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A multivariate approach for top-down project control using earned value management

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ABSTRACT

Project monitoring and the related decision to proceed to corrective action are crucial components of an integrated project management and control decision support system (DSS). Earned value management/earned schedule (EVM/ES) is a project control methodology that is typically applied for top-down project schedule control. However, traditional models do not correctly account for the multivariate nature of the EVM/ES measurement system. We therefore propose a multivariate model for EVM/ES, which implements a principal component analysis (PCA) on a simulated schedule control reference. During project progress, the real EVM/ES observations can then be projected onto these principal components. This allows for two new multivariate schedule control metrics (T^2 and SPE) to be calculated, which can be dynamically monitored on project control charts. Using a computational experiment, we show that these multivariate schedule control metrics lead to performance improvements and practical advantages in comparison with traditional univariate EVM/ES models.

1. Introduction

Project management (PM) is a subdomain of Operations Research that gained quick momentum with the inception of project planning approaches such as the critical path method (CPM [1]) and the program evaluation and research technique (PERT [2]). These methods aim to construct a baseline schedule in the absence of resource restrictions. Explicit incorporation of resources constituted a logical next step and led to an explosion of solution techniques, problem formulations and extensions. An overview of the resource-constrained project scheduling problem and its many extensions can be found in the standard texts of [3, 4] and [5]. While a realistic baseline plan is of great importance, every project proceeds to the execution phase, disrupting the baseline schedule. Hence, the baseline schedule mainly serves as a reference point throughout project control. Due to the inherent presence of schedule disruptions, controlling the project's performance using techniques such as earned value management (EVM) is key to a project's success. EVM is a project control methodology that originated in the 1960s at the US Department of Defense. EVM aggregates the progress of individual activities to a higher level of the work breakdown structure (WBS) and provides the project manager with an indication of the overall health of the project. Because of the aggregation of information at a low level to a higher level of the WBS structure, EVM is known as a top-down control method ([6]). Three key metrics, namely planned value (PV), earned value (EV) and actual cost (AC) lie at the core of a number of performance indicators. These performance indicators quantify the progress in terms of time and cost and should act as a trigger for corrective action when the project objective is endangered. The fundamentals of EVM can be found in the books of [7] and [8]. Throughout the years, a number of different project control problems have been investigated from a theoretical and empirical perspective. In the next paragraph, a short yet non-exhaustive overview is given of the main themes in project control research.

Three project control research directions are forecasting, stability and triggers for corrective action. They are briefly described along the following lines. One of the main research themes revolved around forecasting the final budget and duration of a project by means of progress data. While initial studies emphasized the cost objective (cf. [9–12]), the paper of [13] introduced the earned schedule concept that renewed academics' interest in the time objective. Project duration forecasting has been investigated by [14] and [15]. [6] called on researchers to find ways in which risk analysis and project control can be of mutual benefit. [16] responded to this call by integrating sensitivity indexes with earned schedule (ES) forecasting methods. Incidentally, a research track that reacted to the recent trend of big data and artificial intelligence emerged. [17] and [18] provided case studies on how support vector machines can be used for project control, which [19] tested on a large set of topologically diverse projects.

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A second main theme related to the stability of project control indexes. The Cost Performance Index (CPI), a well-known performance metric to measure and control the cost of the project in progress, has been the subject of scrutiny of many studies ([20] and [21]), leading to the acceptance and rejection of its stable behaviour. [22] criticized the criterion for assessing stability and proposed an alternative in a study in which forecasting stability was examined. A third research track focussed on triggers for corrective action. [23] analyzed the timing of control points, while [24] specified performance limits on the activity level. [25] examined variation on the project level using novel metrics, defined as the Schedule and Cost Control Index. [26] proposed the concept of statistical project control using earned value management and argued for the use of control charts in project control.

The studies cited above all focus on a single problem or criterion and little to no effort is given to integrating the various research streams into an integrated decision framework. Future research will undoubtedly be aimed at the integration of multiple criteria (cf. [27, 28] and [29]) or the development of an integrated project scheduling and control decision support system (DSS). [30] and [31] showed that the presence and quality of an information system led to improved decision-making, project manager satisfaction and better project scheduling, monitoring and control. While research on decision support systems for project control is extremely scarce, these systems found entry in project risk management ([32] and [33]). While to the best of our knowledge no widely accepted project control decision support system exists, [34] mentions a number of elements that should be contained within such a system. These elements include status reporting, comparison with the baseline schedule, deviation analysis and implementation of corrective actions. While it is not our ambition to propose a DSS in this paper, we contribute to the analysis of project performance deviations from the baseline plan. Hence, we advance a crucial building block of a DSS. Based on the presented research, project managers can act on a warning signal to take corrective action. As a result, this paper's study lies on the interface between project monitoring and taking action. In this paper, we extract relevant information from multiple project control variables. Using principal component analysis (PCA), the information is combined and can be translated to a control chart. We believe that the presented multivariate model will aid project managers in a number of ways. First of all, examining a single control chart instead of one chart for every variable contributes to the ease of use and may lead to less misleading signals. In order to verify if this is the case, the performance of this paper's multivariate control chart will be compared with the results of [26]. Secondly, a warning signal may prompt project managers to take corrective action. A good control chart should be capable of detecting performance problems and, at the same time, it should not issue a warning signal when no problem is found. Similar to [26], we will refer to these criteria as detection performance and probability of overreaction, respectively. Consequently, a second reason for project managers to incorporate the presented multivariate model is because of its improved reliability at detecting problems.

The outline of this paper is as follows. Section 2 introduces multivariate measurements in batch process control and translates these concepts to a project control environment. The employed technique for extracting relevant information from these multivariate measurements is PCA. Section 3 follows the same structure as Section 2. First, some details are provided on the PCA calculations after which a link to schedule control is made. Principal components are the outcome of a PCA and are a linear combination of the original variables. They represent the basis for a new coordinate system onto which the EVM/ES observations during project execution can be projected. In Section 4, we will demonstrate how two new performance metrics, Hotelling's T^2 and squared prediction error, can be calculated based on the PCA of Section 3. The performance of the multivariate method is tested by means of a large computational experiment that contains a diverse set of projects. Section 5 elaborates on how data was generated and explains the role played by Monte Carlo simulations. Additionally, the settings that were used for the simulations are detailed. Section 6 provides results of the computational experiment and benchmarks the performance of this paper's method to the univariate methods of [26]. Final conclusions on this paper's observations and contributions are drawn in Section 7. Four appendices to this paper are available online. They can be freely accessed on the statistical project control research page at www.projectmanagement.ugent.be.

2. Multivariate nature of schedule control

This paper advocates the use of a multivariate model for top-down schedule control. Multivariate techniques have a rich history in batch process control, which will be explained in Section 2.1. In Section 2.2, the multivariate nature of top-down schedule control is presented in a formal way. Subsequently, the implications related to this multivariate nature are discussed for the top-down schedule control process. Finally, we indicate why multivariate techniques are suited to deal with these implications.

2.1. Multivariate measurements in batch process control

Traditional univariate control charts such as CUSUM charts and Shewhart charts [35] have been widely used in batch process monitoring to monitor the key performance measurements of a batch process [36]. However, since these measurements are all driven by the same underlying events but are monitored independently, the interpretation of these control charts is difficult and might lead to misleading conclusions [37]. Therefore, MacGregor & Kourti [37] introduced the use of multivariate control charts in a batch process control context. In [38], MacGregor identified data overload, redundancy and noise as problems common to many multivariate measurement systems. In order to overcome these problems, numerous multivariate projection methods, such as PCA, have been used since the first application of Hotelling's multivariate t-test measure [39]. For a recent overview and comparison of these projection methods, the reader is referred to Bersimis et al. [40]. It is our belief that PCA is ideally suited for multivariate schedule control. In Section 2.2, a justification for the use of this technique is given.

2.2. Multivariate measurements in top-down schedule control

In order to present a formal characterisation of the top-down schedule control process, let us consider a vector $\boldsymbol{x}$ of EVM/ES measurements along the lifetime of the project as an observation for a multivariate random variable X. This random variable X represents the schedule performance measurements of a project (SV, SPI, SV(t), SPI(t)) as observed at the top WBS level. In EVM/ES, X is a function of the underlying activity level performance which can be expressed as the multivariate random variable D, containing the real durations for all activities in the project. In this research, we do not intend to calculate the activity level schedule performance explicitly. Instead, we would like to infer *a state of schedule control*, i.e. whether the activity durations conform to a pre-defined state of control, based on aggregated EVM data. In Section 5 we elaborate on how this state of schedule control is defined.

Based on this implicit inference process, control charts and their corresponding control limits are constructed. In Section 4, we will provide more details on how these charts and limits will be developed and how the information gathered from all four performance measures can be combined into a single control chart. These control charts will be presented to the project manager and will produce a signal when a control limit is exceeded. The project manager is then provided with an indication that the underlying activity durations do not conform with the pre-defined state of control and will likely invest time and resources to drill down the WBS of the project to find the activities that cause the departure from this pre-defined state of control.