PAPERS

Project Management Knowledge and Effects on Construction Project Outcomes: An Empirical Study

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ABSTRACT

This study examines the relationships among the *PMBOK® Guide*, project performance, customer satisfaction, and project success by assessing the efficacy of management techniques, tools, and skills for implementing infrastructure and building construction. Experienced interviewees from private engineering firms and public agencies were asked to complete a questionnaire, and the responses were analyzed by means of a structural equation model. The analytical results indicate the appropriateness of prioritizing the practice of the *PMBOK® Guide* in the construction industry. This study contributes to the literature by providing insight into interactions among the *PMBOK® Guide* and construction project outcomes in engineering practices. Particularly, the "bidder's conference" and "procurement negotiations" are the priority techniques to minimize bidding and legal procurement problems. Moreover, the study recommends the use of "stakeholder analysis," "communication requirements analysis," and the "communication methods" to perform effective communication management. Although the conclusions are based on the sample collected in Taiwan, the research findings can be used by project managers and educators to tailor the *PMBOK® Guide* to their unique needs and to design effective training programs for construction specialists.

KEYWORDS: *PMBOK® Guide*; perceived performance; customer satisfaction; project success; structural equation model; construction engineering

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INTRODUCTION

The construction industry is closely related to economic development and living lifestyles. Engineering management, as one of the critical disciplines in construction engineering, directly impacts the life and property security in the environment. As society develops, construction projects naturally grow in scale, involving vast numbers of professionals, long life cycles, and complex interfaces. Therefore, the types and quantities of construction-related information have become quite large and complex, which has increased the complexity of construction operations processes. Construction projects now require highly specialized knowledge and experiential feedback. Traditional operational processes may no longer be useful for resolving certain problems. Project management was developed in response to these challenges, by facilitating project implementation and delivery.

Because of the limited information disseminated by global project management educators, the rapid changes in the construction industry urgently require engineers who can apply project management techniques, tools, and skills (TTS) in the work practice. Rapid advances in management science have led to development of project management into a complete system of knowledge (Indelicato, 2009). Project management was initially developed by the defense industry in response to national security needs but has since grown to emphasize the relationships among various operational activities during the project life cycle. In engineering projects, a construction project can be analyzed in terms of five main steps: feasibility analysis, planning, design, construction, and operation. Each stage can also be analyzed as a single project, meaning that a unique product or service is produced at each stage.

Effective project management is essential in a project-oriented industry such as construction (Isik, Arditi, Dikmen, & Birgonul, 2008). Identifying efficient approaches is crucial for project success. To improve project outcomes (e.g., performance; satisfaction, and success), *A Guide to the Project Management Body of Knowledge Guide (PMBOK® Guide*) was developed by the Project Management Institute to identify general project management knowledge, processes, techniques, tools, and skills (PMI, 2008). The *PMBOK® Guide* contains the fundamental, baseline practices that drive business results for any organization, including those organizations in the construction industry. By applying these management techniques, project managers and project teams can enhance the chances of success over a wide range of projects (Zwikael, 2009).

One trend in the construction industry is a growing emphasis on project management. However, project management as pursued by most construction companies is related only to fields such as document management and knowledge communities. Ineffective integration of project management with enterprise operational processes prevents synergistic effects and causes resource waste and reduced operational efficiency. These failures have increased enterprise burdens and have prevented companies from enhancing their competitiveness. Construction engineers and personnel have widely varying understanding of project management knowledge practice.

Specifically, no clear standards have been developed for prioritizing project knowledge needed for task execution (Bryde & Wright, 2007; Zwikael, 2009). Most companies determine which management techniques or tools are needed for a particular project based on personal experience or on legacies passed down by industry predecessors. These methods are not scientific or objective. Management personnel may be unable to make accurate judgments regarding the project management skills or tools needed for a specific project before engineering is implemented. A current literature review shows that no studies have attempted to identify a priority list of *PMBOK® Guide* techniques, tools, and skills or to empirically measure their effects on project outcomes—namely, perceived performance, customer (stakeholder) satisfaction, and project success.

The association between *PMBOK® Guide* practice and construction project outcomes needs further clarification. Therefore, this study empirically examined the impact of the project management knowledge of project managers and stakeholders on final construction project outcomes. Particularly, the project management knowledge examined in this study is the techniques/tools/skills (TTS) in the *PMBOK® Guide* of application domains. The results of this study are expected to be critical for improving understanding of how the *PMBOK® Guide* affects project success.

First, a hypothetical research model was constructed by reviewing the relevant literature. Construction industry project personnel in Taiwan were then surveyed regarding the application of project management TTS and their impact on project outcomes in terms of performance in project participation, business owner satisfaction, and the frequency of project success. Structural equation modeling (SEM) was then performed to identify the management techniques with the greatest impact on performance, business owner satisfaction, and project success. The objective was to use the empirical findings to provide a reference for practitioners when allocating and prioritizing management techniques that should be used in modern construction projects.

The remainder of this article is organized as follows. The section "Literature Findings and Research Hypotheses" reviews the literature on *PMBOK® Guide* applications, project performance (PP) evaluation, customer satisfaction (CS), and project success (PS) requirements related to construction engineering and management. Based on the literature, the research hypotheses are formulated, and the empirical model is developed. The "Research Method and Flow" section outlines the research methodology and analysis methods applied in this study. The next section, "Analytical Process and Results," describes the data profile, including construct indicators in the questionnaire, descriptive statistics, analytical results using the proposed SEM, and discussion. The final section, "Conclusion and Recommendations," concludes the managerial implications for construction engineering practice.

Literature Findings and Research Hypotheses

Comparison of Conceptual Frameworks of PMBOK® Guide and Project Performance

Application of SEM in a project management study by Kim, Han, Kim, and Park (2009) found that the key factors in project performance and project success were communications management, cost management, and scope management. Cho, Hong, and Hyun (2009) and Konchar and Sanvido (1998) noted that cost, progress, and quality management significantly affect project performance. Anantatmula (2008), Kang, O'Brien, Thomas, and Chapman (2008), and O'Connor and Yang (2004) also confirmed that the growing use of information technologies has significantly improved performance. Exceptional product and service quality can also increase project performance (Ling, Ibbs, & Hoo, 2006).

Particularly, Hwang, Thomas, and Caldas (2010) developed a hierarchical structure of pharmaceutical projects so as to make a clear comparison. To exhibit the uniqueness of pharmaceutical construction projects in deliveries, industry-specific metrics (i.e., project cost, schedule, and dimensional performance) tailored to the processes were produced. Their studies (Hwang, Thomas, & Caldas; 2010, 2011) indicated that the stakeholders can efficiently measure and evaluate the performance of pharmaceutical facility construction projects by employing the proposed metrics.

A study by Dvir, Raz, and Shenhar (2003) suggested that defining objectives and functional requirements and applying technological specifications are critical for successful national security defense-related projects. Yang, O'Connor, and Wang (2006) found that information technology and automated technologies contribute to the success of small and medium-sized projects; Yang (2007) also suggested that automated technologies are critical for successful task execution. A study of European Foundation for Quality Management (EFQM) business models by Qureshi, Warraich, and Hijazi (2009) found that project management and human resource management positively affect project performance.

Yeung, Chan, and Chan (2009) further suggested that cost, quality, time, and safety performance are reliable indicators of project performance. Studies by the Construction Industry Institute (CII) (2009) and Kang et al. (2008) showed that project performance can be measured by factors such as cost, time, safety, design change ratio, and rework ratio. Ling et al. (2006) found that the variable with the greatest impact in the architecture, engineering, and construction industries is the understanding of customer requirements; therefore, achieving this factor is essential for good project performance and customer satisfaction.

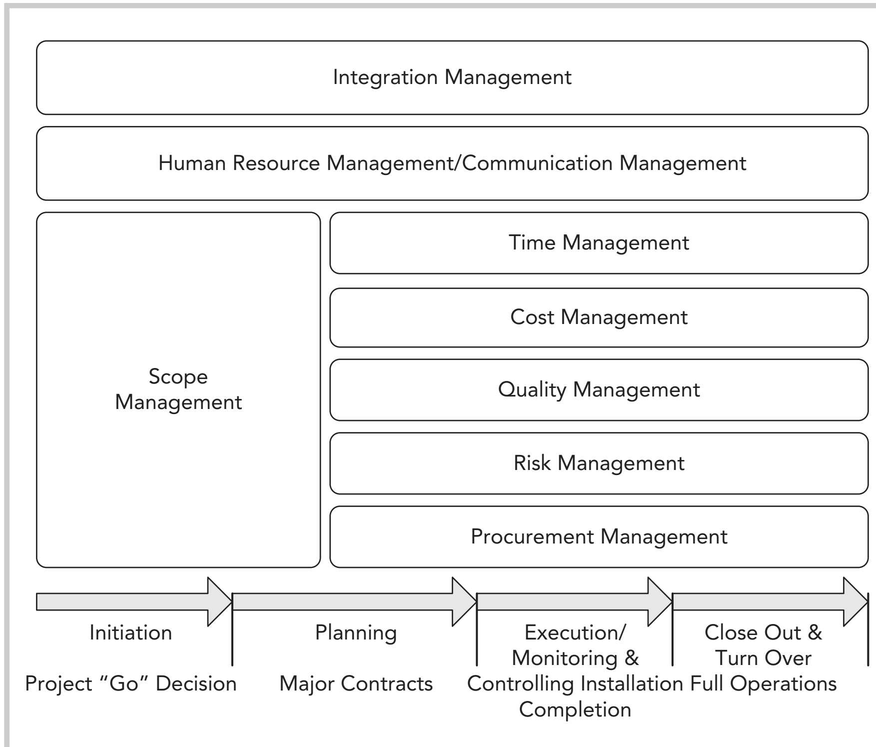

Figure 1: *PMBOK® Guide* and project phase.

Additionally, Cho et al. (2009) analyzed the overall relationship between project performance and project characteristics. They identified causal relationships among 17 project characteristics and five project performance indicators. The five project performance indicators were: "reward ratio," "unit cost," "progress growth," "cost increases," and "speed of completion." Application of the nine *PMBOK® Guide* Knowledge Areas to examine international project practices in Ling, Low, Wang, and Egbelakin (2008) showed that the *PMBOK® Guide* significantly affects the performance of international construction projects in China.

The *PMBOK® Guide* notes that project management processes typically use clearly defined interfaces to indicate individual processes (Figure 1). In practice, however, they often overlap. The need for integrated project management results from the interaction among different processes. Therefore, this study hypothesizes that the research subjects for project management TTS (Table 1) are provided for the management purpose of project scope (PSM), time (PTM), cost (PCM), quality (PQM), human resource (PHrM), communications (PCoM), risk (PRM), and procurement (PPM). Based on the literature, this study proposes the hypotheses listed below. Figure 2 depicts the complex structural linkages (hypotheses) between the *PMBOK® Guide* and project performance (PP) in the research model for testing the initial path hypotheses. Table 1 describes the evaluation indicators corresponding to *PMBOK® Guide* constructs.

> H_{01}: *Use of project management enhances its perceived usefulness for PTM.*
>
> H_{02}: *Use of project management enhances its perceived usefulness for PCM.*
>
> . . . .
>
> H_{63}: *Use of project management enhances its perceived usefulness for PRM.*
>
> H_{64}: *Use of project management enhances its perceived usefulness for PP.*

Hypothesized Linkage Between Project Performance and Customer Satisfaction

As customer requirements diversify and as operating environments change, increasing customer satisfaction has become a key goal pursued by enterprises seeking to increase tangible value (Anderson & Fornell, 2000; Fornell, Johnson, Anderson, Cha, & Bryant, 1996). In 1993, the U.S. government appointed the Fornell research team to develop service standards, primarily to help American enterprises increase their competitiveness in international markets. Another objective was to use standardized benchmarking to analyze the domestic economy and to provide the government with data needed to establish effective economic policy. Fornell surveyed 200 companies in 34 industries to develop the American Customer Satisfaction Index (ACSI) in 1994. The purpose of the ACSI is to provide a holistic measurement of customer satisfaction based on surveys of customer satisfaction with product or service quality. To ensure consistency and comparability, the research model between PP and CS developed in this study incorporates ACSI characteristics

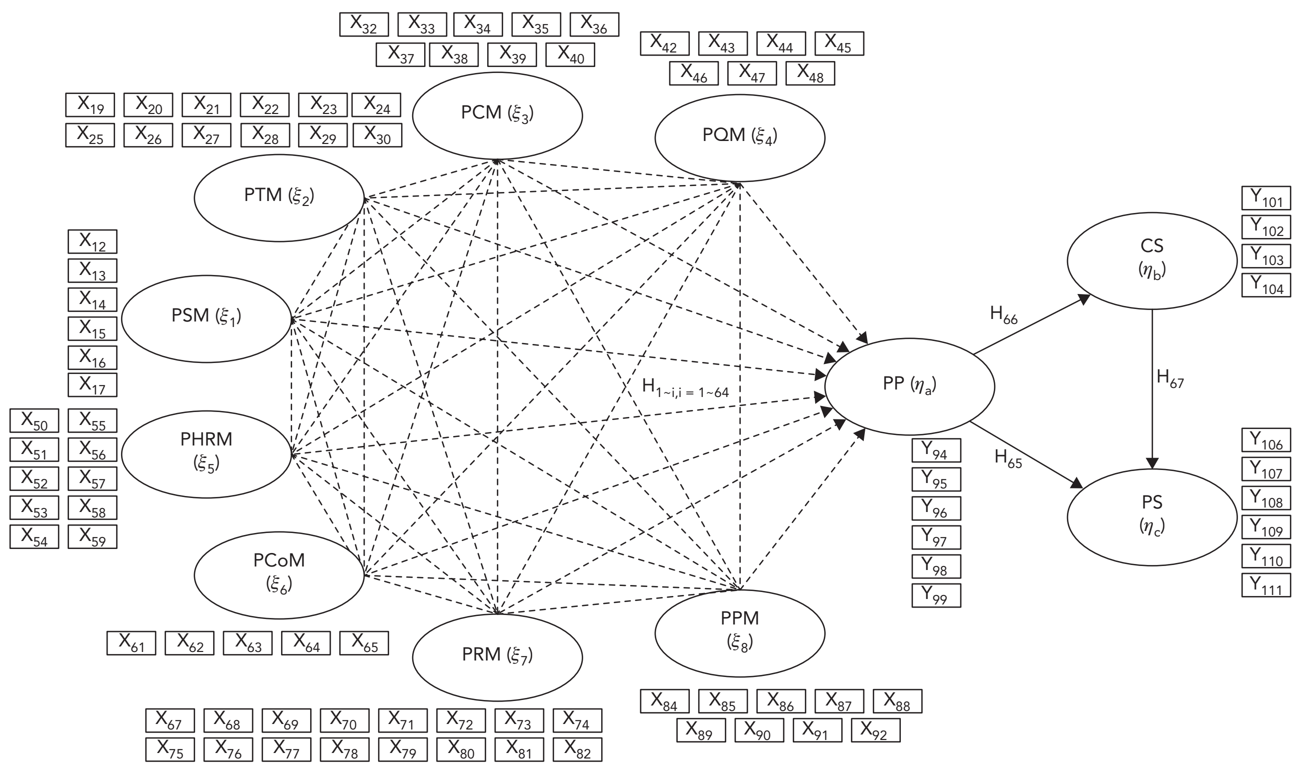

Figure 2: Hypothetical model.

(Anderson & Fornell, 2000; Fornell et al., 1996).

Perceptions of satisfaction include: project objectives, management mechanisms, and the relationships among these factors (Leung, Ng, & Cheung, 2004). The use of SEM to examine service quality, perceived value, and overall satisfaction by Chen (2008) revealed relationships among all three factors. Shin, Moon, and Sohn (2009) also applied SEM to measure customer satisfaction and the service quality of suppliers for the information infrastructure industry. Their indicators were designed to measure four aspects of customer satisfaction: service application processes, service quality, service support, and overall satisfaction. However, whereas these indicators were subjective measurements, the current study explores the causal relationships between project performance and customer satisfaction (i.e., owner satisfaction) and proposes the following hypothesis. Table 2 lists the corresponding evaluation indicators for PP and CS.

H_{66}: As PP improves, CS increases.

Mediating and Direct Effects on Project Success

The indicators conventionally used in the construction industry to indicate the success of projects are cost, progress, performance, and safety (Hughes, Tippett, & Thomas, 2004). However, an empirical study by Yeung et al. (2009) developed an effective assessment model by using the Delphi Method to define standards. This method measures project success in terms of eight indicators: (1) customer satisfaction, (2) cost performance, (3) quality performance, (4) time performance, (5) effective communication, (6) safety performance, (7) trust and respect, and (8) innovation and improvement (Yeung et al., 2009).

During actual project execution, project success may grow to include numerous measurements. For example, factors that determine the success of Mass House Building Projects (MHBPs) can be divided into four categories: environmental impact, and the satisfaction of clients regarding quality, cost, and time (Ahadzie, Proverbs, & Olomolaiye, 2008). Application of Enterprise Resource Planning (ERP) in the building industry by Chung, Skibniewski, Lucas, and Kwak (2008) showed that the main indicators of project success for ERP were progress control and quality management. They also found that progress and quality were essential for successful project execution.

Regarding project costs and project progress success, Yang et al. (2006) noted that a project has succeeded only

Table 1: The indicators of project management tools and techniques in the *PMBOK® Guide*.

Group	Construct	Indicator
Project Management Techniques /Tools/Skills	Scope	Requirement
		Expert scope judgment
		Product analysis
		Alternatives identification
		Work breakdown structure
		Inspection
	Time	Expert time judgment
		Decomposition
		Rolling wave planning
		Analogous estimating
		Parametric estimating
		Three-point estimating
		Reserve analysis
		Critical path method
		Critical chain method
		Resource leveling
		What-if scenario analysis
		Schedule compression
	Cost	Expert cost judgment
		Analogous estimating
		Parametric estimating
		Bottom-up estimating
		Three-point estimating
		Reserve analysis
		Earned value management
		Forecasting
		To-complete performance index
	Quality	Quality audits
		Cost of quality
		Cause-and-effect diagrams
		Control charts
		Benchmarking
		Design of experiments
		Statistical sampling
	Human Resource	Training
		Team-building activities
		Ground rules

(*Continues on next page*)

Table 1: (continued)

Group	Construct	Indicator
		Colocation
		Recognition and rewards
		Observation and conversation
		Project performance appraisals
		Issue log
		Conflict management
		Manager's interpersonal skills
	Communication	Stakeholder analysis
		Communication requirements analysis
		Communication methods
		Reporting systems
		Performance reports
	Risk	Documents reviews
		Information-gathering techniques
		Checklist analysis
		Diagramming techniques
		SWOT analysis
		Expert risk judgment
		Probability and impact matrix
		Risk data quality analysis
		Risk urgency assessment
		Sensitivity analysis
		Expected monetary value analysis
		Modeling and simulation
		Decision tree
		Risk reassessment
		Risk audits
		Variance and trend analysis
	Procurement	Make-or-buy analysis
		Expert law judgment
		Bidder conference
		Independent estimates
		Advertising
		Procurement negotiations
		Procurement performance reviews
		Claims administration
		Negotiated settlements

Construct	Indicator
Project performance	Cost performance
	Schedule performance
	Quality performance
	Safety performance
	Rework
	Change order
Customer satisfaction	Meeting customer's expectations
	Satisfaction of quality
	Satisfaction of schedule
	Service quality of the contractor
Project success	Completed on time
	Completed within budget
	Meeting quality requirement
	Meeting design requirement
	Overall stakeholders' satisfaction
	Reoccurring business

Table 2: Measurement indicators for project performance, customer satisfaction, and project success.

if the actual budget is lower than expected and if the actual progress is faster than expected; otherwise, it has failed. Additionally, in terms of the project execution described previously, the literature on project management defined project success in terms of factors such as objectives, budgeting, progress, and operating efficiency (Tesch, Sobol, Klein, & Jiang, 2009).

Previous studies have defined success in terms of three factors: cost, time, and progress. Other scholars have proposed adding eight other criteria, which results in 11 total criteria: user satisfaction; supplier satisfaction; team satisfaction; satisfaction of stakeholders; progress, cost, and quality performance; meeting the needs of users; achieving project objectives; customer satisfaction (Frame, 2010); and repeat business (Muller, Geraldi, & Turner, 2011). Based on the above discussions, Table 2 lists the measurable indicators for the conceptual constructs. We hypothesize the following causal relations among PP, CS, and PS (Figure 2):

H_{65}: As PP improves, PS improves.

H_{67}: As CS improves, PS improves.

Research Method and Flow

The research method and flow were divided into four phases. Phase 1 of the research method established the SEM framework and the measurement indicators based on literature review. Phase 2 collected survey data and assessed the relationships of indicators and constructs based on the conceptual SEM model. Phase 3 optimized the model specifications to improve the SEM framework before modifying the structural model. Specifically, the goodness of fit (GOF) of the research model was used as a criterion for evolutionary optimization. In the final phase, the relationships of project management TTS, PP, CS, and PS were analyzed using the optimized model.

Survey Process

The survey empirically measured the use of the *PMBOK® Guide* in construction engineering projects and how it affects effectiveness and efficiency in terms of project performance, stakeholder satisfaction, and project success. The questionnaire was evaluated in a pilot study before performing the formal survey. The pretest results for 30 respondents showed that the constructs, along with their indicators, were easily understood and answered. To improve the response rate and data validity during the official survey, the survey package included a postage-paid return envelope and the offer of a gift certificate for completing the questionnaire. After receiving the completed survey form and confirming its completion, the gift certificate was mailed to the physical address of each respondent.

Structural Equation Modeling

The two classes of variables used in the research model were observed indicators and latent constructs. Observed indicators are those that can be measured directly, such as usage of particular techniques, tools, and skills. Latent constructs used in this study, which included body of knowledge, project performance, customer satisfaction, and project success, are latent variables that are not directly measurable. Therefore, latent constructs are measured by means of observable indicators. To establish an appropriate model for testing the research hypotheses regarding the impacts of latent constructs on the other variables, this study used structural equation modeling, which is widely considered the most effective statistical method for this purpose.

Structural equation modeling systematically combines confirmatory factor analysis, multiple regression analysis, and path analysis. It incorporates a measurement model for confirmatory factor analysis of how well latent constructs (i.e., group factors drawn from factor analysis) are represented by observed indicators and a structural model for multiple regression analysis and path analysis to model relationships between latent variables and a final outcome (Chou, Kim, Kuo, & Ou, 2011).

The structural equation model can then be defined in terms of a set of three matrix equations. The first two equations, which represent the measurement model, are:

$$\mathbf{X} = \Lambda_x \boldsymbol{\xi} + \boldsymbol{\delta} \quad (1)$$

and

$$\mathbf{Y} = \Lambda_y \boldsymbol{\xi} + \boldsymbol{\varepsilon} \quad (2)$$

Here Λ_x is a $q \times n$ matrix of coefficients representing the effects of the independent latent variables (LVs) on their indicators, and δ is a $q \times 1$ vector of "errors of measurement" in the indicators. Similarly, Λ_y is a $p \times m$ matrix of coefficients representing the effects of the dependent LVs on their indicators, and ε is a $p \times 1$ vector of errors of measurement in these indicators. Thus, the measurement model defines each of the measured variables as a linear combination of the LVs, plus an error term. The final SEM equation represents the structural model, which defines the relations among the LVs:

$$\boldsymbol{\eta} = \mathbf{B}\boldsymbol{\eta} + \boldsymbol{\Gamma}\boldsymbol{\xi} + \boldsymbol{\zeta} \quad (3)$$

In this equation, **B** is an $m \times m$ matrix of coefficients representing the effect of each dependent LV on each of the other dependent LVs. The matrix Γ is an $m \times n$ matrix of coefficients representing the effect of each independent LV on each dependent LV. Finally, ζ is an $m \times 1$ vector containing residuals, or errors in equations, for each of the dependent LVs. Thus, the structural model defines each dependent LV as a linear combination of independent LVs and other dependent LVs, plus a residual.

The goodness-of-fit indicator is a criterion for assessing the appropriateness of a SEM. The main purpose of assessing GOF is determining whether the theoretical model constructed by researchers reasonably explains the data actually observed. This study uses the following indicators as the fitness criteria for evolutionary optimization:

a. Chi-square/degrees of freedom ratio $\left(\frac{\chi^2}{\text{dof}}\right)$:

As the number of estimation variables in a hypothetical model increases, the degree of freedom increases; the Chi-square value also increases with the number of samples. When considering both the Chi-square value and the degree of freedom, the ratio of the two can be used as an indicator of model fit—that is, values less than 3 indicate a good fit (Hayduk, 1987).

b. Goodness-of-fit index (GFI):

This indicator is the ratio between observed variance and the square of the difference between an observed **S** matrix and a matrix Σ constructed using a theoretical method. This indicator functions similarly to explained variance (R^2) in the regression analysis (Wallgren & Hanse, 2007). The formula for calculating this indicator is:

$$\text{GFI} = \frac{tr(\hat{\sigma}'\mathbf{W}\hat{\sigma})}{tr(\mathbf{s}'\mathbf{W}\mathbf{s})} \quad (4)$$

where the numerator is the sum of the weighted variance reproduced based on theory; the denominator is the total sum of weighted variance from reproduction of covariance based on actual observation, and **W** is the weighted matrix. The GFI value ranges from 0 to 1, where values closest to 1 have the best fit (Hair, Black, Babin, & Anderson, 2010).

c. Incremental fit index (IFI):

The IFI is a category of GOF indicators for SEM; a common indicator in this category is comparative fit index. This indicator must be calculated using other baseline models as a reference point. The GOF of the hypothetical models proposed by the researchers for empirical data is assessed using comparative methods. Typically, the closer the IFI to 1, the better the goodness of fit (Benamati & Lederer, 2008). Equation 5 shows the formula for IFI:

$$\text{IFI} = \frac{\chi^2_{\text{indep}} - \chi^2_{\text{test}}}{\chi^2_{\text{indep}} - \text{dof}_{\text{test}}} \quad (5)$$

where χ^2_{indep} is the Chi-square of the null or base model and χ^2_{test} is the Chi-square of the proposed model.

d. Comparative fit index (CFI):

This indicator reflects not only the difference between a proposed model and a null model, but also the dispersion of a tested model and central Chi-square distribution. The CFI is equal to the discrepancy function adjusted for sample size. Any hypothetical model should have a GOF superior to that of the null model, which is the least ideal model. Therefore, the closer the CFI indicator to 1, the better the non-central Chi-square distribution (Bagozzi & Yi, 1988).

e. Root mean square error of approximation (RMSEA):

The RMSEA measures the difference between a measured observed covariance matrix and an estimated covariance matrix versus the unit degree of freedom (dof). The smaller the RMSEA, the better the model fit. A value less than 0.1 indicates an acceptable model; a value less than 0.08 is a reasonable GOF for the model; and a value less than 0.05 indicates an excellent GOF (Hair et al., 2010). The formula for this indicator is shown in Equation 6:

$$\text{RMSEA} = \sqrt{\frac{\hat{F}_0}{\text{dof}}}, \text{ where } \hat{F}_0 = \frac{\chi^2 - \text{dof}}{N} \quad (6)$$

After carefully considering the above description and review, the following optimization process was performed to examine the indexes:

i. Singular index testing: select five indicators to compare their independent criteria.

ii. Synthesis Index (SI) testing: compare the criteria used in GFI, CFI, and IFI. The closer the value to 1, the better the fit; the RMSEA judgment criteria indicates a better fit as it approaches 0. If GFI, CFI, and IFI are reversed, they constitute the same judgment criterion as RMSEA. Restated, an SI value closer to 0 indicates a better fit. The formula is shown in Equation 7:

$$SI = \frac{1}{GFI} + \frac{1}{CFI} + \frac{1}{IFI} + RMSEA \quad (7)$$

Reliability and Validity Analysis

Internal consistency reliability, which is measured by "Kuder-Richardson reliability" (KRR) and the "α coefficient," is a direct indicator of the consistency of constructs or correlations between constructs. The KRR is typically used to indicate the reliability of the measured variables. Here, this analysis is used to compare reliability between the measured indicators. Cronbach (1951) further modified KRR as follows (Hair et al., 2010):

$$Cronbach's\ \alpha = \frac{k}{k-1}\left(1 - \frac{\sum s_i^2}{s^2}\right) \quad (8)$$

s_i^2: variance of component *i*; s^2: variance in test scores; k: number of questions.

Validity refers to the effectiveness of a tool for measuring a variable of interest. Validity is often measured by average variance extracted (AVE) and composite reliability (CR) (Fornell & Larcker, 1981). First, the loading coefficient is obtained using factor analysis to measure the consistency between indicators and constructs. In CFA, the AVE measures the mean variance extracted for the items loaded on a construct; it indicates the explanatory power of the variance in each indicator for a latent construct. This value can be calculated using Equation 9:

$$AVE = \frac{\sum_{i=1}^{n} \lambda_i^2}{n} \quad (9)$$

where AVE is average variance extracted, λ_i denotes standardized factor loadings of each indicator for the construct, and n is the number of items. The higher the factor loading, the greater the explanatory power of the indicator for a given construct. Hair et al. (2010) suggested that a factor load should exceed 0.7, while Fornell and Larcker (1981) indicated that an AVE exceeding 0.5 is satisfactory.

Composite reliability represents the internal consistency of indicators within a construct where the higher the reliability, the higher the internal consistency in these latent constructs. Fornell and Larcker (1981) suggested a minimum CR of 0.6, while Hair et al. (2010) suggested a threshold of 0.7. The formula for composite reliability is:

$$CR = \frac{\left(\sum_{i=1}^{n} \lambda_i\right)^2}{\left(\sum_{i=1}^{n} \lambda_i\right)^2 + \left(\sum_{i=1}^{n} e_i\right)^2} \quad (10)$$

where *CR* is a composite reliability, λ_i denotes the standardized factor loadings of each indicator for the construct, and e_i is the measurement error for the measured indicator *i*.

Evolutionary Optimization for Model Specification Search

The *PMBOK® Guide* recommends the use of project management techniques to improve project performance and success. However, searching for the combination of project management techniques that obtains the largest improvement in project performance on a case-by-case basis is very time-consuming. Therefore, this study used genetic algorithm (GA), an adaptive heuristic search procedure that can solve large-scale optimization problems.

The goal of GA is finding the optimum of a given function over a given search space. In the initialization step, a set of points in the search space is either selected randomly or specified by the user. A GA iteration is then performed in four sequential steps, including evaluation, selection, reproduction, and replacement, until a stopping condition is met. The sequential steps are (1) evaluation: compute the function so that a starting population of individuals can be ordered from best to worst; (2) selection: select pairs of individuals, usually called parents; (3) reproduction: produce the offspring of pairs of individuals; and (4) replacement: generate a new population of individuals by replacing some worse members of the population with better ones.

Searching for the specific model in SEM is difficult, especially when the number of possible alternative models is large. Therefore, automation is essential for managing this chaotic process. The searching space was focused on the relationship within the project management knowledge bodies and project performance constructs. Several important issues arise before a GA procedure can be established for performing a specification search in SEM. These issues include the following:

• *Choosing a Criterion for Model Selection*

Many criteria have been proposed in the SEM literature for evaluating the GOF of a specified model. Given the numerous fit indices proposed in the SEM literature, several fits (where χ^2; $\frac{\chi^2}{DOF}$; GFI; CFI; IFI, RMSEA, and SI) were selected as criteria for model selection in the GA search in this study.

• *Model Definition and Chromosomal Coding*

Empirical data were collected and the literature was reviewed before creating an initial structural model by assuming possible paths (where $H_{1\sim i, i=1\sim 64}$). The model paths were then coded. For example, if a relationship was observed between project scope and project performance, the path was coded as 1. Otherwise, the path was coded as 0.

• *Generating the Initial Population*

Based on the demonstration case, the chromosome for the structural model can be written with 64 genes. Although many chromosomes can be generated, this study randomly generated three from an initial chromosome for illustration purposes. These members were then used to evaluate their corresponding estimated criteria.

Table 3: Socioeconomic characteristics of survey respondents.

Attribute	Distribution	Frequency	Percent (%)
Gender	Male	114	89.8
	Female	13	10.2
	Total	127	100.0
Age	21–30	34	26.8
	31–40	43	33.9
	41–50	28	22.0
	51–60	19	15.0
	≥ 61	3	2.4
	Total	127	100.0
Education	High school	1	0.8
	University	26	20.5
	Graduate or higher	100	78.7
	Total	127	100.0
Level of awareness and certified training program for *PMBOK® Guide*	Low familiarity	51	40.2
	Below average familiarity	30	23.6
	Average familiarity	29	22.8
	Above-average familiarity	11	8.7
	High familiarity	6	4.7
	Total	127	100.0
License	Licensed registered engineer	60	47.2
	PMP	5	3.9
	None	52	40.9
	Others	10	7.9
	Total	127	100.0
Role in project	Owner/government	60	47.2
	Contractor	24	18.9
	Consultancy/technical services	37	29.1
	Professional	5	3.9
	Others	1	0.8
	Total	127	100.0
Role in company	Person in charge	13	10.2
	Manager	34	26.8
	Designer	8	6.3
	Site manager	4	3.1
	In-house engineers	28	22.0
	On-site engineers	7	5.5

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Table 3: (continued)

Attribute	Distribution	Frequency	Percent (%)
	Professional	1	0.8
	Other	32	25.2
	Totals	127	100.0
Work experience	< 2 years	38	29.9
	2–5 years	25	19.7
	5–10 years	20	15.7
	10–15 years	22	17.3
	15–20 years	11	8.7
	> 20 years	11	8.7
	Total	127	100.0
Practical experience for the *PMBOK® Guide*	< 2 years	44	34.6
	2–5 years	24	18.9
	5–10 years	20	15.7
	10–15 years	21	16.5
	15–20 years	13	10.2
	> 20 years	5	3.9
	Total	127	100.0
Project scale (Unit: NTD)	< 5 million	19	15.0
	5 million–25 million	23	18.1
	25 million–100 million	26	20.5
	100 million–500 million	28	22.0
	> 500 million	31	24.4
	Total	127	100.0

• *Executing the GA Search Procedure*
From this initial population, new offspring were generated by crossover, mutation, and reproduction. The offspring were then decoded for import to Amos 16.0 software in order to calculate their GOF values. If the offspring criterion was better than the one in the initial population, it was replaced to yield the following new population.

• *Establishing a Stopping Criterion and Modifying Model*
Running the GA search procedure revealed the best chromosome in the population according to the evaluation criteria. The optimized model was then modified so that the GOF indices met the standards suggested in the literature.

Analytical Process and Results

Descriptive Statistics

A convenience survey was performed by distributing 299 paper questionnaires. Of these, 115 effective questionnaires were retrieved (including 75 completed by various professional institutions) from industry practitioners. Additionally, 12 surveys were received from online respondents, of which 127 were valid. Therefore, the effective response rate was 40.83%. The questionnaires applied the 10-point Likert scale suggested in previous studies. The empirical data were then used to test the proposed model using GA-SEM methodology as described earlier.

Table 3 shows the demographic data of the surveyed construction managers, project stakeholders, or project team members from randomly selected engineering-related firms. Of the respondents, 89.8% were male and 10.2% were female; most (82.7%) respondents were in the age range of 21 to 50 years. Respondents who had an education level of college or above comprised 99.2% of the total; 86.6% of individuals had an average or poorer understanding of project management knowledge. Although project management techniques are apparently widely used in engineering activities, a relatively small proportion of respondents had a true understanding of the underlying principles of project management. About half (47.2%) of the respondents held a technician's license, while 40.9% did not; only 3.9% were a Project Management Professional (PMP)® credential holder.

Notably, most survey respondents were business owners or government employees (47.2%), followed by individuals working in consulting companies or technical services (29.1%). Most respondents were either managers or other (26.8% and 25.2%, respectively). In-house engineers constituted 22%. In terms of work experience at their current unit, 29.9% had worked for less than two years; 52.7% for 2 to 15 years; and 17.4% for 15 to 20 years. In terms of experience, 34.6% had less than two years of experience in construction project management; 61.3% had 2 to 20 years of experience; and 3.9% had more than 20 years of experience. In terms of the distribution of project scale, more than 60% had experience in projects ranging from 5 million New Taiwan Dollar (NTD; 1 USD is approximately equal to 30 NTD) to 500 million NTD.

The questionnaire survey sampled professionals in the Taiwan area. The SEM maximum likelihood estimation (MLE) was primarily used for model estimation, with the sample matching an approximately normal distribution (Kline, 2005). Kline (2005) has indicated that the normal theoretical peak is kurtosis = 3 (current statistical software will subtract 3; thus, kurtosis = 0 and skew = 0 is normal). In practice, however, a skew with an absolute value within 2 and a kurtosis with an absolute value within 7 can be considered normal, whereas a skew larger than 3 and a kurtosis larger than 20 are considered extreme. Graphic depiction of the data distributions obtained in normal testing in this study showed that the above criteria were met and that the data presented an approximately normal distribution.

Confirmatory Analysis

The main purpose of confirmatory analysis is to test whether the linkages between the measured variables and latent constructs are reliable and valid. The typical method of measuring the reliability of each construct is examining the Cronbach's Alpha (α) coefficient, AVE, and CR (Hair et al., 2010).

Table 4 shows that most factor loadings for the measured indicators exceeded 0.7. However, a total of 19 items did not reach this standard. Moreover, aside from the PPM construct (0.4354) and the PCM construct (0.4859), the AVE of the other constructs exceeded 0.5. The 19 variables with factor loadings of less than 0.7 were deleted after the quality analysis showed that their removal would effectively increase the reliability of the associated constructs.

After reloading these indicators, the AVE of the PSM construct increased from 0.5411 to 0.6068; the AVE of the PTM construct increased from 0.5222 to 0.6058; and the AVE of the PCM construct increased from 0.4859 to 0.6065. The AVE of the PRM construct increased from 0.6388 to 0.6634; that of the PPM construct increased from 0.4354 to 0.5767; and that of the PP construct increased from 0.6380 to 0.6837. The AVE exceeded 0.5 for all constructs, indicating that this survey had acceptable overall reliability and validity.

Regarding the correlation coefficients of the various constructs, a correlation coefficient larger than 0.7 generally represents a strong correlation, whereas a coefficient between 0.3 and 0.7 represents a moderate correlation, and a coefficient smaller than 0.3 represents low correlation. The correlation matrix listed in Table 5 shows that PPM had strong correlations with PCM, PHrM, PRM, PQM, PTM, and PP. The PCM had strong correlations with PCoM, PRM, PQM, PTM, and PSM. The PCoM had strong correlations with PHrM, PQM, PTM, and PP. The PHrM had strong correlations with PQM, PTM, and PP. The PRM had strong correlations with PQM and PTM. The PQM had strong correlations with PTM and PSM. The PTM had strong correlations with PSM. The PP had strong correlations with CS and PS. Lastly, CS had a strong correlation with PS. All of the above constructs had correlation coefficients larger than 0.7.

Conversely, PPM showed only moderate correlations with PCoM, PSM, CS, and PS. The PCM had a moderate correlation with PHrM, PP, CS, and PS. The PCoM had a moderate correlation with PRM, PSM, CS, and PS. The PHrM had a moderate correlation with PRM, PSM, CS, and PS. The PRM had a moderate correlation with PSM, PP, CS, and PS. The PQM had a moderate correlation with PP, CS, and PS. The PTM had a moderate correlation with PP, CS, and PS. The PSM had a moderate correlation with PP, CS, and PS. All of the above associations had correlation coefficients between 0.3 and 0.7, representing a moderate association.

Evolutionary Model Construction and Modification

The modeling process was performed in two phases. The first phase studied relationships between the *PMBOK® Guide* and PP using evolutionary GA optimization due to the complex linkages. The overall SEM analysis of the *PMBOK® Guide*, PP, CS, and PS was then performed in the second phase. The hypothesis paths (H_{08}, H_{09}, H_{32}, H_{40}, and H_{48}), initially assumed to exist according to the literature, were designated Chromosome 1.

By randomly producing three chromosome sets, Chromosome 1 creates four chromosome sets as the initial population for executing the evolution process. Mating, mutation, and replacement steps

Table 4: Confirmatory analysis of variables.

Construct	Indicator	Factor Loading	Average Variance Extracted	Composite Reliability	Cronbach's Alpha (α)
Scope	Requirement	0.65	0.5411	0.875	0.8727
	Expert scope judgment	0.71			
	Product analysis	0.80			
	Alternatives identification	0.84			
	Work breakdown structure	0.76			
	Inspection	0.63			
Time	Expert time judgment	0.53	0.5222	0.9282	0.9275
	Decomposition	0.72			
	Rolling wave planning	0.77			
	Analogous estimating	0.68			
	Parametric estimating	0.66			
	Three-point estimating	0.68			
	Reserve analysis	0.82			
	Critical Path Method	0.62			
	Critical Chain Method	0.81			
	Resource leveling	0.82			
	What-if scenario analysis	0.71			
	Schedule compression	0.79			
Cost	Expert cost judgment	0.46	0.4859	0.8923	0.8932
	Analogous estimating	0.62			
	Parametric estimating	0.60			
	Bottom-up estimating	0.62			
	Three-point estimating	0.72			
	Reserve analysis	0.79			
	Earned value management	0.77			
	Forecasting	0.83			
	To-complete performance index	0.78			
Quality	Quality audits	0.72	0.5622	0.8996	0.8989
	Cost of quality	0.77			
	Cause-and-effect diagrams	0.75			
	Control charts	0.84			
	Benchmarking	0.72			
	Design of experiments	0.70			
	Statistical sampling	0.74			

(*Continues on next page*)

Table 4: (continued)

Construct	Indicator	Factor Loading	Average Variance Extracted	Composite Reliability	Cronbach's Alpha (α)
Human resource	Training	0.77	0.6983	0.9584	0.9577
	Team-building activities	0.75			
	Ground rules	0.86			
	Co-location	0.81			
	Recognition and rewards	0.77			
	Observation and conversation	0.91			
	Project performance appraisals	0.86			
	Issue log	0.86			
	Conflict management	0.86			
	Manager's interpersonal skills	0.89			
Communication	Stakeholder analysis	0.96	0.7232	0.9279	0.9287
	Communication requirements analysis	0.94			
	Communication methods	0.87			
	Reporting systems	0.76			
	Performance reports	0.69			
Risk	Documents reviews	0.52	0.6388	0.9476	0.9653
	Information-gathering techniques	0.78			
	Checklist analysis	0.85			
	Diagramming techniques	0.81			
	SWOT analysis	0.81			
	Expert risk judgment	0.81			
	Probability and impact matrix	0.79			
	Risk data quality analysis	0.88			
	Risk urgency assessment	0.78			
	Sensitivity analysis	0.83			
	Expected monetary value analysis	0.82			
	Modeling and simulation	0.79			
	Decision tree	0.80			
	Risk reassessment	0.85			
	Risk audits	0.78			
	Variance and trend analysis	0.83			

(*Continues on next page*)

Table 4: (continued)					
Construct	Indicator	Factor Loading	Average Variance Extracted	Composite Reliability	Cronbach's Alpha (α)
Procurement	Make-or-buy analysis	0.63	0.4354	0.8680	0.8593
	Expert law judgment	0.63			
	Bidder conference	0.70			
	Independent estimates	0.59			
	Advertising	0.27			
	Procurement negotiations	0.77			
	Procurement performance reviews	0.84			
	Claims administration	0.72			
	Negotiated settlements	0.63			
Project performance	Cost performance	0.83	0.6380	0.9129	0.9088
	Schedule performance	0.83			
	Quality performance	0.89			
	Safety performance	0.80			
	Rework	0.78			
	Change order	0.64			
Customer satisfaction	Meeting customer's expectations	0.96	0.7966	0.9397	0.9392
	Satisfaction of quality	0.94			
	Satisfaction of schedule	0.79			
	Service quality of the contractor	0.87			
Project success	Completed on time	0.76	0.7552	0.9483	0.9448
	Completed within budget	0.75			
	Meeting quality requirement	0.92			
	Meeting design requirement	0.86			
	Stakeholders' satisfaction	0.94			
	Reoccurring business	0.96			

are performed based on the genetic algorithm. Figure 3 shows that the SI values derived from distinct SEM analyses approach a convergence of 4.9 after the 135th evolution. Thus, the structural model of this evolution was adopted as the basis of the second phase of modeling in this study.

During parameter estimation, researchers may discover that the assumed theoretical model does not have a good fit to the observed data. To improve model GOF, researchers tend to increase or remove the paths between constructs or indicators within constructs established in the initial model (Hair et al., 2010). This study performed confirmatory analysis of the above optimized structural model to remove paths with unsatisfactory significance levels. Hypotheses H_{08}, H_{19}, and H_{33} revealed *p* values lower than 0.1 and were therefore unsustainable. Thus, this study deleted these three assumed paths. Table 6 shows the final results.

Second, adjustment indicator errors were identified in order to delete the corresponding observed variables until the GOF index matches the criteria listed in Table 7. The table also shows that the GOF

	PPM	PCM	PCoM	PHrM	PRM	PQM	PTM	PSM	PP	CS
PCM	0.732	–								
PCoM	0.672	0.774	–							
PHrM	0.817	0.698	0.796	–						
PRM	0.709	0.817	0.657	0.643	–					
PQM	0.784	0.794	0.773	0.875	0.745	–				
PTM	0.743	0.871	0.743	0.752	0.824	0.86	–			
PSM	0.642	0.702	0.637	0.682	0.661	0.729	0.797	–		
PP	0.724	0.668	0.703	0.703	0.614	0.693	0.682	0.654	–	
CS	0.594	0.548	0.577	0.577	0.504	0.569	0.560	0.537	0.821	–
PS	0.520	0.480	0.505	0.504	0.441	0.497	0.490	0.469	0.718	0.841

Table 5: Construct correlation matrix.

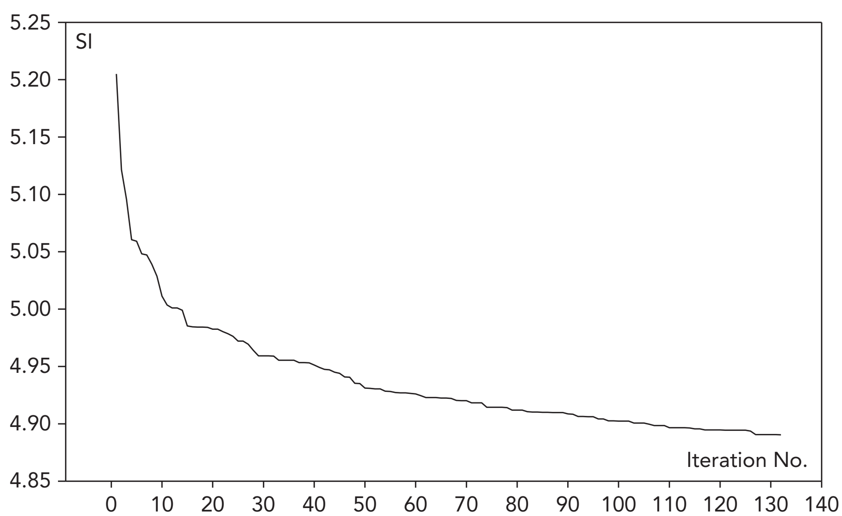

Figure 3: SI convergence diagram.

index values improved after model modification. The $\frac{\chi^2}{\text{dof}}$, GFI, CFI, IFI, and RMSEA increased from 2.316, 0.486, 0.727, 0.729, and 0.102 to 1.549, 0.802, 0.941, 0.942, and 0.066, respectively, which matched values recommended by the literature.

Figure 4 shows the final structural model after completing the modification process. The remaining constructs were PSM construct (product analysis and alternatives identification); PTM construct (rolling wave planning and the Critical Chain Method); PCM construct (forecasting and to-complete performance index); project quality management constructs (cause-and-effect diagrams, control charts, and statistical sampling); PHrM construct (observation and conversation, and issue log); PCoM construct (stakeholder analysis, communication requirements analysis, and communication methods); PRM construct (decision tree, risk reassessment, and variance and trend analysis); PPM construct (bidder conference and procurement negotiations); PP construct (cost performance and schedule performance); CS construct (satisfaction of quality and service quality provided by the contractors); and PS construct (completion on time, completion within budget, meeting quality requirements, recurring business).

Analysis Discussion

Eleven constructs and their corresponding 27 indicators revealed critical associations with each other. The various impacts were categorized as direct, indirect, and overall. Overall impacts include both direct and indirect impacts. Here, direct impact refers to the direct relationships between two constructs in a model, while indirect impact refers to the relationships between two constructs in a model through a mediating construct (Wallgren & Hanse, 2007). Table 8 shows that PCoM and PPM techniques, tools, and skills significantly affect PP, CS, and PS, both directly and indirectly. Thus, the empirical data suggest that enhancing

Hypothesis			Estimate	Statistic
Cost	→	Risk	0.403	0.012**
Procurement	→	Risk	0.398	0.014**
Human resource	→	Quality	0.499	***
Risk	→	Quality	0.412	***
Cost	→	Time	0.273	0.009**
Quality	→	Time	0.439	***
Risk	→	Time	0.369	0.002**
Time	→	Scope	0.799	***
Communication	→	Project performance	0.334	0.004**
Procurement	→	Project performance	0.581	***
Project performance	→	Customer satisfaction	0.846	***
Customer satisfaction	→	Project success	0.860	***

** Significant at 0.05 level. *** Significant at 0.01 level.

Table 6: Path testing results of revised research hypotheses.

Index	Criterion	Source	Value	
			Before Model Modification	After Model Modification
$\frac{\chi^2}{\text{dof}}$	<3	(Hayduk, 1987)	2.316	1.549
GFI	>0.8	(Scott, 1994)	0.486	0.802
CFI	>0.8	(Bagozzi & Yi, 1988)	0.727	0.941
IFI	>0.8	(Benamati & Lederer, 2008)	0.729	0.942
RMSEA	<0.1	(Hu & Bentler, 1999)	0.102	0.066

Table 7: Goodness-of-fit index criterion and output value.

these two techniques is the most efficient way of improving project performance, business owner satisfaction, and project success.

Notably, Table 9 shows that the impact of procurement management on the cost and schedule performance evaluation indicators (0.506 and 0.471) was almost double that of communication management (0.291 and 0.271). Similarly, compared to communication management, procurement management techniques have a 70% larger influence on business owner satisfaction with the engineering quality and service quality provided by contractors. Lastly, procurement and communication management have the largest effects (0.405 and 0.233, respectively) on the recurring business of the project success construct.

The results of the SEM analysis show that PHrM has a strong correlation with PQM, PPM, and PCoM (0.875, 0.817, and 0.796, respectively); time management has a strong correlation with PCM, PRM, PSM, and PQM (0.871, 0.824, 0.797, and 0.860, respectively); and owner satisfaction has a strong correlation with PP and PS (0.821 and 0.821, respectively).

Particularly, the final confirmed model indicates that only PCoM and PPM have statistically significant impacts on project performance, business owner satisfaction, and project success (Table 6). Confirmatory analysis shows that PCoM can be assessed by "stakeholder analysis" (0.949), "communication requirements analysis" (0.945), and "communication methods" (0.872). The PPM can be assessed by "bidder conference" (0.822) and "procurement negotiations" (0.770). For enhanced project performance, the above five techniques described in the *PMBOK®*

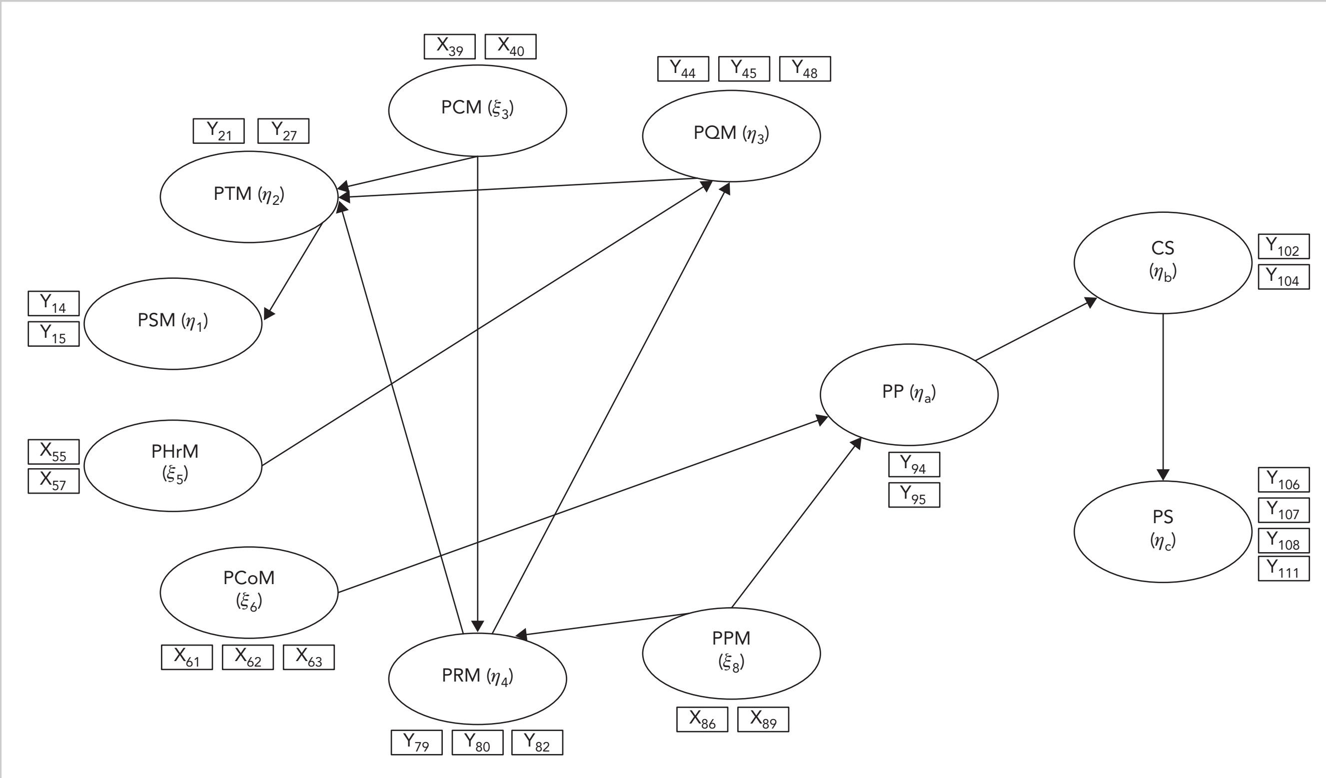

Figure 4: Modified model result.

		PCoM	PPM
PP	Direct effects	0.334	0.581
	Indirect effects	0.000	0.000
	Total effects	0.000	0.581
CS	Direct effects	0.000	0.000
	Indirect effects	0.283	0.491
	Total effects	0.000	0.491
PS	Direct effects	0.000	0.000
	Indirect effects	0.243	0.423
	Total effects	0.000	0.423

Table 8: Impact of body of knowledge on project performance, customer satisfaction, and project success.

Guide should therefore be prioritized by project managers.

Conclusions and Recommendations

Studies of how the *PMBOK® Guide* affects construction practices from the practitioner perspective are rare. This study clarifies the current use of project management techniques, tools, and skills for infrastructure and construction engineering to provide guidance for the practitioners and educators. The systematic approach uses a quantitative model for empirically measuring the interacting effects among the *PMBOK® Guide*, PP, CS, and PS. Project managers can use the model for numerical studies of critical indicators and constructs when prioritizing and allocating the managerial strategies needed to enhance engineering performance, owner satisfaction, and project success.

Construction industry firms often face complex legal regulations on procurement and are therefore subject to legal ordinances and policies. As construction industry products also have high unit prices, ineffective procurement management can potentially result in substantial cost increases. Thus, procurement management requires further attention. To address this issue, this study suggests prioritizing the "bidders conference" and "procurement negotiations" techniques recommended in the *PMBOK® Guide* in order to minimize bidding and legal procurement problems.

		PCoM	PPM
PP	Cost performance	0.291	0.506
	Schedule performance	0.271	0.471
CS	Satisfaction of quality	0.259	0.450
	Service quality provided by the contractors	0.244	0.425
PS	Completed on time	0.189	0.328
	Completed within budget	0.181	0.314
	Meeting quality requirement	0.225	0.390
	Reoccurring business	0.233	0.405

Table 9: Impact of management techniques on project performance, customer satisfaction, and project success.

Meanwhile, as construction technology is already highly developed, communication management is extremely important not only for converging and integrating technology, but also for facilitating the clear and effective communication of stakeholder opinions within project teams. This study recommends the use of "stakeholder analysis," "communication requirements analysis," and the "communication methods" addressed in the *PMBOK® Guide* to perform effective communication management.

The empirical results of this investigation are expected to have many practical applications. For researchers using structural equation models, the proposed perspective can assist in efficiently searching for structural paths. For construction practitioners, this study hopes to improve project performance, increase owner satisfaction, and facilitate the effective use of management techniques by industry workers seeking success under circumstances of limited capital, time, and other relevant resources and thus improve efficiency in the use of management resources. This study contributes to the literature by providing insight into interactions among the *PMBOK® Guide* TTS, PP, CS, and PS in engineering practice. The findings of this study can be used by project managers and educators to tailor the *PMBOK® Guide* to their unique needs and to design effective training programs for construction specialists.

Although this study prioritizes the significance of the *PMBOK® Guide* to the general construction business, the conclusions are based on the sample conveniently collected in Taiwan. Future work can expand the scale of survey and even a cross-nation comparison to consolidate the research findings in particular project types. A further study can be conducted by analyzing the level of awareness for the *PMBOK® Guide* on construction project outcomes. Additionally, a periodic survey is recommended for long-term evaluation of the *PMBOK® Guide* usage on owner satisfaction and project success. This work limits on the utilization of indicators from the *PMBOK® Guide*. Future researchers can update and explore novel indicators that are appropriate to assess the constructs.

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