Abstract

Cost, schedule, and quality are the three major performance indicators for construction organizations and projects. Monitoring these three indicators provides the managers with valuable information in terms of 'current status', 'corrective countermeasure', and 'forecast of future risks'. Among the three indicators, the cost and schedule functions are closely interrelated as they share common data in their controlling processes, and the progress serves as a common basis for analyzing these performances. However, the managerial effort (or workload) required to acquire and maintain detailed progress data has been the major barrier to practical implementation. Although recent advances in data acquisition technologies (DATs) provide solutions to this barrier, to date, there has been no research addressing a comprehensive framework to implement effective automated progress measurement and management (APMM). Previous research in this area has mainly focused on limited construction tasks or limited functions, and still in the initial stage requiring further development. In this context, this paper aims to propose a comprehensive APMM framework that will enhance the practicability by automating throughout progress planning, controlling and reusing processes.

Keywords: performance measurement, progress, cost, schedule, automation

1 Introduction

Under the ever-changing and highly-competitive construction business environment, performance measurement is a crucial issue for any type of construction organization including owners, architects, engineering firms, and contractors. The methodologies and applications utilized in order to monitor organization-wide performance are getting sophisticated and advanced. Nevertheless, the performance measures in the construction industry are very comprehensive and diverse depending on the level of perspectives, organizational strategies, and management policies.

Moreover, the tremendous management efforts required to collect and analyze the performance data make this systematic performance management difficult. Recent advances in data acquisition technologies (DATs) for the construction industry facilitate enormous improvement of efficiency in performance measurement systems.

In this context, the purpose of this paper is to propose a comprehensive framework of automated performance measurement and management systems for the construction industry. First, the performance measures are investigated in order to identify the most important measures in terms of management efficiency. The variables for automated progress measurement and management (APMM) are then defined for theory and implementation issues.
2 Construction performance measures

One of the key issues of performance measurement in construction is the perspective whether it is measured from a project level or an organization level (Bassioni et al. 2004; Lin and Shen 2007; Yu et al. 2007). Organizational performance measurement has traditionally emphasized the financial profitability (Kagioglou et al. 2001). In order to expand the measures and to reflect the distinct construction industry characteristics, Yu et al. (2007) proposed a performance measurement system by developing twelve construction key performance indicators (KPIs) based on balanced scorecard (BSC) suggested by Kaplan and Norton (1992) as illustrated in P2.1 in Figure 1.

Even though the higher-level organization perspective (P2.1 in Figure 1) has broad and balanced measures, the cost, schedule, and quality are the most often used measures in term of the frequency and workload. The three measures are also intensively used from lower-level organization perspective (P2.2) in order to manage multi-projects within an organization (or multi-organizations in a project).

From the perspectives of P2.2 and P3.1 in Figure 1, cost, schedule, and quality are the typical measures (CII 1997; Jung and Kang 2007), while the value is aptly suggested as a composite measure in a global sense (Alarcón 1996). Further detailed project-level measures were investigated including safety, rework, productivity, construction technique, cooperative manner, and so on (NIST 2001; Cox et al. 2003; Ko et al. 2007).

As illustrated in Figure 1, the cost, schedule, quality, and value are core construction performance measures (in P2.2 and P3.1), as being a bridge, providing basic information with other relevant measures in higher or lower level perspectives (in P2.1 and P3.2). Among these four measures, the cost and schedule are more objective and quantitative (CII 1997). In addition, cost and schedule are closely interrelated since they share a lot of common data in their controlling processes (Jung and Gibson 1999). In summary, it is inferred that cost and schedule data are the most contributing ones among the entire performance measures.

Figure 1. Hierarchical structure of construction performance measures
3 Construction cost and schedule measures

Research in the area of cost and schedule controls has often been related to advanced issues in integrated cost and schedule controls (earned value management systems, EVMS) over the two decades (Jung 2005). These studies are categorized into seven groups in this paper in order to depict a path how the automated progress measurement and management (APPM) issues have evolved.

Introductory papers (McConnell 1985; Stevens 1986) presented the concept, principal methods, benefits, and practical issues by illustrating cases and examples. Papers discussing practical solutions in further detail followed. Eldin (1989; 1991) analyzed project WBS and numbering systems for engineering and construction projects. Singh (1991) added an interesting point of EVMS, which is the managerial issues for successful implementation (E1: Introductory practical issues in Figure 2).

The first paper that comparatively analyzed several methodologies combining cost and schedule data was performed by Rasdorf and Abudayyeh (1991). Issues for ‘providing a unified view’ with an ‘inexpensive data-processing environment’ and ‘IT for data acquisition’ were discussed in their paper. Systematic efforts to represent the EVMS components, indices, variances, and their relations in mathematical formulas followed. Carr (1993) developed complex equations for computer applications. Lee and Yi (1999) introduced mathematical matrices to describe the interrelationship between time and cost data sets (E2: Integration methods and models).

Issues for standard numbering were brought up as EVMS data should be shared with many project participants and across different business functions. Reuse of historical data is also considered in the numbering issue. Kang and Paulson (1998) proposed a four level classification system for civil works. Jung and Woo (2004) developed a flexible work breakdown system (WBS) that utilizes a standard numbering system while allowing full flexibility in its structure. An interesting effort to apply a stochastic model to the progress measurement baseline (Budgeted Cost Work Scheduled – BCWS) was proposed by Barraza et al. (2000). It is noteworthy that the accuracy of a planned schedule is very important in order to maintain performance indices more meaningful (E3: WBS and planning). The major purpose of flexible WBS by Jung and Woo (2004) was to reduce the workload, and the workload was firstly attempted to be quantified. EVMS workloads were also evaluated by different management variables including project delivery systems, contract type, outsourcing, specialization, and others (Jung 2005) (E4: Workloads in Figure 2).

The workloads can be significantly reduced if the measurement is automated. It is found that the practitioners have initial difficulty in developing WBS. In order to solve this problem, Jung and Kang (2007) designed an automated WBS generation methodology (E5: Automated planning). Recent research in the area of automated project performance control (Navon 2007; Navon and Sacks 2007) proposed advanced methods and algorithms by using DATs including RFID, GPS, 3D-scanner, etc. (E6: Automated monitoring). Finally, well-organized historical database can be essentially used for future projects. Automated adjusting mechanisms based on historical database were developed for preliminary cost and schedule generations (Jung 2008; Jung et al. 2009) (E7: Automated adjusting).

Different studies have different research perspectives, scopes, and practical implications. Every study contributed remarkably to the advancement of APMM. However, it is found that no comprehensive APMM framework with broad variables has yet been proposed and examined.

4 Construction progress measures

The most commonly perceived concept of progress implies the ‘work completed’ with the ‘associated cost’. Therefore, progress can be defined as the ‘actual work completed in terms of budgeted cost’ (Jung and Kang 2007). This progress (earned value, or budgeted cost for work performed, BCWP) is used as a baseline to which the planned schedule (budgeted cost for work scheduled, BCWS) and the actual cost (actual cost of work performed, ACWP) are compared in order to measure the schedule performance and cost performance, respectively. The results of performance variances and indices are
used for further analysis, including estimating cost at completion, identifying latent risks, and re-planning for remaining work packages.

Variables for progress measurement can be identified by the major processes across the management cycle including planning (C1), controlling (C2), reusing (C3) as depicted in Figure 2. The processes for APMM along with this cycle consist of formulating measurement packages (M1 in Figure 2), choosing measurement methods for each package (M2), applying appropriate measurement algorithm (M3), and utilizing measurement DAT for each package (M4) as fully discussed in Jung and Kang (2007). To reuse the historical database for future projects, an automated adjustment mechanism (Jung 2008; Jung et al. 2009) needs to be incorporated within the processes (M5).

Even though previous research in APMM has mainly focused on the algorithms and DATs (M3 & M4), recent efforts have expanded toward packages (M1), methods (M2), and adjust mechanisms (M5) (Kang and Jung 2009). An automated WBS generation using knowledge-based historical database was developed by Jung and Kang (2007), and analytical developments for automated work packaging were proposed by Ibrahim et al. (2009) and Zhang et al. (2009) (M1 in Figure 2). Studies actively utilizing DATs explored algorithms for tracking labour, materials, and equipments (Navon 2007; Navon and Goldschmidt 2003; Navon and Shpatnitsky 2005; Saks et al. 2006) (M3 & M4 in Figure 2). Further investigations examined the promising areas focused on specific technology, for example, RFID (Jaselskis and Elmisalami 2003) and time-lapsed photographs (Golparvar-Fard et al. 2009).

Another study by Kang and Jung (2009) developed a DAT selecting methodology for all construction tasks based on the criteria of measurement target (e.g. labour or material), spatial scope, level of automation (e.g. manual or semi-automation), and type of information (e.g. location or image) (M4). Examples of active re-use of historical database (Jung et al. 2000; Jung 2008) through automated adjustment strongly supports the needs for APMM (M5). Additional perspective (E1 through E7 in Figure 2) was investigated in order to explore detailed topics for the five mechanisms (M1 through M5).

Figure 2. Framework for automated progress measurement and management
Summary and conclusions

This paper proposes a comprehensive framework for automated progress measurement and management (APMM) in Figure 2 in order to examine a fully automated system that encompasses all construction tasks (M1 in Figure 2) supporting different level of performance perspectives (P1, P2, P3 in Figure 2) throughout a management cycle (C1, C2, C3 in Figure 2). Computerized methodologies for APMM are categorized into five processes including measurement packages (M1), methods (M2), algorithms (M3), DATs (M4), and adjustment (M5). This comprehensive framework illustrates the components of APMM as well as the full usage of APMM results within a broader managerial value chain in the construction industry.

It is found that previous research in relation to APMM has been mostly focused on the algorithms and DATs (M3 & M4) only for specific construction tasks or DATs. No research was performed in the area of automated measurement methods (M2) (e.g. automated earned value). Automated planning (C1:M1) and reusing (C3:M5) were investigated in limited studies, therefore these are the necessary areas for future APMM research. Comprehensiveness encompassing all construction tasks is recommended in order to effectively enhance the practicability of APMM. Incorporating semi-automation would also be required to boost up the economic feasibility of APMM.

Research team of the authors has actively participated in the packages and adjustment areas (M1&M5) for real-world projects and recognizes the significant importance of practical algorithms and DATs (M3 & M4) for better integrated progress management systems. It is strongly believed that this integration would mutually foster the APMM theory and implementation.

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