly computerized applications encompass automated project-tracking tools such as laser scans (Turkan et al., 2013), sophisticated sensors, RFID tags or GPS signals (Navon, 2005). Additionally, other digital approaches, such as information systems or database technology assist project managers in keeping the project under control.

3.3. Methodology

A variety of methodologies have been applied to provide an answer to the research problems covered in Section 3.1 and to achieve the different research contributions listed in Section 3.2. Some approaches have been implemented for a specific research purpose, while others have been used to achieve a range of different objectives. The different methodologies to attain a certain research objective can be subdivided in five comprehensive categories: (i) observational analysis, (ii) extended EVM analysis, (iii) statistical analysis, (iv) artificial intelligence and (v) computerized analysis.

3.3.1. Observational analysis

Articles adopting observational analysis present their results based on a literature survey (Lit) or empirical investigation. In the latter category, a distinction is made between case studies and surveys on general trends in project control. Case studies (Case) deal with clearly defined projects within one or several companies, while management surveys (Man) summarize insights from practitioners, managers or other experts.

3.3.2. Extended EVM analysis

Most articles in our dataset explicitly apply traditional (EVM) or adapted EVM metrics in order to increase forecasting accuracy, incorporate uncertainty or risk, combine multiple indicators in one measure or better fit a specific environment (Context). These new or accustomed indices can either be deterministic (IndexD), providing point estimates, or probabilistic (IndexP) interval estimates. Probabilistic measures include the common statistical distributions as well as fuzzy sets.

3.3.3. Statistical analysis

Statistical analysis can be regarded as a broad concept. On the one hand it includes traditional statistical techniques (Stat), like hypothesis testing, analysis of variance, factor analysis and data envelopment analysis. On the other hand, statistical analysis also comprises curve fitting techniques, statistical control charts and Bayesian statistics.

3.3.3.1. Curve fitting. Curve fitting techniques are applied in order to plan and control the financial performance of a project (Blyth and Kaka, 2006). Instead of only providing an estimate at completion, like EVM does, these methods aim at predicting the cash in and outflows over the entire project life. It might indeed be interesting to know when cash shortages could occur and what their size will be. Regression analysis and growth models provide a means to fit estimated data points to an S-curve (CurveD) (Kenley and Wilson, 1986). However, these curve-fitting techniques do not provide a confidence interval around its estimates. In contrast, stochastic S-curves fill this gap by providing probability distributions for expected performance for a given project completion point. These graphical techniques allow for probabilistically assuring an acceptable final project performance (CurveP) (Barraza and Bueno, 2007).

3.3.3.2. Statistical control charts. Introduced by Shewhart (1931), these charts were originally developed to safeguard the quality in manufacturing processes. Recently, however, they are being applied for project control purposes as well. The main objective is to discern natural variability from systemic variation in order to issue early warning signs when the project progress is in danger (Chart).

3.3.3.3. Bayesian statistics. Based on Bayes' theorem, proposed in the seminal paper by Bayes and Price (1763), conditional probabilities are applied to plug in both the inside and the outside view into the recursive procedure to forecast cost and time at completion (Bayes). The inside view only incorporates information on the project itself, while the outside view utilizes information based on expert knowledge and historical data of similar projects. The Kalman filter (Kalman, 1960), a special case of Bayesian inference, aims at reducing noise in measurement systems, and has been applied in combination with EVM.

3.3.4. Artificial intelligence

Artificial intelligence covers a range of techniques that mimic the human brain. Turing (1950) was one of the first in literature to contemplate about the ability of machines to learn as humans do. Consequently, the objective of artificial intelligence techniques is to make a machine learn from experience in order to apply this knowledge in new situations. Three main items, neural networks (NN), support vector machines (SVM) and other knowledge based systems (KBS), are considered that generalize experience from past projects to be used in new ones. Although these artificial intelligence techniques are commonly used in cost (and time) forecasting before the start of a project, their use is less investigated in updating these forecasts in order to control project performance.

3.3.5. Computerized analysis

Techniques to either simulate data or to automate the project control process are classified as computerized analysis. Monte Carlo simulations (Sim), introduced by Metropolis and Ulam (1949), allow for an elaborate investigation of possible project outcomes while incorporating risk and uncertainty. Section 3.5 provides additional information on validating a methodology using simulated data. Information systems and automated processes (ISA) can significantly improve the efficiency of operational activities. A first step in digitalizing the project control process often consists of implementing a software package or comprehensive information system. Additionally, the data collection process can be automated by the use of 3D imaging techniques as has been done in Turkan et al. (2013).

3.3.6. Miscellaneous

Critical chain in project management, genetic algorithms, dynamic programming and other optimization models are examples of methodologies that have only been encountered once or twice in combination with EVM or project control (MISC).

3.4. Analysis

The analysis, which has been performed in order to achieve the research goal, is generally quantitative in nature. Some papers take into account the uncertainty inherent to each project by using statistical distributions and are therefore labeled as stochastic. These stochastic techniques are able to issue early warning signals based on the expected behavior of the project. Others solely rely on average or expected values in their calculations and are thus labeled as deterministic. Recently, the application of fuzzy techniques has gained popularity because of its probabilistic yet intuitive approach. Consequently, regarding the degree of uncertainty, a distinction can be made between (i) deterministic, (ii) stochastic and (iii) fuzzy methods.

3.4.1. Deterministic

In this paper, a deterministic approach (Det) is defined as a technique that results in point estimates. Consequently, a methodology is regarded as deterministic if its output is deterministic, even though its inputs might be stochastic. EVM, for example, is a deterministic technique, but probabilistic extensions to its measures are not.

3.4.2. Stochastic

Stochastic techniques (Stoch) incorporate a larger degree of variation than deterministic methodologies. Instead of providing point estimates, the result consists of distributions and confidence intervals around the estimates. Stochastic S-curves, for example, provide upper and lower bounds, which indicate the acceptable range for outcomes based on the uncertainty about the estimates and the risk involved.

3.4.3. Fuzzy

When data are not only imprecise but also vague, they can be represented by fuzzy numbers and manipulated by fuzzy methods (Fuz) (Zadeh, 1965). The "Percent Complete", for example, will not always be expressed as a fixed number but will instead be described in linguistic terms. Subsequently, a membership function translates these terms into fuzzy numbers. Finally, a defuzzification method can be used to evaluate and compare these fuzzy numbers.

3.5. Validation

In order to prove the validity of the proposed methodology, it should be tested extensively on a number of realistic projects. We distinguished the following three categories to accomplish this: (i) historical real-world data, (ii) simulated data and (iii) qualitative data. Some authors test their model on historical as well as simulated data. This, however, is not standard practice but could invigorate the validation process.

3.5.1. Historical real-world data

Historical datasets are based on real-world case studies on projects performed by actual companies. Most tests are based on historical data originating from construction projects. A distinction is made between a small dataset (HisS), running from 2 until 100 projects, and a large dataset (HisL) with more than 100 projects. Datasets only containing one case study are classified as qualitative data.

3.5.2. Simulated data

Simulations accompanied by a proper testing framework provide a scientific validation of the method (SimS, SimL). The number of generated project networks and the number of runs should, however, be large enough to cover all likely events. Typically, such simulations are performed by the Monte Carlo method, based on random sampling.

3.5.3. Qualitative data

Papers only presenting one example (One) or a case study on a single project are regarded as qualitative data, since this is insufficient to assert the superiority of the proposed method over existing ones. These cases merely provide an illustration of the proposed methodology. In addition, questionnaires or surveys (Que) are also considered as qualitative data.

3.6. Application

Although most projects encountered in this literature review involve large construction sites, project control techniques have been applied and tested in a number of other application areas. We discern three main categories: (i) the private sector, (ii) the public domain and (iii) general projects. The first subclass represents projects providing private goods as output and includes among others the aforementioned construction projects. The second subclass, on the contrary, comprises public goods provided by a national government to its citizens. Economists have distinguished a public good from a private good by two characteristics: its non-rivalry consumption and its non-excludability (Hummel, 1990). First, consumption of a public good by one customer does not prohibit consumption by another customer. Second, providing the public good to one customer automatically provides it to others.

3.6.1. Private sector

Apart from construction projects (Constr), other applications, like software development (ITS) and production processes (Prod), provide private goods to consumers and enterprises. IT projects are often delayed or barely fulfilling customer requirements. Project control mechanisms are thus indispensable in order to decrease the number of failures and its associated cost. Other applications can be found in multi-project environments (Multi) and high-tech and engineering projects (HT).

3.6.2. Public domain

Projects concerning public goods are subdivided into transportation projects (Trans) and other governmental projects (Gov). The latter comprises defense, aerospace, nuclear power plants and environment-related projects. National defense is presumably the best-known example of public goods, but other governmental institutions provide public goods as well. Additionally, transportation facilities require a tight schedule and careful monitoring since delays can result in major economic costs.

3.6.3. General projects

Articles on general projects (Gen) mainly focus on theoretical models, which do not target a specific industry. Other papers included in this category do not explicitly mention a specific application area. For these reasons, the techniques proposed in these papers are assumed to be generally applicable.

3.7. Classification summary

The classification framework discussed in Sections 3.1 to 3.6 comprises six classes: research problem, contribution,

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methodology, analysis, validation and application. Each class is divided in subclasses, which are further broken down into items. All papers withheld from the journal selection procedure have been classified according to this structure. Appendix A presents a table containing these articles along with the corresponding items for each class. Whenever deemed applicable, we attributed multiple items to a class for a single paper. Abbreviations of the items and their position in the framework relative to the classes and subclasses are provided in Fig. 2. In Section 4, this classification framework will be used to extract trends in current research and to make recommendations for future research.

4. Future research

The third and last objective of this paper is to identify current trends and possible gaps that could shape future research in this promising field. Algorithm 1 discusses the procedure we applied to distill trends and gaps in literature from the classification framework. In Table 3, the combinations of (sub)classes and items we encountered most are listed and possible avenues for the future are proposed. In general, four recommendations can be made with respect to the design of future research: (i) include uncertainty into the method, adding a stochastic component, (ii) test the methodology extensively either on a large historical database or using a simulation experiment, (iii) integrate existing methods with other objective functions than time and cost alone, and (iv) develop and evaluate corrective action procedures.

Algorithm 1. Procedure for finding trends and gaps in literature

Notation
k: number of classes that have been combined, $k = 1, \ldots, 6$
$combination_k$: a specific combination of k subclasses from k different classes
$Nr(combination_k)$: number of occurrences of $combination_k$
$Nr(subclass_j)$: number of papers assigned to $subclass_j$

Step 1: Analysis per individual class

$k \leftarrow 1$
for each $subclass_j$ in $class_i$ **do**
  if $\frac{Max_x Nr(subclass_x) - Nr(subclass_j)}{Nr(papers)/Nr(subclasses)} > 1$ **then** save as possible gap
  end if
end for
$k \leftarrow k + 1$

Step 2: Recursive procedure

for each $combination_k$ of k classes **do**
  if $Nr(combination_k) \geq$ threshold **then**
    save as possible trend
    $k \leftarrow k + 1$
    if $k \leq 4$ **then** go to step 2
    end if
  else if $k \geq 3$ **then** save as possible gap
  end if
end for

Step 3: Qualitative analysis

for all saved possible trends and gaps **do** check relevance
end for

4.1. Trend and gap selection

4.1.1. Step 1: analysis per individual class

Based on the classification framework developed in Section 3, we extracted trends in current research and gaps that could be interesting for future research avenues. As indicated in

Table 2
Classification framework defined by six classes and corresponding subclasses and items.

Research problem (P)			
Preparatory phase (Prep)	WBSdet	Detail WBS	7
	WBSind	Independence work packages	2
	WBStd	Top-down or bottom-up level	2
	Netw	Precedence relations in network	4
	PVchang	Changes in baseline during execution	3
	PVcash	Negative cash flow balance	18
	Client	Contractor–client interaction	6
	TCint	Time–cost integration	9
	TCfocus	Time–cost focus	12
	TCrel	Time–cost relation	3
	CP	Control points	9
	EVMissue	Implementation issues EVM	19
Project execution (Exe)	Data	Time-consuming data collection	14
	Future	Inaccurate view on future performance	5
	ACCfor	Inaccuracy forecasts	13
	Stabil	Instability forecasts	5
	ACCearly	Inaccurate early forecasts	9
	Det	Deterministic nature EVM	17
	OOC	Detect out-of-control performance	8
	Action	Corrective action decision making	6
Multiple projects (Multi)	Res	Resource allocation	2
	Flow	Inefficient information flow	12
	IT	IT failure	3
	PMeff	Effectiveness PM tools	5
	PMapp	Implementation issues PM	4
	Know	Build knowledge base	2
	Learn	Cross project learning	3
	Auto	Automated monitoring framework	5
	Visual	Visualization control process	4
Contribution (C)			
General (Gen)	Gen	General project control	28
Performance (Perf)	Measur	Measurement and control systems	39
	Index	Index-based improvements	10
Forecasting (For)	Cash	Cash flow forecasting	19
	Cost	Cost forecasting	18
	Time	Time forecasting	21
	Acc	Forecast accuracy	6
	Succ	Predict project success	7
Trigger for action (Trigger)	CP	Control points	10
	EW	Early warnings	18
	Action	Action procedures	3
Tools (Tool)	Tool	Decision support tools	32
Methodology (M)			
Observation (Obs)	Lit	Literature review	10
	Case	Case study analysis	17
	Man	Management surveys	11
EVM (EVM)	EVM	Traditional EVM	28
	Context	Adapt EVM to specific context	9
	IndexD	New deterministic indices	11
	IndexP	New probabilistic indices	8
	EVMmisc	Miscellaneous EVM	2
Statistics (Stat)	Stat	Traditional statistics	9
	CurveD	Deterministic curve fitting	19
	CurveP	Probabilistic curve fitting	9
	Chart	Statistical control charts and tolerance limits	7
	Bayes	Bayesian statistics and Kalman filter	10
Artificial intelligence (AI)	NN	Neural networks	6

(continued on next page)

Table 2 (*continued*)

	SVM	Support vector machines	4
	KBS	Knowledge based systems	1
	Sim	Simulation model	14
Computer (Comp)	ISA	Information system and automation	35
Misc.	MISC	Miscellaneous	14
Analysis (An)			
Det		Deterministic	112
Stoch		Stochastic	31
Fuz		Fuzzy	13
NA		Not applicable	31
Validation (V)			
Historical (His)	HisS	Small (2–100 projects)	62
	HisL	Large (>100 projects)	9
Simulated (Sim)	SimS	Small (2–100 projects)	10
	SimL	Large (>100 projects)	14
Qualitative (Qual)	One	Single example or notional data	64
	Que	Questionnaire or survey	14
NA	NA	Not applicable	18
Application (Ap)			
Private sector (Priv)	Constr	Construction industry	88
	ITS	IT and software development	7
	Prod	Production environment	1
	Multi	Multi-project environment	3
	HT	High-tech and engineering	7
	MISC	Miscellaneous	4
Public sector	Trans	Transportation	4
	Gov	Government	7
General (Gen)	Gen	General/not specified	66

Algorithm 1, a first step in our search procedure is to look at the classes individually and select those subclasses that have received very little research attention relative to the other subclasses in this class. Since we only consider one class at a time, the level k, or the number of combined classes, is equal to one. Subclasses containing few papers in comparison to the other subclasses in that class have a high probability of being overlooked at the next levels. Indeed, a combination of a subclass with low occurrence with any other subclass will result in an even lower, or at most equal, number of occurrences. Therefore, this subclass will most likely not be selected as part of a possible trend or gap in *Step 2* of the algorithm. For this reason, a preliminary search for gaps at the first level was performed. The class "Analysis", for example, consists of 112 deterministic, 31 stochastic, 13 fuzzy and 31 papers without quantitative analysis. The stochastic subclass is saved as a potential gap, because $\frac{Max_x Nr(subclass_x) - Nr(subclass_j)}{Nr(papers)/Nr(subclasses)} = \frac{112-31}{187/4} = 1.7 > 1$. A threshold equal to zero means that all subclasses contain an equal number of papers. However, papers are never distributed exactly equal over the subclasses. In order to avoid saving too many possible gaps, we experimented with different values for the threshold and finally opted for a threshold equal to one. After qualitative analysis in Step 3, we retained four gaps at the first level ($k = 1$ in Table 3): stochastic and fuzzy analysis, validation on simulated data and artificial intelligence techniques.

4.1.2. Step 2: recursive analysis

The objective of the recursive procedure in the second step of Algorithm 1 is to find combinations of subclasses that regularly occur together. As level k increases, more details on the possible trend become available. However, we limited the search to combinations of four subclasses ($k = 4$), because higher level combinations are too detailed. Moreover, the number of occurrences per combination becomes quite low when k increases. For k equal to six, a maximum of eight papers present the same combination ($Nr(Combination_{k=6}) \leq 8$), while this was still 21 for level four ($Nr(Combination_{k=4}) \leq 21$).

We started with combinations of two subclasses originating from two different classes ($k = 2$). If the number of occurrences at level k, $Nr(combination_{k=2})$, is above a certain threshold, the combination is saved as a possible trend and k is raised by one unit. The value for the threshold depends on the level k, as well as the number of subclasses in the combined classes. If k is still smaller than four, Step 2 is repeated and new combinations with the subclasses of the remaining four classes are considered. On the other hand, if only a few papers remain and k is at least equal to three, the combination is saved as a possible gap and a new combination is considered for evaluation.

Note that a combination is only saved as a potential gap if the number of occurrences at level k falls below the threshold, but exceeds the threshold at level $k - 1$. For example, with 28 occurrences at level $k = 2$, the combination of EVM based methodologies and performance evaluation is considered as a potential trend. Investigation at the third level, however, disclosed a gap within this trend. Indeed, of these 28 papers, only 5 present stochastic or fuzzy bounds on the estimates. Because this small subset at level $k = 3$ originates from a large set obtained at level $k = 2$, probabilistic EVM performance evaluation is saved as a gap.

Summarizing, gaps are not merely defined as a set of subclasses with little to no research, as this would result in a very large set of possible gaps. Instead, a gap selection constraint is imposed, requiring that a significant amount of research has been done on a subset of these subclasses at level $k - 1$. The gap identified in the example above combines subclasses of three different classes ($k = 3$): contribution, methodology and analysis. When only contribution and methodology are considered ($k = 2$), however, a much larger number of occurrences was observed. Consequently, the examined gap satisfies the gap selection constraint. Since the level at which the gap was found is equal to three, the selection is also conform to the additional restriction to only save gaps as from the third level.

4.1.3. Step 3: qualitative analysis

Evidently, not all trends and gaps that were saved in the previous steps are relevant. For instance, combinations between miscellaneous and non applicable subclasses were discarded. Furthermore, a single trend can be evaluated from different perspectives and thus, they appear multiple times in the saved trends and gaps. From those double counts, we chose the combinations that could be interpreted most logically.

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Table 3
Current trends and opportunities for future research.

k	P	C	M	An	V	Ap	#	Trend	Gap
1	–	–	–	**Stoch**	–	–	**31**	–	**Increase incorporation uncertainty in data, especially for action taking**
2	Exe	–	–	Stoch	–	–	24/31	Counter deterministic nature EVM, detect OOC, action procedures and instability indicators	
2	–	For Trigger	–	Stoch	–	–	30/31	Uncertainty incorporation for forecasting and triggers for action	Elaborate this research trend
3	–	For Trigger	Stat Comp	Stoch	–	–	27/30	SS-curves, Bayes, charts and tolerance limits and simulation models	
2	–	–	–	Stoch	–	Priv	16/31	Private projects: mainly construction	
1	–	–	–	**Fuz**	–	–	**13**	–	**Test benefit incorporation vagueness in data on large database**
2	Prep Exe	–	–	Fuz	–	–	10/13	Counter deterministic nature EVM and cash flow prediction	
2	–	Perf For	–	Fuz	–	–	12/13	Performance evaluation and forecasting	In contrast to stochastic techniques, not explicitly used to trigger for action
2	–	–	EVM	Fuz	–	–	7/13	Extensions to EVM indices	
2	–	–	–	Fuz	One HisS Que	–	13/13	Small dataset	Test on large dataset
1	–	–	–	–	**Sim**	–	**24**	–	**Increase simulation–based validation and develop action procedures**
2	Prep Exe	–	–	–	Sim	–	23/24	Definition CP, counter deterministic nature EVM, detect OOC and action procedures	Develop new action procedures: until now very scarce, most use simulations
2	–	For Trigger	–	–	Sim	–	21/24	Forecasting techniques (8/21) and triggers for action (13/21) often validated using simulations	
3	–	For Trigger	Comp stat	–	Sim	–	18/21	Simulated validation when methodology is simulation model (12/18)	Increase simulated validation for Bayes/SS-curves/charts: until now mostly tested on small historical dataset
2	–	–	–	Stoch	Sim	–	13/24	Stochastic analysis	
2	–	–	–	–	Sim	Gen	17/24	General projects	Specific projects
1	–	–	**AI**	–	–	–	**11**	–	**Include uncertainty in AI techniques to trigger for action**
3	Prep Exe	For	AI	–	–	–	10/11	Forecasting; cash flow analysis, accurate forecasts and estimate project success	Use AI explicitly for action taking
2	–	–	AI	Det	–	–	8/11	Deterministic	Include stochastic component
2	–	–	AI	–	His	–	9/11	Historical data	Test or train on simulated data
2	–	–	AI	–	–	Priv	9/11	Construction industry	
2	–	**Perf**	**EVM**	–	–	–	**28**	**EVM performance evaluation**	**Broaden time–cost scope by including other objective functions**
3	–	Perf	EVM	–	Qual	–	19/28	Validation on single historical project or notional data	Test on larger database
3	–	Perf	EVM	Det	–	–	23/28	Deterministic	
4	Prep	Perf	EVM	Det	–	–	18/23	Time–cost integration, focus and relation (10/18)	Focus on other objective functions than time and cost alone
4	-	Perf	EVM	Det	-	Priv	14/23	Private projects: mainly construction	
3	-	Perf	EVM	Stoch Fuzzy	-	-	5/28	Probabilistic extensions to EVM indices validated on one project or notional data	Develop new stochastic techniques and test these and the few existing on large dataset
2	–	**For**	**Stat**	–	–	–	**26**	**Statistical forecasting**	**Explicitly trigger for action and test on large database**
3	–	For	Stat	Det	–	–	13/26	50% deterministic curve fitting	
4	Prep	For	Stat	Det	HisS One	–	12/13	Small historical dataset or notional data	Test on simulated data or large database
4	–	For	Stat	Det	–	Priv	12/13	Private projects: mainly construction	Apply to other industries
3	–	For	Stat	Stoch Fuz	–	–	13/26	50% probabilistic curve fitting and Bayes	
4	Exe	For	Stat	Stoch Fuz	–	–	9/13	Counter deterministic nature EVM and accuracy early forecasts	
4	–	For	Stat	Stoch Fuz	HisS SimS One NA	–	12/13	Small dataset	Test on large database
4	–	For	Stat	Stoch Fuz	–	Constr	10/13	Construction industry	Apply to other industries

(continued on next page)

Table 3 (*continued*)

k	P	C	M	An	V	Ap	#	Trend	Gap
3	–	For	Bayes CurveP	Stoch Fuz	–	–	13/16	Bayes and SS-curves mainly used for forecasting only	
3	–	Trigger	Bayes CurveP	Stoch Fuz	–	–	3/16		Use Bayes and SS–curves explicitly to trigger action, like statistical control charts
4	Exe	Trigger	Chart	Stoch Fuz	–	–	5/5	Statistical control charts trigger action	
2	–	**Tool**	**Comp**	–	–	–	**25**	**Computerized tools**	**Validate on large database and translate to ther industries**
3	–	Tool	Comp	–	–	Priv	23/25	Construction projects	Apply to other industries
3	–	Tool	Comp	Det	–	–	22/25	Mainly deterministic	Include uncertainty
4	Exe	Tool	Comp	Det	–	–	10/22	Data collection	
4	Multi	Tool	Comp	Det	–	–	9/22	Mainly information flow, but also automation, knowledge base and visualization	Apply to other industries
4	–	Tool	Comp	Det	HisS One NA	–	22/22 Small dataset		Test on large database

k and # indicate the level at which the trend or gap was found and the number of occurrences (with respect to the trend or gap at a higher level), respectively.

Qualitative analysis resulted in a final decision on whether or not to accept a combination as a trend or a gap.

4.2. Results: current trends and gaps for future research

Applying the algorithm described in Section 4.1 on the framework developed in Section 3, we identified a number of trends in current research and possible avenues for the future. These findings are summarized in Table 3 and will be discussed in detail in the following paragraphs. Gaps resulting from Step 1 in Algorithm 1 are situated at the first level (k = 1), since only one class is considered, and are further elaborated on deeper levels. Although these observations started out as gaps, new and growing trends are identified within this (still) limited research area. Step 2 of Algorithm 1 started with combinations of two subclasses, originating from two different classes (k = 2), resulting in current trends in literature. These trends have been combined further, giving rise to more detailed trends and possible research ideas for the future. The level k at which the gap or trend is considered is indicated in the first column of Table 3 and refers to the number of classes that have been combined. The specific subclasses that constitute the trend or gap are displayed in columns 2 until 7. The next column indicates the number of papers in the dataset that correspond to this trend or gap. Finally, the last two columns present additional information on the respective trend or gap. More detailed explanations will be provided in Sections 4.2.1 to 4.2.6, which will elaborate on the seven main trends and gaps displayed in bold in Table 3.

For example, the subclass "Stochastic analysis" was identified as a gap at level one in the first step of the algorithm and represents 31 out of 187 papers. As a recommendation for the future, increased incorporation of uncertainty, especially for action taking, is proposed. This suggestion is based on the trends and gaps found at deeper levels, for which Table 3 indicates the level k, the classes which were combined, and the number of occurrences for the specific combination, expressed as a fraction of the trend or gap identified at a higher level. In the text, references to the table will regularly be provided in order to clarify the number of occurrences (between brackets) for each gap or trend. The abbreviations used in this table and in the text are summarized in Table 2.

4.2.1. Probabilistic analysis

Nearly 85% ($\frac{112+31+13}{187} = \frac{156}{187}$) of all papers has a quantitative nature and can thus be labeled as deterministic, stochastic or fuzzy. Approximately 70% ($\frac{112}{156}$) of these papers present a deterministic approach. Thus, only 30% ($\frac{31+13}{156}$) of the quantitative articles explicitly take into account some degree of uncertainty inherent to a realistic project. Whereas stochastic methods focus primarily on uncertainty in data, fuzzy approaches concentrate on vagueness in data. As a consequence, they are applied in different circumstances, serving different goals. However, the deterministic nature of the traditional EVM methodology has been an argument for the development of both stochastic and fuzzy techniques.

4.2.1.1. Stochastic analysis (Stoch). Stochastic approaches attempt to improve early forecasts, detect out-of-control situations and provide action procedures (Exe) in 24 of the 31 cases. Introduction of accurate (early) forecasts (For) and triggers for action (Trigger) are the most common contributions using stochastic analysis ($\frac{30}{31}$). Tolerance limits, for example, can be constructed by estimating the probability that a certain outcome will occur. Applying these tolerance limits during execution allows the project manager to discern natural variation from unacceptable deviations. Other statistical or computerized techniques (Stat, Comp) serving the same goal are SS-curves, Bayesian statistics, statistical control charts and simulation models.

4.2.1.2. Fuzzy analysis (Fuz). Besides providing an alternative to the deterministic EVM indicators, fuzzy approaches are often applied for cash flow analysis (Exe, Prep) ($\frac{10}{13}$). In contrast to stochastic techniques, they are not explicitly used to trigger for action, but mainly to evaluate performance and produce forecasts (Perf, For) ($\frac{12}{13}$). The traditional EVM indicators (EVM) primarily serve as a basis for extensions to deal with vagueness in data ($\frac{7}{13}$). Until now, fuzzy techniques have only been tested on small datasets (One, HisS, Que), which seems insufficient to advocate increased effort in this domain. However, extensive testing of the existing or new techniques might shed a light on the added value of fuzzy sets in project control.

4.2.2. Validation using simulated data (Sim)

About 90% $\left(\frac{67+24+78}{187}=\frac{169}{187}\right)$ of the papers provide a test procedure, based on historical or simulated data, or at least one example of the proposed method. Only 14% $\left(\frac{24}{169}\right)$ of those articles use simulations, half of which appeared in the last 5 years. Furthermore, an increasing use of simulated data for validation can be observed if the need to take action rises. One third $\left(\frac{8}{24}\right)$ of the papers validated through simulated data aims at improving forecasts (For). This portion increases to 50% $\left(\frac{13}{24}\right)$ for articles presenting triggers for action (Trigger). Statistical and computerized techniques (Stat, Comp) are most often used to attain these objectives $\left(\frac{18}{21}\right)$. In most cases, however, simulated data is only used when the methodology was a simulation model $\left(\frac{12}{18}\right)$. The problems which are most often dealt with by simulation models are the definition of control points and corrective action procedures (Prep, Exe). Research in the latter is still scarce though, and could benefit from extra attention in the future. Statistical methods, such as Bayesian statistics, SS-curves and statistical control charts, also providing triggers for action, are usually only validated on a small historical dataset. Extensive validation of these techniques using a simulation experiment could provide additional insights on the applicability of the methods.

In contrast to the overall trend of deterministic analysis, half of the papers $\left(\frac{13}{24}\right)$ here are stochastic in nature (Stoch). A possible explanation for this observation is the fact that a simulation experiment naturally incorporates the expected behavior of the project, as each run mimics a possible execution of the project. Additionally, a full factorial design allows for assessing the impact of project or environmental characteristics on the performance of the approach, indicating optimal conditions to use the technique under consideration. Consequently, if the trend to incorporate uncertainty into the methodology persists, an increase in simulated validation can be expected.

Interestingly, in 70% $\left(\frac{15}{22}\right)$ of the papers using simulated data for validation, no assumption is made on the kind of project or industry under consideration (Gen). A relevant extension could be to explore whether or not industry specific characteristics could be incorporated in the model to make more accurate estimates. Additionally, large simulation experiments could be performed in areas that have not been subject to extensive testing yet.

4.2.3. Artificial intelligence (AI) techniques

Until now, artificial intelligence techniques have only been used for forecasting purposes (For) $\left(\frac{10}{11}\right)$ and associated tools $\left(\frac{1}{11}\right)$. They mainly aim at improving the accuracy of time and cost forecasts (Exe) and the shape of the PV-curve (Prep). Consequently, a potential extension could consist of explicitly determining action procedures. It could furthermore be interesting to investigate the relevance of adding a stochastic component to these techniques or to use simulated data for training and/or testing.

4.2.4. EVM performance analysis (EVM, Perf)

According to our review, the largest amount of contributions have been made to improve performance evaluation and forecasting techniques, representing 25% $\left(\frac{46}{187}\right)$ and 30% $\left(\frac{58}{187}\right)$ of the papers, respectively. Regarding performance analysis (Perf), approximately 60% $\left(\frac{28}{46}\right)$ of the papers use extended EVM analysis (EVM) to attain the proposed goal. Of these, over 80% $\left(\frac{23}{28}\right)$ proposes a deterministic (Det) approach and 70% $\left(\frac{19}{28}\right)$ validates the method on qualitative data (Qual). Probabilistic performance analysis (Stoch, Fuz) is still scarce and constitutes mainly of fuzzy extensions to the EVM indices $\left(\frac{5}{28}\right)$, which lack, as indicated before, a thorough validation procedure. Including a stochastic component and testing both deterministic and probabilistic approaches on a large database could thus be interesting for future research. An assessment of existing indices could be valuable as well. Classifying these metrics based on their effectiveness, efficiency and application area could meet the practitioners' needs for guidelines about which performance measure to use and how to cope with the issues associated with the EVM methodology (Prep). Finally, approximately 40% $\left(\frac{10}{23}\right)$ of the deterministic approaches deal with the integration and focus on time and cost and the relation between these variables. Integrating other objectives in the time–cost framework, such as quality, sustainability and safety, is often mentioned as an avenue for future research in literature. However, only few papers actually address this issue, which motivates our suggestion to cover this aspect more extensively in the near future.

4.2.5. Statistical forecasting (Stat, For)

With respect to forecasting, almost 50% $\left(\frac{26}{58}\right)$ of the papers apply statistical methods. Half of these techniques are deterministic (Det) $\left(\frac{13}{26}\right)$, primarily consisting of deterministic curve fitting techniques such as regression analysis and growth models. They aim at estimating the shape of the PV-curve or cash flow balance over time (Prep) and are mainly tested on a small historical dataset (HisS, One) from the construction industry (Constr). Therefore, simulation experiments and applications in other industries are possible extensions for the future.

The other 50% $\left(\frac{13}{26}\right)$ of the statistical forecasting papers apply a probabilistic technique (Stoch, Fuz), such as Bayesian statistics or stochastic S-curves. These techniques were mainly developed to counter the problem of inaccurate early forecasts by incorporating the outside view (Exe) $\left(\frac{9}{13}\right)$. Stochastic Bayesian statistics and SS-curves (Bayes, CurveP) were encountered in 16 different papers and exclusively produce forecasts (For) in 80% $\left(\frac{13}{16}\right)$ of the cases. Statistical control charts (Chart), however, are much more frequently used to provide warning signals to take action (Trigger) $\left(\frac{5}{5}\right)$. Since Bayesian statistics and SS-curves provide confidence bounds on their estimates, they can easily be extended to explicitly make suggestions for action taking. Additionally, the effectiveness of these techniques should be tested on a larger database, either consisting of historical or simulated data.

4.2.6. Computerized tools (Comp, Tool)

Information systems and automation processes are mainly used in the construction industry (Priv) $\left(\frac{23}{25}\right)$ applying a deterministic approach (Det) $\left(\frac{22}{25}\right)$. Their primary objective is to facilitate data

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collection (Exe) ($\frac{10}{22}$), but also to enhance information flow, build a knowledge base in the organization and visualize project data (Multi) ($\frac{9}{22}$). Since most papers provide a case study on the implementation of the proposed methodology, the dataset for validation is often very small (HisS, One, NA) ($\frac{22}{22}$). Using information systems and automated detection mechanisms definitely seems like a promising area for future research. However, existing or new approaches should be tested more extensively to examine their relevance and usability in the future. Furthermore, it could be investigated whether techniques applied in the construction industry can be translated to other application areas.

5. Conclusion

The objective of this literature review was threefold. First, an article and journal selection procedure was effectuated in order to delineate the scope of the paper. We only incorporated papers published in high-quality journals, covering a topic related to time and/or cost control. Second, the gathered articles were structured according to a classification framework based on the following six classes, each representing a typical and crucial aspect of a research paper: (i) research problem, (ii) contribution, (iii) methodology, (iv) analysis, (v) validation and (vi) application. The results can be consulted in Appendix A, where each paper is associated with one or multiple items for each class. Based on this classification framework, the third objective was to distill current research trends and avenues for future research.

Summarizing, the most important project control advancements addressed in this literature review aim at: (i) automating data collection, (ii) accurately measuring project performance, based on time, cost and other metrics, (iii) improved forecasting during project progress, especially in the early phase, (iv) issuing reliable early warning signs to keep the project on track, (v) enhance information flow between all interested parties, and (vi) build a knowledge base for cross-project learning.

Improvements to existing techniques as well as new techniques have been proposed in order to realize these ambitions. Validation of the proposed methodology is often only based on one or a few historical cases. Future research should thus focus on extending the testing procedure, either by means of a large and diversified historical dataset or by a well-designed simulation experiment. Furthermore, a shift from deterministic techniques to probabilistic approaches could be opportune for certain research problems such as the detection of unacceptable performance. Additionally, the integration of other objective functions besides time and cost could be incorporated into the control model to more realistically evaluate performance. A last research area that has not received much attention is the development, implementation and analysis of corrective action procedures.

Conflict of interest

There is no conflict of interest.

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Appendix A. Literature list with corresponding item(s) for each of the six classes as discussed in section

Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Abdel-Hamid et al. (1993)	IEEE T SOFTWARE ENG	Software project control: An experimental investigation of judgement with fallible information	IT	Measur	Man	NA	SimS	ITS
Abdelsayed and Navon (1999)	CIV ENG ENVIRON SYST	An information sharing, internet-based, system for project control	IT Flow	Tool	ISA EVM	NA	One	Constr
Abdul-Rahman et al. (2011)	J CIV ENG MANAG	Project performance monitoring methods used in Malaysia and perspectives of introducing EVA as a standard approach	EV Missue	Gen	Man EVM	NA	Que	Constr
Abudayyeh et al. (2001)	ADV ENG SOFTW	An intranet-based cost control system	Flow	Tool	ISA	Det	One	Constr
Abudayyeh and Rasdof (1991)	J CONSTR ENG M	Design of construction industry information management systems	TCint WBSdet Flow	Tool	ISA	Det	One	Constr
Acebes et al. (2014)	INT J PROJ MANAG	A new approach for project control under uncertainty. Going back to the basics	Det Visual	EW	Sim	Stoch	SimS	Gen
Akinci et al. (2006)	AUTOMAT CONSTR	A formalism for utilization of sensor systems and integrated project models for active construction quality control	TCfocus	Measur Tool	ISA	Det	HisS	Constr

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Al-Jibouri (2003)	INT J PROJ MANAG	Monitoring systems and their effectiveness for project cost control in construction	PMeff	Measur	EVM MISC	Det	One	Constr
Aliverdi et al. (2013)	INT J PROJ MANAG	Monitoring project duration and cost in a construction project by applying statistical quality control charts	Det	EW	Chart	Stoch	One	Constr
Anbari (2003)	PROJ MANAG J	Earned value project management method and extensions	TCint	Gen	Lit	Det	NA	Gen
Azimi et al. (2011)	AUTOMAT CONSTR	A framework for an automated and integrated project monitoring and control system for steel fabrication projects	Data Auto	Tool	ISA Sim	Det	One	Constr
Bagherpour et al. (2010)	INT J ADV MANUF TECH	Designing a control mechanism using earned value analysis: an application to production environment	Det	Measur	IndexP	Fuz	One	Prod
Barraza et al. (2000)	J CONSTR ENG M	Probabilistic monitoring of project performance using SS-curves	Det	Cost Time	CurveP	Stoch	NA	Constr
Barraza et al. (2004)	J CONSTR ENG M	Probabilistic Forecasting of Project Performance Using Stochastic S Curves	Det	Cost Time	CurveP	Stoch	One	Constr
Barraza and Bueno (2007)	J CONSTR ENG M	Probabilistic Control of Project Performance Using Control Limit Curves	Det	EW	CurveP	Stoch	One	Constr
Batselier and Van-houcke (2015a)	INT J PROJ MANAG	Construction and evaluation framework for a real-life project database	MISCdata	Tool	Case	NA	HisS	Constr
Batselier and Van-houcke (2015b)	INT J PROJ MANAG	Evaluation of deterministic state-of-the-art forecasting approaches for project duration based on earned value management	TCrel ACCfor	Time Acc	Case IndexD	Det	HisS	Constr
Battikha (2002)	J CONSTR ENG M	QUALICON: Computer-Based System for Construction Quality Management	TCfocus	Measur	ISA	Det	HisS	Constr
Bauch and Chung (2001)	PROJ MANAG J	A statistical project control tool for engineering managers	OOC	EW	Chart	Stoch	HisS	Gen
Benjaoran (2009)	INT J PROJ MANAG	A cost control system development: a collaborative approach for small and medium-sized contractors	EVMissue Flow	Tool	Case ISA	Det	HisS	Constr
Besner and Hobbs (2006)	PROJ MANAG J	The perceived value and potential contribution of project management practices to project success	PMeff	Gen	Man	NA	Que	Gen
Block (1971)	HARVARD BUS REV	Accomplishment/ cost: better project control	TCint	Measur	EVM	Det	One	Gen
Blyth and Kaka (2006)	Eng Constr Arch Manag	A novel multiple linear regression model for forecasting S-curves	PVcash	Cash	CurveD	Det	HisS	Constr
Bosche et al. (2015)	AUTOMAT CONSTR	The value of integrating Scan-to-BIM and Scan-vs- BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components	Data	Tool	ISA	Det	One	Constr
Boukamp and Akinci (2007)	AUTOMAT CONSTR	Automated processing of construction specifications to support inspection and quality control	TCfocus	Measur	ISA	Det	HisS	Constr
Boussabaine and Kaka (1998)	Constr Manag Econ	A neural network approach for cost flow forecasting	PVcash	Cash	CurveD NN	Det	HisS	Constr
Boussabaine and El-hag (1999)	Constr Manag Econ	Applying fuzzy techniques to cash flow analysis	PVcash	Cash	CurveP	Fuz	HisS	Constr
Bowman (2006)	EUR J OPER RES	Developing activity duration specification limits for effective project control	Action	EW Action	Sim	Stoch	SimS	Gen
Brandon (1998)	PROJ MANAG J	Implementing earned value easily and effectively	EVMissue	Gen	EVM	Det	One	Gen
Cao and Hoffman (2011)	INT J PROJ MANAG	A case study approach for developing a project performance evaluation system	EVMissue	Measur	Case Stat	Det	HisS	HT
Caron et al. (2013)	PROJ MANAG J	A Bayesian approach to improve estimate at completion in Earned Value Management	Det	Cost Time	Bayes	Stoch	One	Gen
Chang (2001)	J MANAGE ENG	Defining cost/schedule performance indices and their ranges for design projects	EVMissue	Measur	Context	Det	HisS	Trans
Chao and Chien (2009)	J CONSTR ENG M	Estimating Project S-Curves Using Polynomial Function and Neural Networks	PVcash	Cash	CurveD NN	Det	HisL	Constr

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Chao and Chien (2010)	AUTOMAT CONSTR	A Model for Updating Project S-curve by Using Neural Networks and Matching Progress	PVcash	Cash	CurveD NN	Det	HisS	Constr
Chen and Huang (2007)	INFORM SCIENCES	Applying fuzzy method for measuring criticality in project network	Future	Succ	IndexP MISC	Fuz	One	Gen
Chen (2014)	J MANAGE ENG	Improving Forecasting Accuracy of Project Earned Value Metrics: Linear Modeling Approach	PVchang	Acc	CurveD	Det	HisL	Constr
Chen et al. (2011)	J CIV ENG MANAG	Developing a Cost-Payment Coordination Model for Project Cost Flow Forecasting	Client	Measur	EVM MISC	Det	HisS	Constr
Chen (2008)	AUTOMAT CONSTR	Integration of cost and schedule using extensive matrix method and spreadsheets	TCrel Res	Measur	EVM	Det	One	Constr
Cheng et al. (2010a)	AUTOMAT CONSTR	Estimate at Completion for construction projects using Evolutionary Support Vector Machine Inference Model	ACCfor	Cost	SVM MISC	Det	HisL	Constr
Cheng and Roy (2011)	INT J PROJ MANAG	Evolutionary fuzzy decision model for cash flow prediction using time dependent support vector machines	PVcash	Cash	SVM MISC	Fuz	HisS	Constr
Cheng et al. (2009)	AUTOMAT CONSTR	Artificial intelligence approaches to achieve strategic control over project cash flows	PVcash	Cash	NN MISC	Fuz	HisS	Constr
Cheng et al. (2010b)	AUTOMAT CONSTR	Project success prediction using an evolutionary support vector machine inference model	Future	Succ	SVM MISC	Det	HisS	Constr
Cheung et al. (2004)	AUTOMAT CONSTR	PPMS: a web-based construction project performance monitoring system	Auto	Measur Tool	ISA	Det	One	Constr
Chin et al. (2004)	AUTOMAT CONSTR	A process-based quality management information system	TCfocus	Measur Tool	ISA	Det	One	Constr
Cho et al. (2013)	J COMPUT CIVIL ENG	Database Framework for Cost, Schedule, and Performance Data Integration	TCint WBSdet Flow	Measur	EVM	Det	One	Constr
Chou (2009)	EXPERT SYST APPL	Generalized linear model-based expert system for estimating the cost of transportation projects	ACCfor	Cost Tool	CurveD ISA	Det	HisS	Trans
Chou et al. (2010)	AUTOMAT CONSTR	Visualized EVM system for assessing project performance	Flow	Tool	ISA EVM	Det	One	Constr
Christensen (1993)	PROJ MANAG J	The Estimate at Completion Problem: A Review of Three Studies	ACCfor	Gen	Lit EVM	Det	HisS	Gov
Christensen and Gordon (1998)	PROJ MANAG J	Does a Rubber Baseline Guarantee Cost Overruns on Defense Acquisition Contracts?	PVchang	Gen	Case	NA	HisL	Gov
Cioffi (2005)	INT J PROJ MANAG	A tool for managing projects: an analytic parameterization of the S-curve	PVcash	Cash	CurveD	Det	HisS	Gen
Cioffi (2006a)	J OPER RES SOC	Completing project according to plans: an earned- value improvement index	Future	Succ	IndexD	Det	One	Gen
Cioffi (2006b)	INT J PROJ MANAG	Designing project management: A scientific notation and an improved formalism for earned value calculations	EVMissue	Index	IndexD	Det	One	Gen
Colin and Van-houcke (2014)	OMEGA-INT J MANAGE S	Setting tolerance limits for statistical project control using earned value management	OOC	EW	Chart	Stoch	SimL	Gen
Colin and Van-houcke (2015a)	EXPERT SYST APPL	A comparison of the performance of various project control methods using earned value management systems	OOC	EW CP	Chart	Stoch	SimL	Gen
Colin and Van-houcke (2015b)	INT J PROJ MANAG	Developing a framework for statistical process control approaches in project management	OOC	EW	Chart	Stoch	SimL HisS	Gen
de Falco and Mac-chiaroli (1998)	INT J PROJ MANAG	Timing of control activities in project planning	CP	CP	MISC	Det	NA	Gen
De Marco et al. (2009)	J CONSTR ENG M	Cost and schedule monitoring of industrial building projects: Case study	ACCearly	Cost Time	CurveD	Det	One	Constr
Diekmann and Al-Tabtabai (1992)	INT J PROJ MANAG	Knowledge-based approach to construction project control	Flow TCint	Tool	ISA KBS	NA	NA	Constr

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Dweiri and Kablan (2006)	DECIS SUPPORT SYST	Using fuzzy decision making for the evaluation of the project management internal efficiency	Know TCfocus	Index	IndexP	Fuz	One	Gen
El-Omari and Moselhi (2009)	Eng Constr Arch Manag	Data acquisition from construction sites for tracking purposes	Data	Tool	ISA	Det	NA	Constr
El-Omari and Moselhi (2011)	AUTOMAT CONSTR	Integrating automated data acquisition technologies for progress reporting of construction projects	Flow	Tool	ISA	Det	NA	Constr
Elbeltagi and Dawood (2011)	AUTOMAT CONSTR	Integrated visualized time control system for repetitive construction projects	Visual	Tool	ISA	Det	One	Constr
Eldin (1991)	J CONSTR ENG M	Management of engineering / design phase	TCint	Measur	EVM	Det	One	HT
Elshaer (2013)	INT J PROJ MANAG	Impact of sensitivity information on the prediction of project's duration using earned schedule method	ACCfor	Index	IndexD	Det	SimL	Gen
Erdogmus (2010)	IEEE SOFTWARE	Tracking Progress through Earned Value	EVMissue	Measur	Lit	NA	NA	Gen
Farris et al. (2006)	IEEE T ENG MANAGE	Evaluating the relative performance of engineering design projects: a case study using data envelopment analysis	Learn	Measur	Stat	Det	HisS	Gov
Fleming and Koppelman (2003)	HARVARD BUS REV	What's Your Project's Real Price Tag?	ACCfor	Gen	EVM	Det	NA	Gen
Fouche and Rolstadas (2010)	PROD PLAN CONTROL	The use of performance measurement as a basis for project control of offshore modification oil and gas projects	PVchang	Measur	Case	NA	HisS	MISC
Gallagher and Lee (1996)	MIL OPER RES	Final Costs Estimates for Research & Development Programs Conditioned on Realized Costs	Det	Cost Time	CurveP Bayes	Stoch	HisS SimS	MISC
Gardiner and Stewart (2000)	INT J PROJ MANAG	Revisiting the Golden Triangle of Cost, Time, and Quality: the Role of NPV in Project Control, Success, and Failure	TCfocus	Gen	Man	NA	Que	Gen
Gardoni et al. (2007)	COMPUT-AIDED CIV INF	A probabilistic framework for Bayesian adaptive forecasting of project progress	ACCearly	Time	CurveP Bayes	Stoch	HisS	Gov
Gelbard et al. (2002)	INT J PROJ MANAG	Integrating system analysis and project management tools	Flow	Gen	ISA	NA	One	Gen
Goh and Hall (2013)	MANAGE SCI	Total cost control in project management via satisficing	Action	EW Action	MISC	Stoch	SimL	Gen
Golenko-Ginzburg and Gonik (1997)	J OPER RES SOC	On-line control model for network construction projects	CP	CP	Sim	Stoch	SimS	Constr
Golparvar-Fard et al. (2011)	AUTOMAT CONSTR	Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques	Data	Tool	ISA	Det	HisS	Constr
Golparvar-Fard et al. (2009)	J COMPUT CIVIL ENG	Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs	Data	Tool	ISA	Det	HisS	Constr
Gorog (2009)	INT J PROJ MANAG	A comprehensive model for planning and controlling contractor cash-flow	Client	Measur	IndexD	Det	One	Constr
Gowan et al. (2006)	Inf Manag Comp Sec	Earned value management in a data warehouse project	EVMissue	Measur	Case Context	Det	One	ITS
Haji-Kazemi et al. (2013)	PROJ MANAG J	A Review on Possible Approaches for Detecting Early Warning Signs in Projects	OOC	Gen EW	Lit	NA	NA	Gen
Hanna (2012)	J CONSTR ENG M	Using the Earned Value Management System to Improve Electrical Project Control	EVMissue	Measur	Case Context	Det	One	Constr
Hardie (2001)	INT J PROJ MANAG	The prediction and control of project duration: a recursive model	Netw	Time	MISC	Det	One	Gen
Hayes (2002)	Pharm Tech	Using Earned-Value Analysis to Better Manage Projects	EVMissue	Gen	EVM	Det	NA	MISC
Hazir (2015)	INT J PROJ MANAG	A review of analytical models, approaches and decision support tools in project monitoring and control	Auto	Gen Tool	Lit	NA	NA	Gen

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Hazir and Shtub (2011)	J OPER RES SOC	Effects of the information presentation format on project control	Visual	Gen	Man	NA	Que	Gen
Hegazy and Menesi (2012)	CAN J CIVIL ENG	Enhancing the critical path segments scheduling technique for project control	MISCcpm	Measur	Case MISC	Det	One	Gen
Hegazy and Petzold (2003)	J CONSTR ENG M	Genetic optimization for dynamic project control	Action	EW Action	MISC	Det	One	Constr
Howes (2000)	Eng Constr Arch Manag	Improving the performance of earned value analysis as a construction project management tool	ACCearly	Cost Time	EVM	Det	HisS	Constr
Howes et al. (1992)	BUILD RES INF	Dynamic project control utilizing a new approach to project control	Know	Tool	ISA	NA	NA	Gen
Hunter et al. (2014)	ACTA ASTRONAUT	Improved cost monitoring and control through the Earned Value Management System	EVMissue	Measur	Context	Det	One	Gov
Hwee and Tiong (2002)	INT J PROJ MANAG	Model on cash flow forecasting and risk analysis for contracting firms	PVcash	Cash	IndexD ISA	Det	HisS	Constr
Hyvari (2006)	INT J PROJ MANAG	Project management effectiveness in project-oriented business organizations	PMeff	Gen	Man	NA	Que	Gen
Jaafari (1996)	INT J PROJ MANAG	Time and Priority Allocation Scheduling Techniques for Projects	Det	Time	ISA	Stoch	One	Constr
Jung and Woo (2004)	J CONSTR ENG M	Flexible Work Breakdown Structure for Integrated Cost and Schedule Control	WBSdet CP	CP	EVM	Det	One	Constr
Kaka (1999)	Eng Constr Arch Manag	The development of a benchmark model that uses historical data for monitoring the progress of current construction projects	PVcash	Cash	CurveP	Stoch	HisL	Constr
Kaka and Price (1993)	Constr Manag Econ	Modelling standard cost commitment curves for contractors' cash flow forecasting	PVcash	Cash	CurveD	Det	HisL	Constr
Kaka (1996)	Constr Manag Econ	Towards more flexible and accurate cash flow forecasting	PVcash	Cash	Sim	Stoch	SimS	Constr
Kauffmann et al. (2002)	EMJ-ENG MANAG J	Using Earned Value Methods to Substantiate Change- of-Scope Claims	Client	Measur	Case Context	Det	One	HT
Kenley and Wilson (1986)	Constr Manag Econ	A construction project cash flow model - an idio- graphic approach	PVcash	Cash	CurveD	Det	HisS	Constr
Khamooshi and Go- lafshani (2014)	INT J PROJ MANAG	EDM: Earned Duration Management, a new approach to schedule performance management and measurement	TCrel	Index	IndexD	Det	One	Gen
Khodakarami and Abdi (2014)	INT J PROJ MANAG	Project cost risk analysis: A Bayesian networks approach for modeling dependencies between cost items	WBSind	Cost	Bayes	Stoch	One	Constr
Kim and Kim (2014)	J CONSTR ENG M	Sensitivity of Earned Value Schedule Forecasting to S-Curve Patterns	Stabil	EW Acc	EVM Bayes	Stoch	HisS	Gen
Kim and Rein-schmidt (2009)	J CONSTR ENG M	Probabilistic Forecasting of Project Duration Using Bayesian Inference and the Beta Distribution	ACCearly Det	Time	CurveD Bayes	Stoch	SimS	Constr
Kim and Rein-schmidt (2010)	J CONSTR ENG M	Probabilistic Forecasting of Project Duration Using Kalman Filter and the Earned Value Method	ACCearly Det	Time	Bayes	Stoch	HisS	Constr
Kim and Rein-schmidt (2011)	J CONSTR ENG M	Combination of project cost forecasts in earned value management	ACCearly Det	Cost	Bayes	Stoch	SimS	Constr
Kim et al. (2003)	INT J PROJ MANAG	A model for effective implementation of Earned Value Management methodology	EVMissue	Gen	Man	NA	Que	Gen
Kim et al. (2014a)	J CLEAN PROD	Integrated CO2, Cost, and Schedule Management System for Building Construction Projects using the Earned Value Management Theory	TCfocus	Measur	Context	Det	One	Constr
Kim et al. (2014b)	AUTOMAT CONSTR	Automated dimensional quality assessment of precast concrete panels using terrestrial laser scanning	TCfocus	Measur	ISA	NA	HisS	Constr
Kim et al. (2008)	CAN J CIVIL ENG	Integrated cost and schedule control in the Korean construction industry based on a modified work- packaging model	WBSdet	Measur	Context	Det	HisS	Constr

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Kim (2009)	CAN J CIVIL ENG	Project success indicators focusing on residential projects: Are schedule performance index and cost performance index accurate measures in earned value?	EVMissue	Index	EVM Case	Stoch	HisS	Constr
Kim and Ballard (2010)	J MANAGE ENG	Management thinking in the earned value method system and the last planner system	WBSind	Gen	EVM	NA	Que	Constr
Ko and Cheng (2007)	J CONSTR ENG M	Dynamic prediction of project success using artificial intelligence	Future	Succ	NN MISC	Det	HisS	Constr
Kogan et al. (2002)	IIE TRANS	Optimal control in homogeneous projects: analytically solvable deterministic cases	CP	CP	MISC	Det	HisS	Gen
Kwak and Anbari (2009)	INT J PROJ MANAG	Analyzing project management research: Perspectives from top management journals	PMeff	Gen	Lit	NA	NA	Gen
Kwak and Anbari (2012)	PROJ MANAG J	History, Practices, and Future of Earned Value Management in Government: Perspectives From NASA	EVMissue	Gen	Context	Det	HisS	Gov
Lanford and McCann (1983)	LONG RANGE PLANN	Effective Planning and Control of Large Projects - Using Work Breakdown Structure	TCint WBSdet	Gen	EVM	Det	One	Gen
Lauras et al. (2010)	DECIS SUPPORT SYST	Towards a multi-dimensional project Performance Measurement System	TCfocus	Measur	MISC	Det	One	Gen
Lee (2008)	J URBAN PLAN DEV	Cost Overrun and Cause in Korean Social Overhead Capital Projects: Roads, Rails, Airports, and Ports	EVMissue	Gen	Case	NA	HisL	Trans
Lee and Rojas (2014)	AUTOMAT CONSTR	Activity Gazer: A multi-dimensional visual representation of project performance	Visual	Measur	ISA	Det	Que	Constr
Lee et al. (2006)	AUTOMAT CONSTR	Dynamic planning and control methodology for strategic and operational construction project management	Netw	Tool	Sim	Det	One	Constr
Leu and Lin (2008)	J CONSTR ENG M	Project Performance Evaluation Based on Statistical Process Control Techniques	OOC	EW	Chart	Det	HisS	Constr
Li et al. (2005)	CAN J CIVIL ENG	A reasoning process in support of integrated project control	MISCreaso	Tool	ISA	Fuz	Que	Constr
Li et al. (2006)	Eng Constr Arch Manag	Internet-based database management system for project control	Flow	Tool	ISA	Det	One	Constr
Liberatore et al. (2001)	J CONSTR ENG M	Project management in construction: Software use and research directions	PMapp	Gen Tool	Man	NA	Que	Constr
Lipke et al. (2009)	INT J PROJ MANAG	Prediction of project outcome - The application of statistical methods to earned value management and earned schedule performance indexes	ACCfor	Cost Time	EVM Stat	Stoch	HisS	Gen
Lorenz et al. (2012)	IEEE T PLASMA SCI	Implementation of Earned Value Management Tools in the Wendelstein 7-X Project	EVMissue	Measur	Case	Det	One	HT
Magnaye et al. (2014)	INT J PROJ MANAG	Earned readiness management for scheduling, monitoring and evaluating the development of complex product systems	TCfocus	Index	IndexD	Det	One	HT
Maravas and Pan-touvakis (2012)	INT J PROJ MANAG	Project cash flow analysis in the presence of uncertainty in activity duration and cost	PVcash	Cash	CurveP	Fuz	One	Constr
Mavrotas et al. (2005)	INT J PROJ MANAG	A model on cash flow forecasting and early warning for multi-project programmes: application to the operational programme for the information society in Greece	PVcash	Cash	CurveD	Det	HisL	Multi
McConnell (1985)	J MANAGE ENG	Earned Value Technique for Performance Measurement	TCint	Measur	EVM	Det	NA	Gen
McKim et al. (2000)	J CONSTR ENG M	Project performance control in reconstruction projects	PMapp	Gen	Man	NA	HisS	Constr
Miskawi (1989)	Constr Manag Econ	An S-curve equation for project control	PVcash	Cash	CurveD	Det	HisS	Constr
Mortaji et al. (2013)	J INTELL FUZZY SYST	Fuzzy earned value management using L-R numbers	Det	Index	IndexP	Fuz	One	Gen

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Moselhi et al. (2004)	Constr Manag Econ	Web-based integrated project control system	Flow	Tool	ISA EVM	Det	One	Constr
Moslemi Naeni and Salehipour (2011)	EXPERT SYST APPL	Evaluating fuzzy earned value indices and estimates by applying alpha cuts	Det Data	Cost Time	IndexP	Fuz	One	Gen
Moslemi Naeni et al. (2014)	INT J PROJ MANAG	A fuzzy approach for the earned value management	Det Data	Cost Time	IndexP	Fuz	One	Gen
Munch and Heidrich (2004)	J SYST SOFTWARE	Software project control centers: concepts and approaches	Flow	Tool	Lit	NA	NA	ITS
Narbaev and De Marco (2014b)	INT J PROJ MANAG	An Earned Schedule-based regression model to improve cost estimate at completion	ACCearly	Cost	EVM CurveD	Det	HisS	Constr
Narbaev and De Marco (2014a)	J CONSTR ENG M	Combination of growth model and earned schedule to forecast project cost at completion	ACCearly	Cost	CurveD Bayes	Det	HisS	Constr
Nassar et al. (2005)	J CONSTR ENG M	Using Weibull analysis for evaluation of cost and schedule performance	Det	Succ	CurveP	Stoch	HisS	Constr
Navon (2005)	AUTOMAT CONSTR	Automated project performance control of construction projects	Data	Tool	ISA	Det	HisS	Constr
Nguyen and Ibbs (2010)	J CONSTR ENG M	Case Law and Variations in Cumulative Impact Productivity Claims	Client	Measur	Context	Det	One	Constr
Olawale and Sun (2015)	INT J PROJ MANAG	Construction project control in the UK: Current practice, existing problems and recommendations for future improvement	PMapp	Gen	Man	NA	Que	Constr
Pajares and Lopez-Paredes (2011)	INT J PROJ MANAG	An extension of the EVM analysis for project monitoring: The Cost Control Index and the Schedule Control Index	OOC	EW	IndexP	Stoch	One	Gen
Paquin et al. (2000)	IEEE T ENG MANAGE	Assessing and controlling the quality of a project end product: The earned quality method	TCfocus	Measur	IndexD	Det	One	Gen
Park (2004)	KSCE J CIV ENG	Cash Flow Forecasting in Construction Project	PVcash	Cash	CurveD Stat	Det	HisS	Constr
Park et al. (2005)	J MANAGE ENG	Cash flow forecasting model for general contractors using moving weights of cost categories	PVcash	Cash	CurveD Stat	Det	HisS	Constr
Partovi and Burton (1993)	IEEE T ENG MANAGE	Timing of monitoring and control of CPM projects	CP	CP	Sim	NA	SimL	Gen
Patanakul et al. (2010)	J Gen Manag	An empirical study on the use of project management tools and techniques across project life-cycle and their impact on project success	PMapp	Gen	Case	NA	Que	Gen
Perkusich et al. (2015)	EXPERT SYST APPL	A procedure to detect problems of processes in software development projects using Bayesian networks	IT	EW	Bayes	Stoch	HisS	ITS
Pewdum et al. (2009)	Eng Constr Arch Manag	Forecasting final budget and duration of highway construction projects	ACCfor	Cost Time	NN	Det	HisS	Trans
Pillai et al. (2002)	INT J PROJ MANAG	Performance measurement of R&D projects in a multi-project, concurrent engineering environment	MISCphas	Measur	IndexD	Det	HisS	Multi
Plaza (2008)	INFORM SYST FRONT	Team performance and information system implementation: Application of the progress curve to the earned value method in an information system project	Netw Learn	Time	ISA	Det	One	ITS
Plaza and Turetken (2009)	DECIS SUPPORT SYST	A model-based DSS for integrating the impact of learning in project control	Netw Learn	Time	EVMmisc ISA	Det	One	ITS
Ponz-Tienda et al. (2012)	J ZHEJIANG UNIV-SC A	Complete fuzzy scheduling and fuzzy earned value management in construction projects	Det	Index	IndexP	Fuz	One	Constr
Rasdorf and Abu-dayyeh (1991)	J CONSTR ENG M	Cost and schedule control integration: issues and needs	TCint	Gen	Lit	NA	NA	Constr
Raz and Erel (2000)	EUR J OPER RES	Optimal timing of project control points	CP	CP	MISC	Det	SimS	Gen

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Robinson (1997)	PROJ MANAG J	The Performance Measurement Baseline-A Statistical View	OOC	EW	Stat	Stoch	One	Gen
Rozenes et al. (2004)	INT J PROJ MANAG	MPCS: Multidimensional Project Control System	TCfocus	Measur	EVM MISC	Det	One	Gen
Rozenes et al. (2006)	PROJ MANAG J	Project Control: Literature Review	EVMissue	Gen	Lit	NA	NA	Gen
Ruskin (2004)	EMJ-ENG MANAG J	Two Issues concerning the Use of Earned Value Measurements	WBSdet Data	CP	EVM	Det	One	Gen
Russell et al. (1997)	J CONSTR ENG M	Continuous assessment of project performance	Future	Succ	CurveD	Det	HisS	Constr
Sabeghi et al. (2015)	COMPUT OPER RES	Determining the timing of project control points using a facility location model and simulation	CP Action	CP EW	Sim	Stoch	SimL	Gen
Sacks et al. (2005)	J CONSTR ENG M	Feasibility of automated monitoring of lifting equipment in support of project control	Data Auto	Tool	ISA	Det	HisS	Constr
Shahi et al. (2013)	AUTOMAT CONSTR	Onsite 3D marking for construction activity tracking	Data	Tool	ISA	Det	One	Constr
Shtub (1992)	R&D MANAGE	Evaluation of Two Schedule Control Techniques for the Development and Implementation of New Technologies: A Simulation Study	EVMissue	Gen	EVM Sim	Det	Sim	HT
Swartz (2008)	PROJ MANAG J	Managerial Perceptions of Project Stability	Stabil	Acc	Man Stat	Det	Que	Gov
Teicholz (1993)	J COMPUT CIVIL ENG	Forecasting final cost and budget of construction projects	ACCfor	Cost	Stat	Det	HisL	Constr
Townsend et al. (2014)	EMJ-ENG MANAG J	A Schedule-Performance Approach for Level-of-Effort Tasks	ACCfor	Measur	IndexD Chart	Det	HisS	HT
Turkan et al. (2013)	J CONSTR ENG M	Toward Automated Earned Value Tracking Using 3D Imaging Tools	Data	Tool	ISA	Det	HisS	Constr
Turner (2000)	INT J PROJ MANAG	Controlling progress with planned cost or budgeted cost	EVMissue	Index	EVM	Det	One	Gen
Vandevoorde and Vanhoucke (2006)	INT J PROJ MANAG	A comparison of different project duration forecasting methods using earned value metrics	ACCfor	Time	Case	Det	HisS	Gen
Vanhoucke (2010b)	OMEGA-INT J MANAGE S	Using activity sensitivity and network topology information to monitor project time performance	CP Action	EW	Sim	Det	SimL	Gen
Vanhoucke (2011)	OMEGA-INT J MANAGE S	On the dynamic use of project performance and schedule risk information during project tracking	CP WBStd	CP	Sim	Det	SimL	Gen
Vanhoucke (2012)	INT J PROJ MANAG	Measuring the efficiency of project control using fictitious and empirical project data	Action WBStd	EW	Sim	Det	SimL HisS	Gen
Vanhoucke and Van-devoorde (2007)	J OPER RES SOC	A simulation and evaluation of earned value metrics to forecast the project duration	ACCfor	Time	Sim	Det	SimL	Gen
Vitner et al. (2006)	INT J PROJ MANAG	Using data envelope analysis to compare project efficiency in a multi-project environment	Res	Measur	Stat	Det	HisS	Multi
von Wangenheim et al. (2012)	INFORM SOFTWARE TECH	DELIVER! - An educational game for teaching earned value management in computing courses	MISCteach	Tool	EVM MISC	NA	Que	Gen
Wang and Hao (2007)	IEEE T FUZZY SYST	Fuzzy Linguistic PERT	MISCpert	Succ	MISC	Fuz	One	Gen
Wang et al. (2014)	AUTOMAT CONSTR	An innovative method for project control in LNG project through 5D CAD: A case study	Data Auto	Tool	ISA	Det	One	Gen
Warburton (2011)	INT J PROJ MANAG	A time-dependent earned value model for software projects	ACCearly Stabil	Index	CurveD	Det	One	ITS
Wauters and Vanhoucke (2015)	J CONSTR ENG M	Study of the Stability of Earned Value Management Forecasting	Stabil	Acc	Sim	Det	SimL HisS	Gen

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Author(s)	Journal	Title	Problem (P)	Contribution (C)	Methodology (M)	Analysis (An)	Validation (V)	Application (Ap)
Wauters and Vanhoucke (2014)	AUTOMAT CONSTR	Support Vector Machine Regression for project control forecasting	ACCfor	Cost Time	SVM	Det	SimL	Gen
Williams (2005)	IEEE T ENG MANAGE	Assessing and moving on from the dominant project management discourse in the light of project overruns	PMeff	Gen	Lit	NA	NA	Gen
Willoughby (1995)	J MANAGE ENG	Managing design under lump-sum contract	Client	Measur	Case	Det	HisS	MISC
Yang et al. (2007)	J CONSTR ENG M	Management of daily progress in a construction project of multiple apartment buildings	Data WBSdet	Measur	EVMmisc	Det	HisS	Constr
Zhang and El-maghraby (2014)	EUR J OPER RES	The relevance of the ”alphorn of uncertainty” to the financial management of projects under uncertainty	Client	Cash	Sim	Stoch	SimL	Gen
Zwikael et al. (2000)	PROJ MANAG J	Evaluation of Models for Forecasting the Final Cost of a Project	Stabil	Acc	Case	Det	HisS	Gen

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijproman.2015.06.003.

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