# Knowledge-Based Standard Progress Measurement for Integrated Cost and Schedule Performance Control

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**Abstract:** Though the progress of construction projects is most often used as a critical index for effective project management, the method, structure, data, and accuracy of detailed progress measurement may vary depending on specific characteristics of a project. This situation can lead to misinterpretation of the project status, especially under a multiproject management environment. It is also a daunting task for the inexperienced engineers to formulate and monitor the project-specific work packages. At the same time, maintaining very detailed and highly accurate progress information requires excessive managerial efforts. In order to address this issue, this study proposes the concept of standard progress measurement package. Issues for standardization of the work breakdown structure that can embody distinct characteristics of different construction projects are investigated. The proposed methodology facilitates automated formulating of work packages by using a historical database and also automates the gathering of progress information through the use of standardized methods and tools. A case-study project is evaluated in order to examine the practicability of the proposed system.

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## Introduction

Cost, schedule, and quality are the three major indicators for construction project performance. Accordingly, integration of cost and schedule control systems has been an issue of great concern for researchers and practitioners as these two important control systems are closely interrelated, sharing numerous common data (Rasdorf and Abudayyeh 1991; Jung and Gibson 1999; Jung and Woo 2004) in their controlling processes.

In recent efforts to systemize construction management processes, standard methods and procedures coupled with information technology have been widely adapted. The earned value management system (EVMS), which integrates cost and schedule control, is a good example. Two important features of EVMS are the combination of two different construction business functions (i.e., cost and schedule) into a unified perspective and the provision of highly detailed standard methods and procedures so as to compulsorily maintain data integrity among many different project participants (Jung and Woo 2001).

The progress (or earned value) is key information in the integrated cost and schedule control as it provides a baseline for comparison with the planned schedule and/or actual costs. However, the method, structure, data, and accuracy of detailed progress measurements may vary depending on the characteristics of a project, organization, or location. Regardless of the variation in the methods utilized, in terms of accuracy, ideally the progress data should be analyzed and maintained in a highly detailed form. Nevertheless, the excessive workload required to manipulate very detailed progress data is also a critical issue (Deng and Hung 1998; Rasdorf and Abudayyeh 1991; Jung and Woo 2004) for effective cost and schedule control.

No previous research or professional practice has comprehensively addressed the issues of standard progress measurement methodology in terms of its practicability, accuracy, efficiency, and potentiality for automation. In this context, the purpose of this study is to develop an effective progress measurement system utilizing standard progress measurement packages (SPMPs), as depicted in Fig. 1. A prime objective of developing SPMPs is to identify manageable work packages with reliable progress measurement (*enhancing accuracy*).

Even though those are not addressed in detail, this study also discusses applying standard measures and procedures to as many projects as possible so as to attain a corporate-wide index (*making standards*), facilitating the process of work breakdown structure (WBS) formulation by using a prestructured historical database (*alleviating workload*), and accommodating self-evolving features of standard packages by analyzing the changes of managerial policy under an ever-changing business environment (*sustaining adaptability*).

A case study is used throughout this paper in order to illustrate and examine the proposed methodology. The case-project is a research center constructed by a case-company. The research center is basically comprised of an eleven-story office building (two stories underground and nine stories above ground) and a laboratory. Specifics of the project include: 17,087 $m^2$ of total floor area, 19-month project duration. A general contractor's viewpoint as a case-company is applied in this case-study, and the architectural work alone is analyzed excluding earthwork, mechanical,

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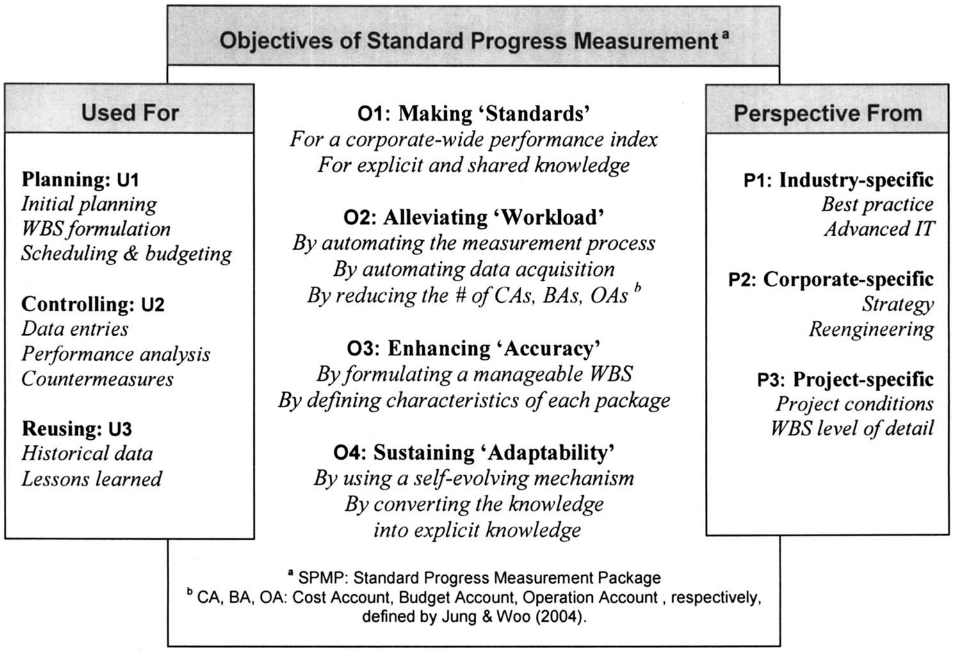


**Fig. 1.** Objectives and issues for SPMPs

**Table 1.** Details of Case-Project

| Description | Specifics | Remarks |
|---|---|---|
| (a) Case-project outlines[a] | | |
| Main use | Research center | An office building and a laboratory |
| Location | Suwon City, South Korea | At Sungkyunkwan University |
| Project delivery method | Design-bid-build | With a third party supervisor |
| Contract type | Lump sum and unit price | |
| Construction duration | January 19, 2000 to July 31, 2001 (19 months) | |
| Site area | 481,264 $m^2$ | |
| Building area | 2,347 $m^2$ | |
| Number of stories | 2 (underground) +9 (above ground) | |
| Total floor area | 17,087 $m^2$ | |
| Structure | Reinforced concrete<br>Precast steel reinforced concrete | Composite precast members used for the superstructure in the office building |
| Construction budget[b] | $12,500.000 | Construction only |
| Number of subcontract packages[b] | 27 | Civil and architectural 21, electrical 1, mechanical 5 |
| Percent of subcontract[b] | 70% | Amount of subcontracts/total budget |
| Number of staff members on site[b] | 8 | General contractor only |
| (b) Progress measurement package evaluation outlines[c] | | |
| Number of standard PMPs | 131 | SPMP_office |
| Number of standard budget items | 6,157 | SMPM_office |
| Number of PMPs | 61 | Case-project, without locators |
| Number of PMP activities | 233 | Case-project, with locators |
| Number of budget items | 433 | Case-project, without locators |
| Number of budget items allocated | 1,290[d] | Case-project, with locators |
| Accuracy score (PAI) | 717 | Out of 10.00 |

[a]The same case-project is also used in Jung and Woo (2004), where details for a workload evaluation are presented.
[b]Descriptions are represented from the general contractor's viewpoint.
[c]Further details are described later in this paper.
[d]Some assumptions are applied for the purpose of simulation.

and electrical. Details of the case-project are summarized in Table 1.

## Progress Measurement in Construction

By definition, "progress" refers to the "advance toward a specific end." The degree of "advance" for a construction project can be determined in many different ways. In their study for measuring construction productivity, Thomas and Mathews (1986) assert that the "progress in terms of work unit completed" and "the associated cost in terms of man-hours or dollars" are typically tracked in order to measure productivity. For the purpose of construction payment, progress can be explained as the "percentages of direct cost incurred plus a portion of overhead and profit" (Stokes 1978). From the viewpoints of cost engineers or scheduling engineers, somewhat different considerations for progress may also be inferred.

Nevertheless, the most commonly perceived concept of progress implies the "work completed" and the "associated cost." Therefore, progress in this study is defined as the "actual work completed in terms of budgeted cost." This definition is identical to the meaning of "earned value," or budgeted cost for work performed (BCWP) in EVMS.

### *Progress in Earned Value Management*

Benefits from integrating cost and schedule control (EVMS) have been asserted by numerous researchers and practitioners since this idea was first promoted in the 1960s. The basic concept utilizes the focal point for the integration of scope, cost, and scheduling (Rasdorf and Abudayyeh 1991; Fleming and Koppleman 1996).

According to a document of the American National Standard Institute (ANSI) for EVMS, a "control account" (CA) as the focal point acts for "a management control point at which budgets and actual costs are accumulated and compared to earned value for management control purposes" (EIA 1998).

The progress (earned value, or 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 replanning for remaining work packages.

The level of progress measurement packages is a critical issue in terms of the "workload" (i.e., manageability) required to maintain the control system and the "accuracy" of the packages (Jung et al. 2001). In other words, it is ideal if very detailed progress data can be gathered and analyzed for any project. However, this situation may require an excess of managerial effort with limited usage of the data. At the same time, it is very likely that less detailed packages would provide more inaccurate information. In order to address this issue, the level of detail for progress measurement should be carefully selected as a trade-off between the workload and accuracy, incorporating strategy, objectives, and management policy of construction projects.

### *Progress Measurement Workload*

The most significant part of workload is collecting and maintaining data that is generated throughout the project life cycle. In particular, EVMS requires more complex data structures and additional management efforts as it integrates two different aspects of business functions (cost and schedule).

Therefore, optimizing (or minimizing) the workload is the critical success factor for practical implementation. This optimization can be achieved (1) by automating data acquisition; (2) by reengineering the cost and scheduling control processes; and/or (3) by adjusting the level of details (Jung 2005).

Automating data acquisition can be obtained by applying such data acquisition technologies as RFID, GPS, or 3D laser scanning (Navon 2005) or by electronically interconnecting databases from relevant business functions (e.g., material management or daily work report). However, utilizing IT is less specific to a project or a company. Rather, it is *industry-specific*, as similar tools and methods can be generally applicable to any type of project (P1 in Fig. 1). On the contrary, the scheme of reengineering varies extensively depending on the organization (Jung et al. 2000). Practical solutions are very different for each company, as they are *organization-specific* (P2 in Fig. 1). Finally, adjusting the level of detail is a *project-specific* issue (P3 in Fig. 1). Basically, the level of detail is determined by the managerial requirements of each project. However, common characteristics within the same type of facilities in a company can be identified in order to effectively utilize the standardized methods.

The three schemes discussed previously should be deliberated in a comprehensive manner, because they complement each other. However, this paper focuses on "adjusting the level of details" by using standardized progress measurement packages that can alleviate the workload for initial WBS formulation (*planning*), data entries (*controlling*), and historical data retrieval (*reusing*). This usage is depicted as U1, U2, and U3 in Fig. 1.

### *Progress Measurement Accuracy*

Several different progress measurement methods are developed and used in construction projects. Definitions and classifications may vary slightly. This study utilizes three major types of measurement methods categorized by Thomas and Mathews (1986): estimated percent complete method, earned value method, and physical measurement method. As listed in Table 2, each method has strengths and weaknesses.

Among these three measurement methods, the earned value method may utilize various techniques for different type of work packages. Fleming and Koppleman (1996) specify seven techniques including percent complete estimate, weighted milestones, fixed formula by task, percent complete and milestone gates, earned standards, apportioned relationships to discrete work, and level of effort. Note that Fleming and Koppleman categorize "percent complete estimate" as one of the earned value techniques whereas Thomas and Mathews (1986) separate it, as described in Table 2.

### *Standards Making*

Standardization of WBS or CA seems extremely difficult in practice, because each construction project is unique and has different managerial requirements. However, this standardization would significantly contribute to reduce the workload and enhance the accuracy of the progress measurement if properly applied.

In their research exploring a process model of standardization in the information and communication technology (ICT) industry, Fomin et al. (2003) define three recursive activities of "design (creating and choosing design alternatives), sense-making (attach-

**Table 2.** Progress Measurement Methods (Adapted from Thomas and Mathews 1986; Fleming and Koppleman 1996)

| Method | Techniques[a] | Advantages[b] | Disadvantages[b] |
|---|---|---|---|
| Estimated percent complete | • Percent complete estimate<br>• Percent complete and milestone gates | Simple<br>Relatively small effort required<br>Suitable for straightforward items | Relying exclusively upon an individual's ability |
| Earned value | • Weighted milestones<br>• Fixed formula by task<br>• Earned standards<br>• Apportioned relationships to discrete work<br>• Level of effort | Greater detail and objectivity than the "estimated percent complete" method | Not detailed as the "physical measurement method" |
| Physical measurement | | The most detailed and reliable<br>Relatively objective<br>Easy to audit | Lack of timely information<br>High cost of data collection |

[a]The techniques are defined by Fleming and Koppleman (1996) and regrouped here by the writers.
[b]The advantages and disadvantages discussed by Thomas and Mathews (1986).

ing meaning to design alternatives), and negotiation (agreeing between designs, fixing the actor network)," which can be a good point of departure for construction WBS standardization.

Managerial similarity within a specific type of construction project (e.g., office buildings) or within a company makes it possible to develop reasonable standard progress measurement packages ("design"). An ever-changing business environment and construction technology may require seamless modification of the standards ("sense-making"). Finally, the standards must incorporate conflicting interests between different projects and different actors ("negotiation"). Again, conflicting interests simultaneously occur between the workload and accuracy in terms of effectiveness.

## Standard Progress Measurement Package

In order to incorporate different interests (the workload, accuracy, and standards issues discussed previously), the SPMP proposed in this study pursues corporate-wide standard packages which are self-evolving. Major features of the proposed methodology are illustrated in the following, and the conceptual components are depicted in Fig. 2 and Table 3.

### *Alleviating Workload*

A work package or a CA is typically composed of two major properties (e.g., first-floor concrete work); one is the classification of commodity breakdown (budget accounts), and the other is arrangement of physical breakdown (locators, e.g., facility, space, or element). Therefore, a small increase in the number of CAs or budget accounts (BAs) under integrated control systems can cause enormous expansion of workloads. In addition, physical breakdown is generally more project specific than commodity breakdown (Jung and Woo 2004).

In order to effectively address this issue, this paper defines a progress measurement package (PMP) as "a major work package composed of assigned budget accounts." A PMP with a physical breakdown (a locator) is then defined as a "PMP activity," which is used as an activity for the CPM schedule or as a CA for EVMS. For example, a commodity group of budget accounts (e.g., concrete, reinforcing bars, and forms) constitutes a PMP (e.g., con-

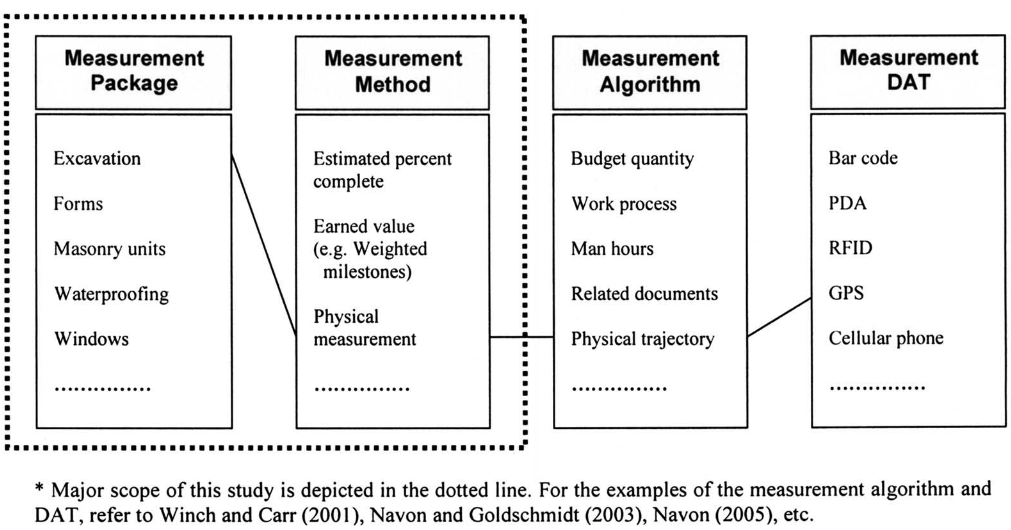


**Fig. 2.** Components of a SPMP

**Table 3.** Structure of a Progress Measurement Package

| Attribute | Example | Value[c] |
|---|---|---|
| PMP title | Formwork (BC3020)[a] | |
| Assigned budget accounts | Wood Form, Material (7411) | |
| | Steel Form, Material (7430) | 4 items |
| | Formwork, labor—Wood form (7412) | |
| | Formwork, labor—steel Form (7431) | |
| Budget weighting (W) | Sum of the four above mentioned items (7411, 7430, 7412, 731) | 11.49% |
| Locator type | By one floor: (50) | One floor |
| Duration type | Less than 1 week (1) | $D<1$ week |
| Complexity type | One major work item, partial progress not accepted (Al) | A1 |
| Measurement method | Weighted milestone (5) | |
| Measurement algorithm | Workers' locations[b] | |
| Measurement DAT | GPS technology for tracking movement of workers[b] | |
| PMP scores | SW—budget weighting score (type: above 5%) | 5 |
| | SD—duration score (type; 1) | 1.0 |
| | SC—complexity score (type; A1) | 10 |
| | SA—accuracy score=SD×SC=1.0×10 | 10 |
| | SAw—weighted accuracy score score=SA×W=10×11.49 | 114.9 |
| Other information | Relevant information including: | |
| | dates (ES, EF, LS, LF, AS, AF); earned value; costs | |
| | progress curve (planned versus actual); and others | |

[a]The letters and numbers in parentheses indicate the code numbers of a relational database.

[b]For an advanced example, the concept of automated labor monitoring (Navon and Goldschmidt 2003) is introduced.

[c]The complete list of 61 PMPs for the case-project and meanings of the values are presented in Tables 3 and 4.

crete work). The group of budget accounts assigned to a specific locator (e.g., first-floor) forms a PMP activity (e.g., first-floor concrete work). Therefore, many PMP activities can stem from each PMP (e.g., ten PMP activities for a concrete work for a ten-story building). Because of the very similar properties of the PMP activities within a PMP, planning and measuring of the workload can be minimized by using this approach. Note that the locator type in Table 3 utilizes the terminology "by one floor" rather than "1st or 2nd floor" for the purpose of standardization.

The proposed PMP structure, as illustrated in Table 3 and Fig. 2, facilitates selection of the required level of detail for the progress measurement, cost control, and schedule control as follows. Each package can be evaluated as a PMP based on the budget accounts assigned; an appropriate locator is then selected from the predefined standard PMPs in order to reduce the workload. A flexible WBS concept (Jung and Woo 2004) is adopted to easily reduce the total number of PMPs. Finally, the standard earned value measurement method described in Table 2 is also widely adapted in the case-study.

## Enhancing Accuracy

For the purpose of enhancing the reliability and promptness of the PMP measurement, three factors affecting the accuracy of progress measurement are identified and used as the criteria for formulating and selecting PMPs. These three factors are the budget weighting, duration, and complexity of PMPs (F1–F3 in Table 4).

### Budget Weighting (F1)

"Budget weighting" indicates the relative importance of a PMP among others in terms of monetary amount. The Pareto's principle (80/20 rule) is applied. In other words, 20% of PMPs with the highest budget weighting would account for 80% of the total budget amount. This factor easily identifies the most important PMPs that would affect the overall measurement accuracy of a project. The case-project shows that 11 PMPs out of 61 total PMPs (16%) account for 67% of the total budget amount (PMPs that have budget weighting above 3% in Table 4). This factor can be used to prioritize the PMPs so as to enhance accuracy with optimized workload.

### Duration (F2)

The proposed system is intended to measure a project's progress on a weekly basis. Therefore, if a PMP is scheduled to be finished within a week, it is very likely that the PMP can be measured by a fixed formula (0/100) with ease and high accuracy. The second factor, "duration," is used in this manner. Five standard duration types are predefined for the purpose of automating and simplifying the process. Substantial duration data for scheduling updates are also used for each project and for the historical database. In the case-project, 34 PMPs (55.7%) out of the total of 61 are scheduled for less than one week. This particular case is well designed for accurate progress measurement on a weekly basis.

### Complexity (F3)

The last factor, "complexity," denotes the level of ease in determining accurate progress measurement for each PMP. The simplicity of work items within a PMP and the proximity of physical locations of the work included are the bases for judgment. For example, a PMP activity of "form work for the second floor" has only one type of work item, and the work envelope is very limited. On the contrary, a PMP activity of "ornamental metal for an office" contains many different work items and the location is dispersed. Because the complexity affects the accuracy, the initial score for complexity defined in Table 4 is used to quantify the accuracy adjustment. In the case-project, as illustrated in Table 4, 32 PMPs (52.5%) have one major work item in each package. Partial progress is accepted, and the major work item is clusterd for the 32 PMPs.

## Sustaining Adaptability

As discussed, applying the same standard PMPs to every single project is not possible. Therefore, the SPMPs have two mecha-

**Table 4.** Factors for Progress Measurement Accuracy

| Factor | Code | Description | Score | Number of PMPs[a] |
|---|---|---|---|---|
| Budget weighting (F1) | 1 | Above 5% | 5 | 6 |
| | 2 | Above 3 to 5% | 4 | 5 |
| | 3 | Above 1 to 3% | 3 | 14 |
| | 4 | Above 0.5 to 1% | 2 | 10 |
| | 5 | Below 0.5% | 1 | 26 |
| Duration (F2) | 1 | Less than one week | 1 | 34 |
| | 2 | One week to less than two weeks | 0.8 | 12 |
| | 3 | Two weeks to less than one month | 0.6 | 11 |
| | 4 | One month to less than two months | 0.4 | 3 |
| | 5 | More than two months | 0.2 | 1 |
| Complexity (F3) | A1 | One major work item, partial progress not accepted | 10 | 5 |
| | A2 | One major work item, partial progress accepted, work clustered | 8 | 32 |
| | A3 | One major work item, partial progress accepted, work scattered | 6 | 2 |
| | B1 | Limited major work item, partial progress not accepted | 10 | — |
| | B2 | Limited major work items, partial progress accepted, work clustered | 7 | 10 |
| | B3 | Limited major items, partial progress accepted, work scattered | 5 | 2 |
| | C1 | Many major work items, partial progress not accepted | 10 | — |
| | C2 | Many major work items, partial progress accepted, work clustered | 6 | — |
| | C3 | Many major work items, partial progress accepted, work scattered | 4 | 8 |
| | D1 | Prefabricated items for site installation only, work clustered | 10 | 2 |
| | D2 | Prefabricated items for site installation only, work scattered | 8 | — |
| | E1 | Overhead cost | 10 | — |
| Physical breakdown (locator) | 10 | By an element (e.g., column, beam, slab, etc.) | | — |
| | 20 | By a room | | — |
| | 30 | By a stairwell | | 2 |
| | 40 | By a zone | | — |
| | 50 | By one floor | | 30 |
| | 51 | By two floors | | 3 |
| | 52 | By three floors | | 1 |
| | 58 | By an assemble (e.g., assemble of steel or PC members) | | 2 |
| | 60 | By one building | | 3 |
| | 70 | By a section of works | | 2 |
| | 80 | By project | | 18 |

[a]The number of PMPs of the case-project (total number is 61 as noted in Table 5).

nisms in this regard: the alternative PMPs that are provided for composing or decomposing and an evolving mechanism as the environment and management policies change.

For example, the PMP of "concrete" can be decomposed into three PMPs, "formwork," "rebar," and "concrete pouring," or vice versa. The alternatives are predefined as well, and a limited number of nonstandard PMPs can be created for a specific project. As the historical database is accumulated, the PMP used most often will be chosen as the standard. In other words, if most of the projects in an organization select the decomposed PMPs (e.g., formwork, rebar, and concrete pouring instead of concrete), then the decomposed ones are selected as standards. This implies that the SPMPs evolve to incorporate management trends and requirements.

## Standard Progress Measurement Process

The three factors of "budget weighting (F1), duration (F2), and complexity (F3)" defined in Table 4 are independent of each other by their nature. Among these factors, budget weighting is utilized to control the accuracy from a macro perspective. Namely, a PMP with greater budget weighting has priority when reorganizing PMPs (formulating and adjusting WBS) for a project.

On the other hand, duration and complexity are controlling factors for PMPs at a micro level. The accuracy of a PMP can be improved by manipulating these two factors. A good example is a concrete PMP. In general, concrete work has a higher budget weighting, and thus it needs to be packaged into smaller PMP activities by assigning a detailed locator (e.g., a specific element or a zone on each floor).

For a new construction project, project PMPs can be automatically generated by copying them from a set of standards (SPMPs, I1 in Fig. 3). The appropriateness of an individual PMP is then evaluated to fit the characteristics of the project (I2). All PMPs for the project are evaluated again by comparing the project indices with company standard indices (I3). If the project indices are found to be reasonable, then the PMPs are used. If not, some PMPs can be changed and reevaluated (return to I1). After completion of the project, the PMPs with actual project data will be added to the historical PMP repository (I5), which will in turn update the SPMPs. Fig. 3 illustrates the PMP implementation cycle.

### *Developing PMPs (I1)*

The first step is to develop a project's WBS with careful requirements for integrated cost and schedule control. Selected WBS packages of managerial importance are chosen as PMPs. Budget items are allocated to each PMP, the locator type is determined, and the duration type is defined.

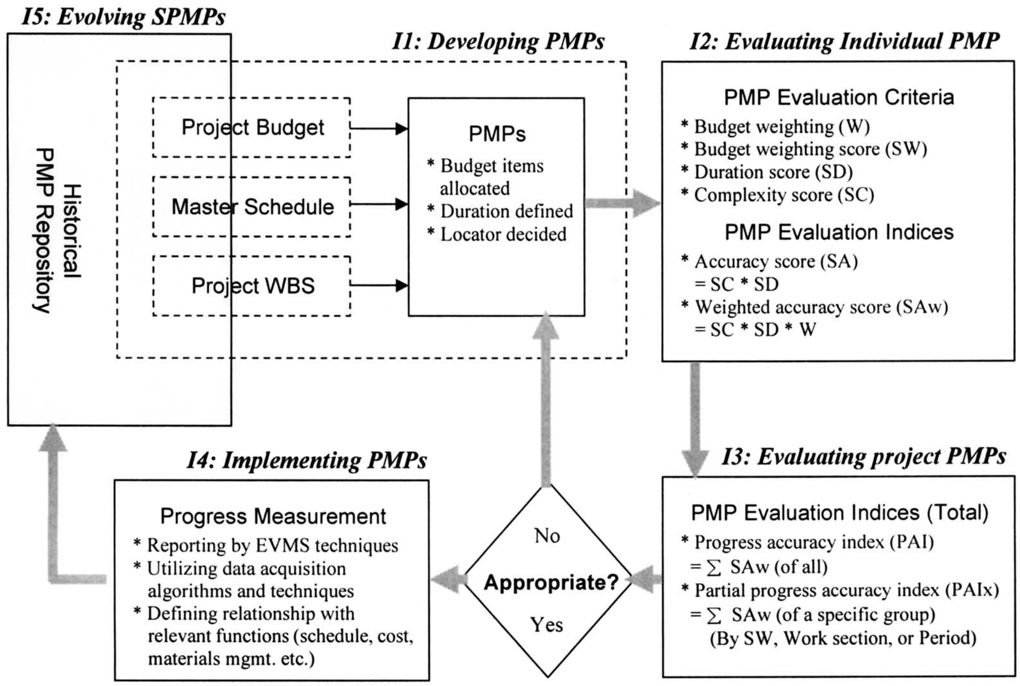


**Fig. 3.** Process of PMP implementation

The automated progress measurement system (APMS) proposed in the present study automates this WBS generation by using SPMPs. The budget items for a new project are automatically distributed over PMPs with a standard duration, a standard complexity type, and a standard physical breakdown (locator), as shown in Tables 4 and 5. The standard code numbers used both for PMPs and budget items make this automated distribution possible. Project specifics such as numbers of buildings, floors, and zones are the initial input for the automated process. By using the project specifics and the predefined standard locators, the APMS can easily generate PMPs and allocate the budget according to the contents of SPMPs.

### Evaluating Individual PMP (I2)

Based on the predefined properties of the SPMPs, each PMP generated (in I1 of Fig. 3) has a budget weighting (W), a budget weighting score (SW), a duration score (SD), a complexity score (SC), an accuracy score (SA), and a weighted accuracy score (SAw), as illustrated in Table 5. SW is calculated by dividing the budget amount of each PMP by the total budget amount. The values of SD and SC are predefined in Table 4.

SA of a PMP is then obtained by multiplying the SC by the SD. The duration score herein is used as an independent adjusting factor to the complexity score, because a longer duration lowers the accuracy of a PMP's progress measurement. Finally, the SAw is calculated by multiplying the SA by each PMP's W

$$SA = SC \times SD \tag{1}$$

$$SAw = SA \times W \tag{2}$$

### Evaluating Project PMPs (I3)

The progress accuracy index (PAI), which is the total of all PMP's weighted accuracy scores, is used as an index for determining the appropriateness of the entire body of PMPs for a project. The PAI can further explore specific groups of PMPs by budget weighting ranges, work sections, or periods (e.g., PMPs above 5% budget weighting, PMPs for mechanical, or PMPs for August 2006, respectively)

$$PAI = \Sigma SAw/100 \text{ (for a project)} \tag{3}$$

$$PAIx = \Sigma SAw/100 \text{ (for a specific group of PMPs)} \tag{4}$$

Therefore, if the PAI of a project is not satisfactory, selected PMPs can be adjusted in order to raise the score. Two major methods of adjusting PMPs are (1) combining or decomposing the PMP commodity group of "work section items;" and/or (2) changing the locators of "facility, space, or element." Adjusted PMPs are determinant for automatic changing of budget weights, duration scores, and complexity scores.

PAIx can be used to facilitate identification and adjustment of PMPs with less effort. They also verify evenly distributed appropriateness of the measurement accuracy over different PMPs, work sections, and time periods. As noted earlier, a higher PAI or PAIx is not always a good solution because higher PAI scores require more site engineer man hours. The score is a base to compare with previous cases in order to find optimized workload and accuracy.

### Monitoring and Controlling PMPs (I4)

Even though automated PMP generation and evaluation effectively handles the early stage of the progress measurement procedure, monitoring and controlling all detailed PMPs may require a great deal of effort, especially for collecting and analyzing progress data. The automated progress measurement system (APMS) in this study entails the use of corporate standard progress measurement algorithms and tools, as depicted in Fig. 2 and Table 3.

**Table 5.** List of PMPs of the Case-Project

| SPMP ID | PMP title | Budget item Number | Budget item % (W) | Type Locator | Type Duration | Score C[a] | SW | SD | SC | SA | SAw |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BB10 | Excavation and fill | 5 | 0.97 | A section | 1 month ≤ $D$ < 2 months | B2 | 3 | 0.4 | 7 | 2.8 | 2.72 |
| BC10 | Scaffolding and temporary | 11 | 2.11 | One building | $D$ ≥ 2 months | C3 | 3 | 0.2 | 4 | 0.8 | 1.69 |
| BC3010 | Cast-in-place concrete | 5 | 8.45 | One floor | $D$ < 1 week | A1 | 5 | 1.0 | 10 | 10.0 | 84.5 |
| *BC3020* | *Formwork*[b] | *4* | *11.49* | *One floor* | $D$ < 1 week | *A1* | *5* | *1.0* | *10* | *10.0* | *114.9* |
| BC3030 | Reinforcing steel | 9 | 7.03 | One floor | $D$ < 1 week | A1 | 5 | 1.0 | 10 | 10.0 | 70.3 |
| BC40A | Plant-precast concrete | 2 | 1.86 | One floor | 1 week ≤ $D$ < 2 weeks | D1 | 3 | 0.8 | 10 | 8.0 | 14.88 |
| BC5010 | Structural steel | 21 | 6.71 | An assemble | 1 month ≤ $D$ < 2 months | D1 | 5 | 0.4 | 10 | 4.0 | 26.84 |
| BC5020 | Steel erection | 17 | 1.38 | An assemble | $D$ < 1 week | A1 | 3 | 1.0 | 10 | 10.0 | 13.8 |
| BC5030 | Steel deck | 5 | 3.78 | One floor | $D$ < 1 week | Al | 4 | 1.0 | 10 | 10.0 | 37.8 |
| BC60A | Brick masonry | 8 | 3.06 | Two floors | 1 week ≤ $D$ < 2 weeks | A2 | 4 | 0.8 | 8 | 6.4 | 19.58 |
| BC60B | CMU | 12 | 0.72 | One floor | 1 week ≤ $D$ < 2 weeks | A2 | 2 | 0.8 | 8 | 6.4 | 4.61 |
| BD10 | Roofing accessories | 6 | 0.32 | Project | $D$ < 1 week | B2 | 1 | 1.0 | 7 | 7.0 | 2.24 |
| BE20A | Cementitious waterproofing | 5 | 0.18 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 1.44 |
| BE20B | Sheet waterproofing | 9 | 0.44 | One floor | 2 weeks ≤ $D$ < 1 month | B2 | 1 | 0.6 | 7 | 4.2 | 1.85 |
| BE20C | Fluid-applied waterproofing | 2 | 0.06 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 0.48 |
| BE20D | Special waterproofing | 2 | 0.65 | One floor | 1 week ≤ $D$ < 2 weeks | A2 | 2 | 0.8 | 8 | 6.4 | 4.16 |
| BE20F | Joint sealants | 2 | 0.04 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 0.32 |
| BE2505 | Cement plaster (interior) | 13 | 2.26 | One floor | 1 week ≤ $D$ < 2 weeks | A2 | 3 | 0.8 | 8 | 6.4 | 14.46 |
| BE2510 | Cement plaster (exterior) | 3 | 0.11 | One floor | 1 week ≤ $D$ < 2 weeks | A2 | 1 | 0.8 | 8 | 6.4 | 0.7 |
| BE2515 | Cement plaster (floor) | 4 | 1.27 | One floor | $D$ < 1 week | A2 | 3 | 1.0 | 8 | 8.0 | 10.16 |
| BE2530 | Cement plaster (stair) | 6 | 0.25 | A stairwell | 1 month ≤ $D$ < 2 months | A2 | 1 | 0.4 | 8 | 3.2 | 0.8 |
| BE2535 | Coatings for concrete | 2 | 0.12 | Two floors | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 0.96 |
| BE2540 | Concrete finishing | 4 | 0.32 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 2.56 |
| BE2545 | Insulation mortar | 2 | 0.05 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 0.4 |
| BE2570 | Cementitious decks | 4 | 0.45 | Two floors | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 3.6 |
| BE30A | Ceramic tile (floor) | 5 | 0.28 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 2.24 |
| BE30B | Stone tile | 5 | 0.32 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 2.56 |
| BE30C | Ceramic tile (wall) | 5 | 0.33 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 2.64 |
| BE35A | Stone flooring (exterior) | 6 | 0.39 | One floor | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 3.12 |
| BE35C | Stone facing (interior) | 5 | 0.39 | One floor | $D$ < 1 week | B2 | 1 | 1.0 | 7 | 7.0 | 2.73 |
| BE35D | stone facing (exterior) | 5 | 8.75 | One floor | $D$ < 1 week | A2 | 5 | 1.0 | 8 | 8.0 | 70.0 |
| BE35H | Stone jams and sills | 4 | 0.16 | One building | $D$ < 1 week | A3 | 1 | 1.0 | 6 | 6.0 | 0.96 |
| BE35K | Metal truss | 1 | 6.11 | One floor | $D$ < 1 week | A2 | 5 | 1.0 | 8 | 8.0 | 48.88 |
| BE40A | Stainless steel handrails | 6 | 0.63 | A stairwell | $D$ < 1 week | A2 | 2 | 1.0 | 8 | 8.0 | 5.04 |
| BE40D | Gratings and trenches | 5 | 0.21 | A section | $D$ < 1 week | C3 | 1 | 1.0 | 4 | 4.0 | 0.84 |
| BE40E | Aluminum metal fabrication | 3 | 0.50 | Project | 1 week ≤ $D$ < 2 weeks | A2 | 1 | 0.8 | 8 | 6.4 | 3.20 |
| BE40F | Aluminum ceiling | 1 | 0.03 | Project | $D$ < 1 week | B3 | 1 | 1.0 | 5 | 5.0 | 0.15 |
| BE40G | Fan coil unit covers | 1 | 0.74 | One floor | $D$ < 1 week | A3 | 2 | 1.0 | 6 | 6.0 | 4.44 |
| BE40H | Miscellaneous metalwork | 14 | 0.77 | One building | 2 weeks ≤ $D$ < 1 month | C3 | 2 | 0.6 | 4 | 2.4 | 1.85 |
| BE5005 | Steel doors | 9 | 1.35 | Project | 2 weeks ≤ $D$ < 1 month | A2 | 3 | 0.6 | 8 | 4.8 | 6.48 |
| BE5010 | Stainless steel doors | 7 | 0.12 | Project | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 0.96 |
| BE5015 | Aluminum windows | 34 | 3.08 | Project | 2 weeks ≤ $D$ < 1 month | A2 | 4 | 0.6 | 8 | 4.8 | 14.78 |
| BE5030 | Hardware | 32 | 1.24 | Project | 2 weeks ≤ $D$ < 1 month | C3 | 3 | 0.6 | 4 | 2.4 | 2.98 |
| BE55A | Glazing (interior) | 10 | 0.31 | Project | 2 weeks ≤ $D$ < 1 month | B3 | 1 | 0.6 | 5 | 3.0 | 0.93 |
| BE55B | Glazing (exterior) | 6 | 1.42 | Project | 2 weeks ≤ $D$ < 1 month | B2 | 3 | 0.6 | 7 | 4.2 | 5.96 |
| BE60A | Painting (interior) | 13 | 1.08 | Three floors | 2 weeks ≤ $D$ < 1 month | A2 | 3 | 0.6 | 8 | 4.8 | 5.18 |
| BE60B | Painting (exterior) | 1 | 0.02 | Project | 1 week ≤ $D$ < 2 weeks | A2 | 1 | 0.8 | 8 | 6.4 | 0.13 |
| BE60C | Painting (misc) | 3 | 0.08 | Project | 1 week ≤ $D$ < 2 weeks | B2 | 1 | 0.8 | 7 | 5.6 | 0.45 |
| BE65A | Resilient flooring | 3 | 1.53 | One floor | $D$ < 1 week | A2 | 3 | 1.0 | 8 | 8.0 | 12.24 |
| BE65B | Access flooring | 1 | 0.04 | Project | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 0.32 |
| BE65C | OA flooring | 1 | 0.25 | Project | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 2.0 |
| BE65D | System furniture | 15 | 1.08 | Project | 2 weeks ≤ $D$ < 1 month | C3 | 3 | 0.6 | 4 | 2.4 | 2.59 |
| BE65E | Compartments and cubicles | 3 | 0.30 | Project | $D$ < 1 week | A2 | 1 | 1.0 | 8 | 8.0 | 2.4 |
| BE65F | Ceiling | 17 | 4.22 | One floor | 1 week ≤ $D$ < 2 weeks | B2 | 4 | 0.8 | 7 | 5.6 | 23.63 |
| BE65G | Gypsum board assemblies | 3 | 3.86 | One floor | 1 week ≤ $D$ < 2 weeks | B2 | 4 | 0.8 | 7 | 5.6 | 21.62 |

**Table 5.** (*Continued.*)

| SPMP ID | PMP title | Budget item | | Type | | Score | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Number | % (W) | Locator | Duration | C[a] | SW | SD | SC | SA | SAw |
| BE70A | Cementitious fireproofing | 1 | 1.27 | One floor | $D<1$ week | A2 | 3 | 1.0 | 8 | 8.0 | 10.16 |
| BE70B | Acoustical wall | 2 | 0.76 | One floor | $D<1$ week | B2 | 2 | 1.0 | 7 | 7.0 | 5.32 |
| BE70C | Building insulation | 5 | 1.16 | One floor | 1 week $\leq D<2$ weeks | B2 | 3 | 0.8 | 7 | 5.6 | 6.50 |
| BE75 | Miscellaneous finishing | 4 | 0.69 | Project | $D<1$ week | C3 | 2 | 1.0 | 4 | 4.0 | 2.76 |
| BE8010 | Planting | 15 | 0.85 | Project | 2 weeks $\leq D<1$ month | C3 | 2 | 0.6 | 4 | 2.4 | 2.04 |
| BE8020 | Pavement and landscape | 19 | 1.60 | Project | 2 weeks $\leq$ 1 month | C3 | 3 | 0.6 | 4 | 2.4 | 3.84 |
| | Total 61 PMPs | 433 | 100.00 | | | | | | | | 7.1767 |

[a]C=complexity type.

[b]Details for the "formwork (BC3020)" PMP are described in Table 3.

An advanced example by Navon and Goldschmidt (2003) involves utilizing a global positioning system (GPS) in order to track the movement of workers. In this case, the GPS is a measurement tool, and interpreting the movement of workers for progress is a measurement algorithm. The case-project of this study used traditional algorithms and tools as standards for the most of PMPs. However, a set of PDAs and proprietary developed software (Winch and Carr 2001) by the case-company is recommended as an input device.

### *Evolving Standard PMPs (I5)*

As historical project data accumulate, the automated progress measurement system (APMS) will self-evolve with more suitable and practical SPMPs. When a project is completed, project data with a PMP structure are stored into a historical PMP depository. By analyzing the historical PMP contents and trends, new standards can be easily determined. At present, updates should be performed by an experienced head office engineer through regular monitoring of managerial changes. However, an automated method such as case-based reasoning will be developed in order to facilitate this process.

Another feature of the proposed system is that different sets of SPMPs can be used in order to fit different types of construction projects. For example, SPMP_apartment, SPMP_office, and SPMP_hospital can be separately defined for easier use. Nevertheless, standard budget items assigned in the same standard PMP are identical among these different sets of SPMPs, while default duration and default locator may vary. This issue is related to corporate-wide integrity regardless of type of construction.

## A Case Study and Implications

In order to examine the practicability of the proposed system, initial SPMPs for office buildings are developed and PMPs for a case-study project are formulated first. Architectural PMPs (excluding earthwork, electrical, and mechanical packages) are analyzed in the case-study.

Fig. 4 depicts the data structure of the SPMP_office. The first version of SPMP_office contains 131 SPMPs and 6,157 standard budget items generally applicable to office building projects for the case-company, as shown in Table 1. These 6,157 budget items are allocated into 131 standard PMPs. Each standard PMP has a predefined duration type, complexity type, and other properties, as shown in Table 3.

The case-project is an office building as described in the introduction of this paper and outlined in Table 1. Sixty-one SPMPs out of 131 were applicable for the case-project (in Table 5), and 233 PMP activities are generated by applying the locators. These 233 PMP activities are the CPM activities for integrated cost and schedule control. Four hundred thirty-three budget items of the case-project are allocated to 233 PMP activities, resulting in 1,290 budget items with locators (physical breakdown). Note that this case is a slightly modified version of "Scenario 1" of the same case-project introduced in Jung and Woo (2004). The number of CAs, BAs, and OAs (250, 544, and 1329, respectively, from Scenario 1 of Table 5 in Jung and Woo 2004) correspond to the number of PMPs activities (CAs), budget items (BAs), and budget items allocated to PMP activities (OAs) (233, 433, and 1290, respectively) in this paper. Budget weights are calculated and evaluation indices are obtained (the process of I1 in Fig. 3).

Throughout several workshops with the managers of the case-company, the PMPs and PMP activities were evaluated in order to ensure their practicality and applicability in terms of progress measurement requirements for the case-study company (I2 in Fig. 3). The numbers of PMPs and PMP activities were also verified as being reasonable, considering the characteristics of Korean general contractors (Jung and Woo 2001). Thus, it also accommodates scheduling without CPM applications if there is a practical barrier to CPM tool usage.

An initial quantitative evaluation of the project PMPs (I3 in Fig. 3) was performed. The SAw of all 61 PMPs was found to be 7.17 in Table 5, where 10 is ideally the highest score without considering required workload. Partial weighted accuracy scores (PAIx) were also examined, as shown in Fig. 5. For "PAI_work_section," the "temporary work" (e.g., scaffoldings and others) showed the lowest score. The first and second months of the case-project had very low "PAI_period" scores because most of the work for this time frame was largely related to site preparation and temporary work. Note that graph (b) in Fig. 5 does not include March 2000, when the major earthwork was executed, which is not included in this case-study. The PMPs with budget weightings between 0.5 and 1% scored the lowest in "PAI_ budget_ weighting." It is concluded that the PAI and PAIx of the case-project satisfy the case-company's progress measurement requirements.

In order to examine the proposed scoring system and the appropriateness of standard scores (including SA, SAw, PAI, and PAIx), each PMP was reevaluated in a different manner by using another workshop. Accuracy scores in this workshop were determined by expert discussion and judgment without utilizing the proposed scoring system in Table 4. Most of the PMPs showed no significant difference between these two scores. PMPs with considerably different scores were reviewed and modified.

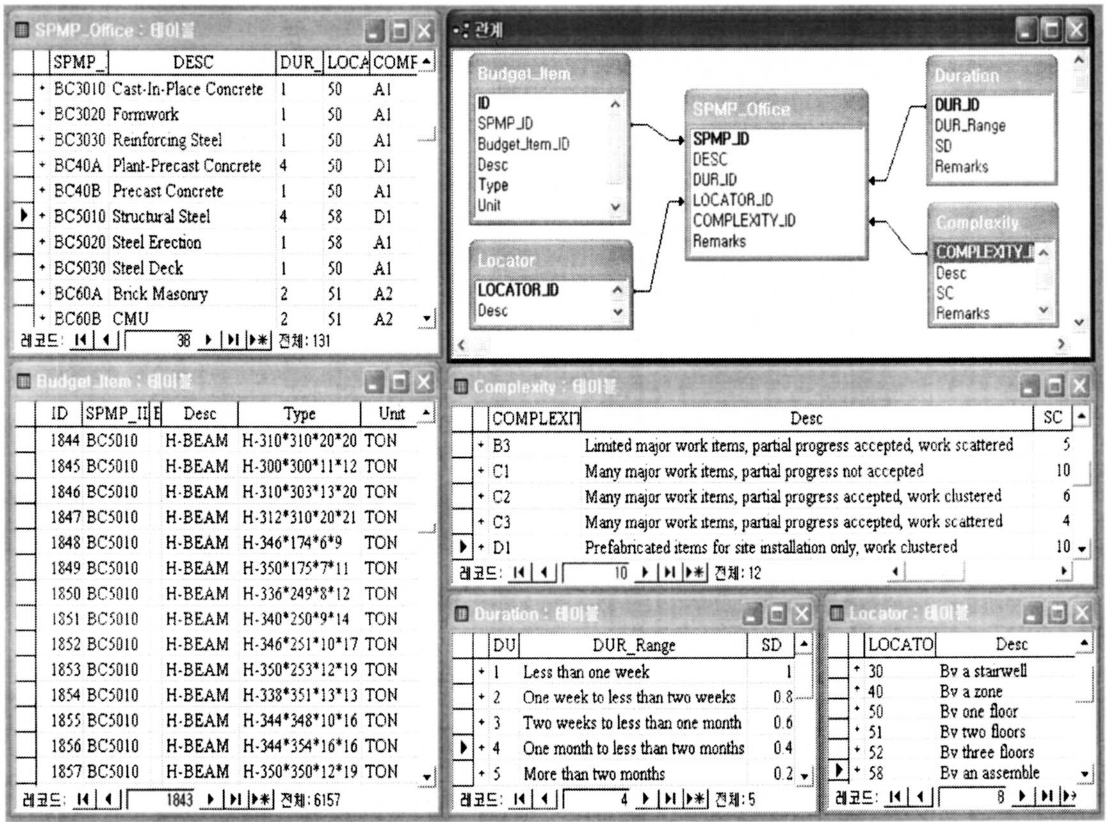


**Fig. 4.** Relational database of SPMP

Throughout these evaluations and simulations, identifying manageable work packages for progress measurement with desirable accuracy were satisfied, which is one of the major research objectives in this paper.

The results of the case-project evaluation were directly used to update the properties of the initial standard for SPMP_office, even though the case-project does not include all packages (I5 in Fig. 3). In this manner, the default values of standard PMPs can be repeatedly tested and adjusted through additional simulations and pilot projects. Once a satisfactory SPMP_office is obtained, PAI and PAIx of a new project can be compared with the standard PAI and standard PAIx in order to evaluate the overall appropriateness of the project PMPs (I3 in Fig. 3). This process can effectively distinguish the PMPs those need to be adjusted in order to fit project specifics.

## Conclusions

Progress is a key performance index for construction projects. Therefore, a standard progress measurement system in terms of classification, method, procedure, accuracy, and data acquisition would provide a valuable management tool, especially under multiproject management requirements or for inexperienced site engineers.

This study proposed an APMS that utilizes corporate-wide SPMPs based on a historical database and knowledge. Research objectives (making standards, alleviating workload, enhancing accuracy, and sustaining adaptability) of this study were attained by the proposed concepts and tools. The case-study reveals that the proposed methodology effectively facilitates the process of developing and controlling PMPs. Ongoing exploration of data acquisition technology applications will soon equip this system with a more efficient data collection engine.

The earthwork, mechanical, and electrical divisions have not been completed for the case-study, and the guideline scores for the accuracy factors and indices (SD, SC, PAI, and PAIx) are still under further updates through additional case-based simulations. However, the proposed methodology is sufficiently flexible to incorporate all different construction divisions (work sections) for any construction organization. SPMPs will also serve as a self-evolving data repository for progress measurement as well as historical database reuse.

The writers believe that systematic measurement of construction project progress as knowledge based management is of great importance in this competitive industry. Enhancing the accuracy of progress information by using standardized and automated systems would greatly contribute to project control systems including scheduling, cost control, materials management, and other related construction business functions.


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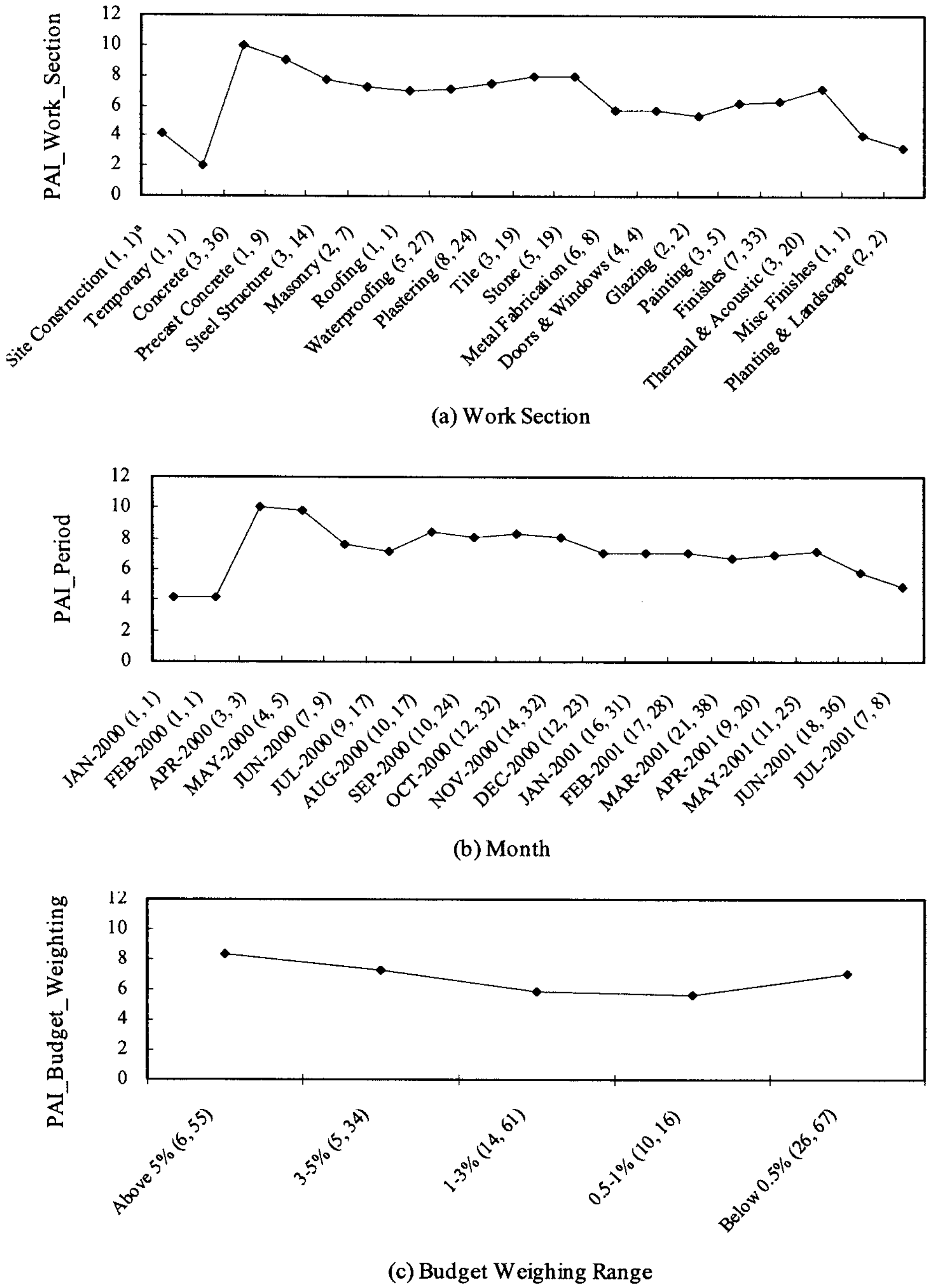


[a]The numbers in parentheses are (# of PMPs, # of PMP activities).

**Fig. 5.** PAIx scores (case-project)

## References


Deng, M. Z. M., and Hung, Y. E. (1998). "Integrated cost and schedule control: Hong Kong perspective." *Proj. Manage. J.*, 29(4), 43–49.

Electronic Industries Alliance (EIA). (1998). "Earned value management systems." *EIA publication no. ANSI/EIA-748-1998*, Arlington, Va.

Fleming, Q. W., and Koppleman, J. M. (1996). *Earned value project management*, Project Management Institute (PMI), Upper Darby, Pa.

Fomin, V., Keil, T., and Lyytinen, K. (2003). "Theorizing about standardization: Integrating fragments of process theory in light of telecommunication standardization war." *Sprouts: Working Papers on Information Environments. Systems and Organizations*, 3(1), 29–60.

Jung, Y. (2005). "Integrated cost and schedule control: Variables for theory and implementation." *Proc., Construction Research Congress 2005*, San Diego, 34.

Jung, Y., and Gibson, G. E. (1999). "Planning for computer integrated construction." *J. Comput. Civ. Eng.*, 13(4), 217–225.

Jung, Y., Park, H., and Moon, J.-Y. (2000). "Requirements for integrated cost and schedule control: Process redesign guidelines for the Korean contractors." *Working paper no. 25*, Construction & Economy Research Institute of Korea (CERIK), Seoul, Korea.

Jung, Y., Seo, J.-B., Lee, S.-H., and Kim, Y.-K. (2001). "Determining effective level of detail for EVMS applications for the construction project management." *Research Rep. No. R05-2000-000-00360-0*, Korea Science and Engineering Fund (KOSEF), Seoul, Korea.

Jung, Y., and Woo, S. (2001). "EVMS prototype system for the Korean general contractors." *J. of the Korean Society of Civ. Engineers*, 21(3), 365–374.

Jung, Y., and Woo, S. (2004). "Flexible work breakdown structure for integrated cost and schedule control." *J. Constr. Eng. Manage.*, 130(5), 616–625.

Navon, R. (2005). "Automated project performance control of construction projects." *Autom. Constr.*, 14(4), 467–476.

Navon, R., and Goldschmidt, E. (2003). "Can labor inputs be measured and controlled automatically?" *J. Constr. Eng. Manage.*, 129(4), 437–445.

Rasdorf, W. J., and Abudayyeh, O. Y. (1991). "Cost- and schedule-control integration: Issues and needs." *J. Constr. Eng. Manage.*, 117(3), 486–502.

Stokes, M. (1978). *Int. construction contracts*, McGraw-Hill, New York.

Thomas, H. R., and Mathews, C. T. (1986). "An analysis of the methods for measuring construction productivity." *CII source document 13*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.

Winch, G., and Carr, B. (2001). "Benchmarking on-site productivity in France and the UK: A CALIBRE approach." *Constr. Manage. Econom.*, 19(6), 577–590.