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ARTICLE

A data-driven approach for identifying project manager competency weights

Awad S. Hanna, Karim A. Iskandar, Wafik Lotfallah, Michael W. Ibrahim, and Jeffrey S. Russell

Abstract: Competent project managers (PMs) are the backbone of any construction project. It is extremely important to constantly develop and enhance their competencies. However, to establish effective training and development plans for PMs, the relative importance of the key competencies that define a PM's performance should be first understood. Instead of subjectively weighting the relative importance of differing competencies, this paper aims at developing an automated model that uses real-life data to compute the PM competency weights. The rationale behind the model is to maximize the distance in a higher dimensional space between average and exceptional PM performances. The model solves an eigenvalue problem, and identifies a single data-based weight for each competency. The model is generic and can be applied to various research settings to alleviate the problems associated with opinion-based assessment and reduce individuals' subjectivity. Findings within this paper reveal the most critical competencies that enable PMs to perform their roles in construction projects exceptionally.

Key words: modeling, decision support systems, eigenvalues, eigenvectors, project managers, competence, construction management.

Résumé : Des gestionnaires de projet (GP) compétents sont la pierre angulaire de n'importe quel projet de construction. Il est extrêmement important de constamment développer et améliorer leurs compétences. Cependant, afin d'établir des plans de formation et de perfectionnement efficaces pour les GP, l'importance relative des compétences clés qui définissent le rendement d'un GP devrait d'abord être comprise. Au lieu de subjectivement pondérer l'importance relative des différentes compétences, dans cet article, on vise à développer un modèle automatisé qui utilise des données réelles pour calculer les pondérations de compétence de GP. Le raisonnement qui sous-tend le modèle est de maximiser la distance, dans un espace de dimensions supérieures, entre les rendements moyens et exceptionnels des GP. Le modèle résout un problème de valeurs propres et établit une seule pondération à partir des données pour chaque compétence. Le modèle est générique et peut être appliqué à différents contextes de recherche afin d'atténuer les problèmes associés à l'évaluation d'après les opinions et de réduire la subjectivité des intervenants. Les résultats de cette étude révèlent les compétences les plus critiques qui permettent aux GP de remplir leurs fonctions de façon exceptionnelle dans le cadre de projets de construction. [Traduit par la Rédaction]

Mots-clés : modélisation, systèmes d'aide à la décision, valeurs propres, vecteurs propres, gestionnaires de projets, compétence, gestion de construction.

Introduction

Project managers (PMs) maintain ultimate responsibility for completing construction projects in compliance with owner requirements, as well as within budget and time constraints. Project managers must be competent to succeed in their roles and to accomplish project objectives. Faced with this fact, improving the performance of PMs through effective training and development plans is crucial to the success of projects and the survival of construction companies. A PM's performance regarding different competencies should first be assessed to implement effective training and development plans and to pinpoint critical improvement gaps.

A critical step to assess a PM's performance is to determine the weights (i.e., the relative importance) of the main competencies that he or she should possess. Unfortunately, researchers usually rely on directly weighting the competencies themselves, or averaging the opinions of a group of individuals regarding the relative importance of those competencies. In general, opinion-based assessment appears in many subject matters and research areas, other than PM competency assessment. As a result, this paper addresses the issue of subjectivity associated with opinion-based assessment, by developing an automated model that can compute the weights of a comprehensive list of 48 PM competencies. The model serves as a substitute means for previous opinion-based assessment.

The automated model is first developed and then applied to an actual dataset that consists of 62 observations. Each observation comprises one pair of PMs: an average PM and an exceptional PM. The performance of each PM is defined by his or her level of proficiency regarding each of the 48 competencies. The level of proficiency of PMs is determined by a supervisor who can clearly

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differentiate between one that is average and one that is exceptional. The automated model is generic, and can be used within any research context that involves the assessment of two groups with opposed aspects. In the context of this paper, the model is applied to an actual dataset to compute the competency weights that maximize the distance between average and exceptional PM performances.

Literature review

According to prior research (Drejer 2001; Nordhaug 1998; Sanchez et al. 1996), the term "competence" can be defined as the ability to mobilize and combine the necessary resources, such as knowledge, skills, and attitudes, to implement an activity. Competencies are specific personal qualities that are "causally related to effective and (or) superior performance" (Boyatzis 1982). In fact, competencies are not equal in terms of importance or contribution to PM performance. Therefore, weighting different PM competencies and identifying their relative importance is a key component for assessing PM performance and identifying exceptional PMs.

While some researchers have examined different types of competencies and their natures (Bredillet et al. 2015; Brière et al. 2015; Cheng et al. 2005; Crawford 2005; Dubois 1993; Lucia & Lepsinger 1999; Medina and Medina 2014; Morris et al. 2006; Suikki et al. 2006), other researchers have developed various PM competency tools and frameworks, such as the International Project Management Association Competence Baseline (IPMA 2006), the Global Alliance for Project and Program Manager Standards (GAPPS 2007), the Project Management Institute's Project Manager Competency Development (PMCD) Framework (PMI 2007), and the Project Manager Competency Assessment Tool (PM CAT) (CII-RT-306 2014). These tools assist in establishing PM development plans, tailoring PM training programs, and providing guidelines for PMs.

Unfortunately, some of the previously developed PM competency tools have a considerable shortcoming: The weighting procedure of differing competencies is often based on experts' personal opinions regarding the relative importance of competencies. There are existing methods used by researchers that involve subjective measurements and opinion, such as are the Delphi approach, the analytic hierarchy process (AHP), and data envelope analysis (DEA). The Delphi approach is a widely used means in the literature that involves collecting information and reaching consensus among experts on various factors to resolve a complex problem (Landeta 2006). The Delphi method provides valuable solutions to problems inherent in the traditional group opinion based on direct interaction as it reduces the influence of some undesirable psychological effects among participants. However, the method has several weaknesses, including experts' subjectivity and bias, the limitation of the interaction involved in written and controlled feedback, the difficulty of checking the method's accuracy and reliability, and the time and effort required to conduct it (Landeta 2006). Analytic hierarchy process is a multi-criteria decision making method that enables the user to observe a certain hierarchy and to find relations and associations between different options (Wind and Saaty 1980). It is widely used in many research fields; however, it heavily relies on personal opinions throughout its process as participating evaluators have to rate the elements of the analytical hierarchy process.

Data envelopment analysis (DEA) is another recognized method in the literature that uses linear programming techniques to convert inputs to outputs with the purpose of evaluating the performance of comparable organizations or products. DEA involves decision making units (DMUs) having a set of inputs and outputs. A relative efficiency is calculated based on linear relations between the inputs and outputs of the DMUs under analysis. In other words, DEA determines how efficient a DMU is in producing a certain level of output, based on the amount of input it uses, compared to similar DMUs (Mardani et al. 2016). Although these methods are successfully used in many research and business fields, they involve a substantial amount of subjectivity, and most of them do not suit the purpose of this paper, which is to derive relative importance of competencies based on performance data, not opinion data.

To alleviate the problems associated with the aforementioned shortcoming, an automated model is developed in this paper, and then applied to a dataset that encompasses 62 supervisors, 124 PMs, and 48 PM competencies, to derive relative importance of competencies based on performance data, not opinion data. The list of competencies used in this paper was adopted from the Construction Industry Institute (CII-RT-306 2014). The 62 PM supervisors were from 29 different US companies, including owners (42%), contractors (31%), engineers (15%), and architects (12%). Besides representing many parties in the construction industry, the data was representative as it was collected from companies with various sizes. Twenty-eight percent of the responding companies had annual revenue less than 250 million US Dollars, 12% had annual revenue between 250 million and 1 billion US Dollars, 24% had annual revenue between 1 billion and 25 billion US Dollars, 28% had annual revenue between 25 billion and 50 billion US Dollars, and 8% had annual revenue greater than 50 billion US Dollars. The distribution between private and public company projects was 47% and 53%, respectively. The location of the respondents' projects and PMs were as follow:

- United States (92%): AL, DC, GA, LA, MD, MI, MN, MO, NC, NJ, NY, OH, PA, TN, TX, VA, Puerto Rico
- International (8%): England; Canada; Brazil; Spain; The Netherlands; Peru.

The research scope includes PM competencies related to any phase of engineering procurement construction (EPC) projects with any types (institutional, industrial, commercial, among others). These projects are limited to those with a defined duration, budget, and scope. They also include all contract types and all project delivery methods. Project scope can be complex, multi-disciplined and (or) for multifunctional purposes. However, project types that are excluded from the scope of this study are: portfolios, programs, IT projects, and research and development projects.

Introduction to the mathematical model

Before proceeding to the mathematical model, the rationale of this paper is simplified using the following simple example:

Suppose we only have three supervisors. Each supervisor rates two PMs, one average and one exceptional, and each PM received a rating for each of the 48 competencies. We now have six sets of numbers: three sets for the average PMs and three sets for their corresponding exceptional PMs, where each set comprises of 48 ratings.

If we make the assumption that the 48 competencies are equally important (i.e., having equal weights), we can get an overall score for each of the six PMs by calculating the mean of the 48 competency ratings for each of them.

To further illustrate the example, let us assume that the overall scores of the six PMs are as follows:

- Average PM 1 score = 0.45; Average PM 2 score = 0.2; Average PM 3 score = 0.3
- Exceptional PM 1 score = 0.65; Exceptional PM 2 score = 0.6; Exceptional PM 3 score = 0.9

Note that each of the above scores is the mean of the 48 competency ratings for that PM. We can now let those overall scores be the coordinates of two points in the three dimensional space, namely the point (0.45, 0.2, 0.3) representing the average PMs, and the point (0.65, 0.6, 0.9) representing the exceptional PMs.

Fig. 1. Three-dimensional illustration of the vector connecting average PMs' scores to exceptional PMs' scores. [Colour online.]

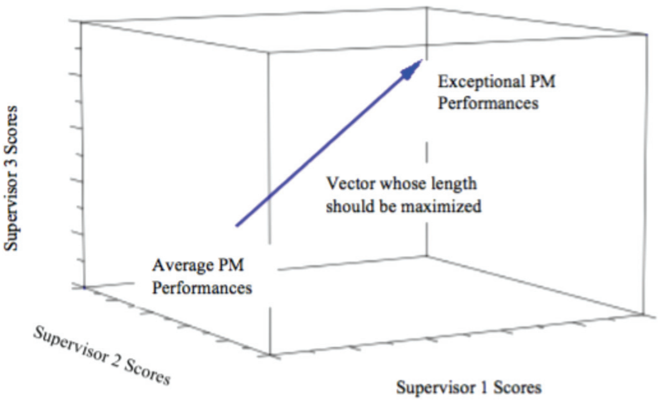

Figure 1 illustrates those two points as well as the vector connecting them. Note that, since this example deals with only three supervisors, the shown vector lives in the three dimensional unit cube. However, since our dataset includes 62 supervisors, that vector really belongs to the 62 dimensional unit hypercube.

Now, if we allow the weights of the 48 competencies to change, these points and the vector joining them will also change. We then seek the values of the weights that maximize the length of this vector. Maximizing the length of this vector reveals all gaps and unravels all differences in performance that exist between average and exceptional PMs. The weights corresponding to the vector whose length is maximized are the final targeted weights of this study.

Table 1 represents the mean and range of PM scores data for average and exceptional PMs, under the initial assumption that all 48 competencies have equal weight (i.e., are of equal importance).

The mathematical formulation presented herein dramatically enhances the objectivity of the proposed model relative to commonly used techniques. The model derives the competency weights based on relative rather than absolute information. The model does not consider the average PM to be absolutely average, or the exceptional PM to be absolutely exceptional. Instead, each average PM is perceived as being average relative to his or her corresponding exceptional PM rather than being perceived as an absolute average. The result of considering each pair of PMs as relative to their corresponding supervisor is the minimization of subjectivity. Consequently, the model alleviates the problem of having a supervisor who tends to be generally and naturally an underrating respondent. This supervisor will underrate his or her PMs compared to other supervisors. However, he or she will underrate both his or her average PM as well as his or her exceptional PM, but the difference, and in turn the analysis, will not be affected by such underrating behavior. Therefore, the proposed formulation creates pairs of average and exceptional PMs connected by vectors, where each member of the pair is rated by the same supervisor. This criterion creates 1 objective population of "relative performance" rather than 2 subjective populations of "absolute performances." This becomes the focus of the study — to determine the weight values that define the relationship between average and exceptional, rather than the hard limits of either.

The mathematical model

We start by defining our notations for the model. For each $j = 1, 2, \ldots, n$, let $0 \le x_j \le 1$ be the rating of a PM in Competency j. For simplicity, the score of that PM will be given by a linear weighted function

Table 1. Range of PM scores if weights were equal.

	Value		
PM category	Mean value	Minimum value	Maximum value
Average PMs	0.63	0.39	0.85
Exceptional PMs	0.83	0.58	0.95

$$(1) \qquad f(x_1, x_2, \ldots, x_n) = \sum_{j=1}^{n} w_j x_j$$

where w_j ($j = 1, 2, \ldots, n$) are the unknown weights of the competencies, satisfying the condition:

$$(2) \qquad (^*) \quad \sum_{j=1}^{n} w_j = 1$$

Using the matrix notation, we let the ratings (row) vector $\boldsymbol{X}$ and the weights (column) vector $\boldsymbol{W}$ be defined by

$$(3) \qquad \boldsymbol{X} = [x_1 \ \ x_2 \ \ \cdots \ \ x_n] \qquad \boldsymbol{W} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}$$

Thus, the scoring function f is simply given by

$$(4) \qquad f(X) = \boldsymbol{XW} = [x_1 \ \ x_2 \ \ \cdots \ \ x_n]\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}$$

with the normalization condition (*) expressed by

$$(5) \qquad [1 \ \ 1 \ \ \cdots \ \ 1]\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = 1$$

Recall that the data on which this model is based upon is the assessment obtained by m construction supervisors for n competencies of PMs, where each supervisor i ($i = 1, 2, \ldots, m$) evaluated two PMs, one is an average PM, and the other is an exceptional PM. The ratings that Supervisor i gave to Competency j for his or her average and exceptional PMs will be denoted by a_{ij} and e_{ij}, respectively. The ratings of all supervisors can therefore be expressed using the following two $m \times n$ matrices $\boldsymbol{A} = [a_{ij}]_{m \times n}$ and $\boldsymbol{E} = [e_{ij}]_{m \times n}$.

Note that the ith rows A_i and E_i in the matrices A and E denote the ratings of a Supervisor "i" to an average and an exceptional PM, respectively. Thus, the scores of the average and exceptional PMs are thereby given by the $m \times 1$ column vectors:

$$(6) \qquad \begin{aligned} [f(A_i)]_{m\times 1} &= \left[\sum_{j=1}^{n} a_{ij} w_j\right]_{m\times 1} = \mathbf{A}W \\ [f(E_i)]_{m\times 1} &= \left[\sum_{j=1}^{n} e_{ij} w_j\right]_{m\times 1} = \mathbf{E}W \end{aligned}$$

The difference between these score vectors is then given by

$$\mathbf{E}\boldsymbol{W} - \mathbf{A}\boldsymbol{W} = (\mathbf{E} - \mathbf{A})\boldsymbol{W} = \mathbf{D}\boldsymbol{W} \tag{7}$$

where we have used the matrix **D** of the rating differences defined by:

$$\mathbf{D} = \mathbf{E} - \mathbf{A} = [e_{ij} - a_{ij}]_{m\times n} \tag{8}$$

The rationale behind selecting the weight vector $\boldsymbol{W}$ is to maximize the length of the vector $\mathbf{D}\boldsymbol{W}$. This vector, which was illustrated in the previous section in Fig. 1, connects the point $\mathbf{A}\boldsymbol{W}$ to the point $\mathbf{E}\boldsymbol{W}$, which both belong to the unit hypercube of the mth dimensional space of ratings. Maximizing the length of the vector $\mathbf{D}\boldsymbol{W}$ reveals the gap between the average and the exceptional PMs, and results in our targeted weights.

However, we note that Condition (*) allows the weights w_j to take negative values. In fact, we can verify that, under that condition, the set of vectors $\mathbf{D}\boldsymbol{W}$ forms a hyper plane in the nth dimensional space that includes all columns of the matrix **D**. Thus, even if we restrict all weights to be nonnegative, the length of the vector $\mathbf{D}\boldsymbol{W}$ would be maximized by letting $w_j = 0$ for all j, where column j in **D** is not of maximal length.

To solve this problem, we will temporarily replace the weight vector $\boldsymbol{W}$ by a vector $\boldsymbol{U}$ of unit length, thus resulting into a compact set of vectors $\mathbf{D}\boldsymbol{U}$. So we will select the unit vector $\boldsymbol{U}$ that maximizes the (square of) the length of the vector $\mathbf{D}\boldsymbol{U}$, i.e., we need to maximize the function:

$$h(\boldsymbol{U}) = \|\mathbf{D}\boldsymbol{U}\|^2 = (\mathbf{D}\boldsymbol{U})^{\mathrm{T}}(\mathbf{D}\boldsymbol{U}) = \boldsymbol{U}^{\mathrm{T}}\mathbf{D}^{\mathrm{T}}\mathbf{D}\boldsymbol{U} \tag{9}$$

subject to the constraint

$$(^{**}) \quad g(\boldsymbol{U}) = \boldsymbol{U}^{\mathrm{T}}\boldsymbol{U} = 1 \tag{10}$$

Using the theory of Lagrange multipliers of matrix calculus, we find all vectors $\boldsymbol{U}$ satisfying (**) (above), along with the vector equation

$$\frac{\partial h}{\partial \boldsymbol{U}} = \lambda \frac{\partial g}{\partial \boldsymbol{U}} \tag{11}$$

where λ is the Lagrange multiplier. This leads to

$$\frac{\partial(\boldsymbol{U}^{\mathrm{T}}\mathbf{D}^{\mathrm{T}}\mathbf{D}\boldsymbol{U})}{\partial \boldsymbol{U}} = \lambda \frac{\partial(\boldsymbol{U}^{\mathrm{T}}\boldsymbol{U})}{\partial \boldsymbol{U}} \tag{12}$$

$$\mathbf{D}^{\mathrm{T}}\mathbf{D}\boldsymbol{U} = \lambda\boldsymbol{U} \tag{13}$$

Thus, $\boldsymbol{U}$ is a unit eigenvector $\boldsymbol{U}$ (with positive components) of the $n \times n$ square matrix $\boldsymbol{C} = \mathbf{D}^{\mathbf{T}}\mathbf{D}$, that maximizes the function $h(\boldsymbol{U}) = \boldsymbol{U}^{\mathbf{T}}\boldsymbol{C}\boldsymbol{U}$.

The weight vector $\boldsymbol{W}$ can be taken to be a scalar multiple of $\boldsymbol{U}$ (and thus an eigenvector of C) satisfying Condition (*), which leads to the formula

$$\boldsymbol{W} = \frac{1}{\sum_{j=1}^{n} u_j}\boldsymbol{U} \tag{14}$$

To avoid overestimating the weights of those categories with a large number of competencies while underestimating the weights of those categories with a small number of competencies, we follow the following procedure:

1. We treat every category independently to select the weights of each competency within its category.
2. These weights will be used to calculate the differences in the category ratings of the exceptional and average PMs.
3. Those differences are used to calculate the weights of the categories.
4. Finally, the weight of each competency is calculated as the product of its weight within its category and the weight of its category.

We start by assuming a natural partition of the set of competencies into four disjoint subsets as follows:

$$\{1, 2, \ldots, n\} = N_1 \cup N_2 \cup N_3 \cup N_4 \tag{15}$$

where in our case

$$\begin{array}{ll} N_1 = \{1, 2, \ldots, 6\} & N_2 = \{7, 8, \ldots, 22\} \\ N_3 = \{23, 24, \ldots, 38\} & N_4 = \{39, 40, \ldots, 48\} \end{array} \tag{16}$$

Letting n_k be the size of the partition N_K, we get that $n = n_1 + n_2 + n_3 + n_4$. This also partitions the difference matrix **D** as follows:

$$\mathbf{D} = [\mathbf{D}_1|\mathbf{D}_2|\mathbf{D}_3|\mathbf{D}_4] \tag{17}$$

where each $\mathbf{D}_{\boldsymbol{k}}$ ($k = 1, \ldots, 4$) is an $m \times n_k$ matrix carrying the rating differences $e_{ij} - a_{ij}$, where j ranges only over the competencies of Category k.

We now describe the procedure (outlined above) for getting the weight vector $\boldsymbol{W}$ as follows:

Step 1

For each Category k, find the eigenvector $\boldsymbol{V_k}$ of the matrix $\mathbf{D}_{\boldsymbol{k}}^{\mathrm{T}}\mathbf{D}_{\boldsymbol{k}}$ with positive components satisfying: $[1 \quad 1 \quad \cdots \quad 1]_{1\times n_k}\boldsymbol{V_k} = 1$. These are the weights of the competencies within Category k.

Step 2

To calculate the weights of the four categories, we use the $m \times 4$ matrix Δ defined by:

$$\Delta = [\mathbf{D}_1\boldsymbol{V}_1|\mathbf{D}_2\boldsymbol{V}_2|\mathbf{D}_3\boldsymbol{V}_3|\mathbf{D}_4\boldsymbol{V}_4] \tag{18}$$

Note that Column k of Δ is $\mathbf{D}_{\boldsymbol{k}}\boldsymbol{V_k}$, which gives the differences between the ratings of the exceptional and the average PMs for Category k. Thus, the role of the matrix Δ is similar to that of the matrix **D**.

Step 3

Find the eigenvector $\boldsymbol{\alpha}$ of the matrix $\Delta^{\mathbf{T}}\Delta$ with positive components satisfying: $[1\,1\,1\,1]\boldsymbol{\alpha} = 1$. These are the category weights.

Step 4

Finally, the weight vector containing the weights of all competencies is given by

$$\boldsymbol{W} = \begin{bmatrix} \alpha_1\boldsymbol{V}_1 \\ \alpha_2\boldsymbol{V}_2 \\ \alpha_3\boldsymbol{V}_3 \\ \alpha_4\boldsymbol{V}_4 \end{bmatrix} \tag{19}$$

Note that Condition (*): $\sum_{j=1}^{n} w_j = 1$ holds.

The above procedure was implemented using the programming language R (See Appendix A for a complete R script of the model).

Results and discussion

The numerical output of the model includes three sets of values: category weights, competency weights within each category, and

Table 2. Category weights.

Category name	Data-based weight (%)	Opinion-based weight (%)
Knowledge and experience	23.36	22.1
Management	20.49	25.0
Cognitive	33.54	23.6
Leadership	22.61	29.3

competency weights relative to all other competencies. This section will discuss the competency weights with respect to the resulting "data-based" weights of the model, and will pinpoint the deviations from the "opinion-based" weights that were perceived by experts.

Category weights (α)

According to the data-based weights shown in Table 2, the category of "Cognitive" competencies is ranked first among the four categories with a relative weight of 33.54%, followed by "Knowledge and experience" (23.36%), "Leadership" (22.61%), and "Management" (20.49%). Accordingly, PMs must have adequate cognitive attributes to exceptionally manage their projects. More specifically, PMs should apply analytical and strategic thinking on different project issues and always suggest solutions when problems arise. In addition, they must continuously listen to different project parties and transfer necessary information in a timely manner. It is worth mentioning that the importance of the "Cognitive" category was significantly underestimated by experts as this category had an opinion-based weight and a data-based weight of 23.6% and 33.54%, respectively. Therefore, cognitive competencies were found to be essential in distinguishing between average and exceptional PMs.

Competency weights within each category (V)

Using the data-based values (V) indicated by the model, this section focuses on critical competencies within each category.

Knowledge and experience (V_1)

With respect to the data-based weights, Table 3 shows that the "Business and financial acumen" competency is ranked first within the "Knowledge and experience" category. Therefore, to be exceptional, PMs should understand business, financial, and market aspects of projects and use relevant methods and techniques to apply their knowledge on their projects. Additionally, it is recommended that PMs implement available information technologies to manage different project processes. It is also important that they understand the project life cycle and continuously monitor similar projects.

Although experts emphasized the importance of the competency "Certification and training", this paper's model indicated a data-based weight of 3.57% for this competency within its category, compared to an opinion-based weight of 14%. This competency centers on pursuing certifications required by the company, as well as certifications offered by external organizations that PMs may take on their own accord. By examining the ratings of this competency for the two PM groups, it was found that they have low values, ranging from 0.1 to 0.3, in both groups. It should be noted that the bigger the difference between the two groups' ratings, the bigger the resulting weight. This explains the significantly lower weight indicated by the model for this competency within its category. Consequently, this paper's model showed that experts overestimated the weight of this competency, and that the mere fact of a PM pursuing certifications and training is not by itself an indication of exceptional job performance.

Management (V_2)

Table 4 shows that none of the competencies belonging to the "Management" category should be overlooked by PMs. Consequently, PMs should plan, execute, and control project processes to successfully achieve project goals. They should ensure adequate communication between stakeholders and build knowledge networks to make sound decisions by consulting experts from external organizations. Furthermore, PMs should focus on their clients' needs to meet project requirements. It is also essential that PMs control project cost and schedule performance, as well as monitor known and unforeseen risks. By comparing the data-based to the opinion-based weights, it can be found that experts relatively underrated the ability to resolve conflicts, and the ability to ensure adequate communication amongst project stakeholders.

Table 3. Competency weights within the "knowledge and experience" category.

Competency name	Data-based weight (%)	Opinion-based weight (%)
Business and financial acumen	23.86	18.6
Disciplinary understanding of all phases of projects and their interrelationship	20.00	20.1
Continuously monitors and is aware of similar projects	18.59	13.5
Awareness of and knowledge to use state-of-the-art technology	17.94	13.8
Disciplinary understanding of a pm job	16.05	20.1
Certification and training	3.57	14.0

Table 4. Competency weights within the "management" category.

Competency name	Data-based weight (%)	Opinion-based weight (%)
Communications management	7.75	6.5
Integration management	7.62	5.7
Issues management/conflict resolution	7.46	6.5
Focus on client's needs	7.29	6.9
Build knowledge network	7.06	6.0
Project controls	6.94	7.0
Business developments/ability to sell	6.81	6.3
Ability to look ahead and plan	6.63	6.4
Organizational savvy	6.30	6.3
Knowledge and management of legal issues	6.04	5.5
Organize project staff and process expertise	5.64	6.9
Internal and external relations	5.43	6.3
Risk management	5.30	5.9
Quality management	5.17	5.7
Human resource management	5.01	5.3
Leadership in safety	3.56	6.8

Even though there is little difference between the weights within the "Management" category, the "Leadership in safety" competency ranks lowest according to the data-based weights. This competency focuses on the ability to establish a culture of safety at the job site. By examining the ratings of this competency for the two PM groups, it was found that they have high values, ranging from 0.6 to 1, in both groups. Although the relatively small difference in values between the two groups justifies the low weight of this competency within its category, the high ratings assigned for both groups indicate that "Leadership in safety" should be a fundamental attribute for all PMs.

Cognitive (V_3)

Table 5 shows that the top three cognitive PM competencies with respect to the data-based weights are: "Energetic and enthusiastic", "Assertive/aggressive/result-driven/decisive", and "Positive attitude/selflessness." Apart from these three competencies, PMs should also possess the ability to address concerns and commit-

Table 5. Competency weights within the "cognitive" category.

Competency name	Data-based weight (%)	Opinion-based weight (%)
Energetic and enthusiastic	11.66	5.4
Assertive/aggressive/result driven/decisive	11.61	4.9
Positive attitude/selflessness	10.60	5.3
Adaptable/approachable/attentively-listen to others	7.57	5.3
Accountable/responsible/reliable	6.77	5.3
Detail oriented/organized	6.52	5.3
Courage	5.31	6.7
Vision	5.04	7.0
Mature/possesses self-control skills/ professional	4.95	5.4
Self-awareness	4.66	6.9
Impact and influence	4.62	7.0
Initiative	4.48	7.5
Strategic thinking	4.33	7.2
Analytical thinking	4.23	6.8
Personal effectiveness	3.93	6.7
Achievement and action	3.72	7.0

Table 6. Competency weights within the "leadership" category.

Competency name	Data-based weight (%)	Opinion-based weight (%)
Develop and mentor others	11.32	9.2
Build coalitions within project team	10.98	10.5
Possess strategic insight	10.71	10.0
Build trust	10.46	11.1
Build consensus	10.32	9.2
Innovation	10.17	9.3
Team builder	10.12	11.1
Directness/influential	9.53	9.7
Engage others	9.46	10.1
Cultural and ethnic sensitivity/leverages diverse thinking	6.94	9.8

ments, and should show willingness to learn and participate at the job site. In addition, it is vital to apply logical thinking to different project situations while anticipating unforeseen conditions. Furthermore, PMs must be proactive and have direct and positive impact on different project participants. It is worth mentioning that experts underestimated the importance of the three top ranked "Cognitive" competencies. More specifically, the competency "Being assertive/aggressive/result driven" had a data-based weight of 11.61% versus an opinion-based weight of 4.9%. Also, the competency "Being energetic/enthusiastic" has a data-based weight of 11.66% versus an opinion-based weight of 5.4%. Lastly, the competency "Having a positive attitude" has a data-based weight of 10.6% versus an opinion-based weight of 5.3%. Overall, according to this paper's model, cognitive competencies were found to be crucial for PMs to exceptionally perform their roles in construction projects.

Leadership (V_4)

As shown in Table 6 and according to the data-based weights, PMs should practice leadership and build teams by developing alliances between different parties. They should also train and mentor others to leverage their talents. Moreover, PMs should effectively listen and clearly transmit complicated ideas to different project participants. By comparing the data-based to the opinion-based weights, it can be found that experts relatively underrated the ability of developing and mentoring others as well as the ability to reach consensus amongst project team.

Although many of the competencies in the "Leadership" category rank close together, the "Cultural and ethnic sensitivity/ leverages diverse thinking" competency had the lowest weight ranking. This competency is concerned with aspects of language, behaviors, and beliefs, and is centered on understanding how diversity can benefit a project by providing varying perspectives from different cultures, genders, and personal experiences. By examining the ratings of this competency for the two PM groups, it was found that they have high values, ranging from 0.6 to 1, in both groups. This relatively small difference in ratings between the two groups explains the lower weight of this competency within its category, but also indicates that "Cultural and ethnic sensitivity/leverages diverse thinking" should be a fundamental attribute for all PMs.

Competency weights relative to all other competencies (*W*)

According to the weights provided in Table 7, the top eight overall competencies were found to be the primary knowledge and cognitive skills required for PMs to proficiently lead project teams and engage them in efficient work. These top eight competencies were found to account for one third of the weights of all competencies combined. They are

1. Business and financial acumen (5.57%) (*knowledge and experience*)
2. Disciplinary understanding of all phases of projects and their interrelationships (4.67%) (*knowledge and experience*)
3. Continuously monitor and are aware of similar projects (4.34%) (*knowledge and experience*)
4. Knowledge to use the state-of-the-art technology (4.19%) (*knowledge and experience*)
5. Energetic and enthusiastic (3.91%) (*cognitive*)
6. Assertive/aggressive/result-driven/decisive (3.89%) (*cognitive*)
7. Disciplinary understanding of their job (3.75%) (*knowledge and experience*)
8. Positive attitude/selflessness (3.55%) (*cognitive*)

Conclusions

This study provides the construction field with an automated model applied to a dataset of 48 PM competencies to select the weights that maximize the distance between average and exceptional PM performances. The model identifies three sets of values: the competency weights within their categories, the category weights, and the overall competency weight relative to all competencies. The "Cognitive" category was found to have the highest weight, followed by "Knowledge and Experience," "Leadership," and "Management." Rather than simply averaging direct opinions of experts regarding the weights of competencies themselves, this paper's model computes accurate data-based weights for PM competencies. The data-based weights of this study enable supervisors to have a better understanding of the performance of their PMs, thus pinpointing the most critical competencies that distinguish between average and exceptional PMs.

Findings revealed that to exceptionally perform their jobs, PMs should understand business, financial, and market aspects associated with the project and should maintain a thorough understanding of the interrelationships between different project phases. It is also important for PMs to be up-to-date with technology and construction methods used in other similar projects. In addition, PMs must be proactive, energetic, and assertive. They should also have the ability to analyze different perspectives to make effective management decisions, properly address controversial opinions, and show improvement and achievement at the job site. Furthermore, it is essential that PMs are able to reach consensus on critical issues between different project participants. Moreover, PMs should have the ability to implement project management best practices throughout the project life cycle and to identify potential legal issues. They must also ensure that adequate communication occurs within project stakeholders.

Table 7. Overall competency weights (W).

Category name	Competency name	Competency weight (%)	Competency rank
Knowledge and experience	Business and financial acumen	5.57	1
	Disciplinary understanding of all phases of projects and their interrelationship	4.67	2
	Continuously monitors and is aware of similar projects	4.34	3
	Awareness of and knowledge to use state-of-the-art technology	4.19	4
	Disciplinary understanding of a PM job	3.75	7
	Certification and training	0.83	47
Management	Communications management	1.59	24
	Integration management	1.56	27
	Issues management/conflict resolution	1.53	29
	Focus on client's needs	1.49	31
	Build knowledge network	1.45	33
	Project controls	1.42	34
	Business developments/ability to sell	1.40	36
	Ability to look ahead and plan	1.36	37
	Organizational savvy	1.29	39
	Knowledge and management of legal issues	1.24	41
	Organize project staff and process expertise	1.16	42
	Internal and external relations	1.11	43
	Risk management	1.09	44
	Quality management	1.06	45
	Human resource management	1.03	46
	Leadership in safety	0.73	48
Cognitive	Energetic and enthusiastic	3.91	5
	Assertive/aggressive/result driven/decisive	3.89	6
	Positive attitude/selflessness	3.55	8
	Adaptable/approachable/attentively listen to others	2.54	10
	Accountable/responsible/reliable	2.27	17
	Detail oriented/organized	2.19	18
	Courage	1.78	21
	Vision	1.69	22
	Mature/possesses self-control skills/professional	1.66	23
	Self-awareness	1.56	26
	Impact and influence	1.55	28
	Initiative	1.50	30
	Strategic thinking	1.45	32
	Analytical thinking	1.42	35
	Personal effectiveness	1.32	38
	Achievement and action	1.25	40
Leadership	Develop and mentor others	2.56	9
	Build coalitions within project team	2.48	11
	Possess strategic insight	2.42	12
	Build trust	2.36	13
	Build consensus	2.33	14
	Innovation	2.30	15
	Team builder	2.29	16
	Directness/influential	2.15	19
	Engage others	2.14	20
	Cultural and ethnic sensitivity/leverages diverse thinking	1.57	25

Finally, the competency weights provided by this study enable PMs to focus on the aforementioned critical competencies and to be aware of their competency strengths and weaknesses.

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Appendix A: R script of the model

R is a system for statistical computation and graphics. Among its features, R includes a programming language, high level graphics, interfaces to other languages and debugging facilities (Team 2000). More specifically, R enables users to write functions that take expressions as input, which is often useful for statistical modeling and graphics. Also, R's data structures include vectors, matrices, arrays, and data frames. Equations of this paper's model were written and solved in R version 3.1.1. Following is the R script of the model:

```
d < - read.csv("data.csv",header = TRUE) # d = "data.frame"
n.rows = dim(d)[1]
m = n.rows
### Category k ###
delta = d[1:m, 1:j ]
delta ## Report matrix "D"
dim(delta)
delta.t < - t(delta) ## Report matrix "D Transpose"
dim(delta.t)
C < - as.matrix(delta.t) %*% as.matrix(delta)
C ## Report matrix "C"
dim(C)
eigen(C)
## Select eigenvalue and its corresponding eigenvector
eigenvector < - eigen(C)$vectors[,j]
eigenvector ## Report the selected eigenvector
eigenvalue < - eigen(C)$values[j]
eigenvalue ## Report the selected eigenvalue
## Get the unit vector
u.i < - –1 * eigenvector ## Report the vector "U"
## Check that the length of the unit vector =1 (Check that Sigma
u.i^2 =1)
norm(as.matrix(u.i),type = c("F"))
Sigma.u.i < - sum(u.i)
V < - (1/Sigma.u.i) * u.i
V ## Report the weights "V"
sum(V) ## Check that the sum of the weights = 1
### Getting the category weights ###
delta1 = d[1:n, 1:6 ]
delta1
dim(delta1)
Within.cat.weights1 < - as.matrix(d[1:6,49])
Within.cat.weights1 ## Report V1
A1 < - as.matrix(delta1) %*% Within.cat.weights1
A1 ## Report "D V" of category 1
delta2 = d[1:n, 7:22 ]
delta2
dim(delta2)
Within.cat.weights2 < - as.matrix(d[1:16,50])
Within.cat.weights2 ## Report V2
A2 < - as.matrix(delta2) %*% Within.cat.weights2
A2 ## Report "D V" of category 2
delta3 = d[1:n, 23:38 ]
delta3
dim(delta3)
Within.cat.weights3 < - as.matrix(d[1:16,51])
Within.cat.weights3 ## Report V3
A3 < - as.matrix(delta3) %*% Within.cat.weights3
A3 ## Report "D V" of category 3
delta4 = d[1:n, 39:48 ]
delta4
dim(delta4)
Within.cat.weights4 < - as.matrix(d[1:10,52])
Within.cat.weights4 ## Report V4
A4 < - as.matrix(delta4) %*% Within.cat.weights4
A4 ## Report "D V" of category 4
new.delta < - as.matrix(cbind(A1,A2,A3,A4)) ## Get " Δ "
## Repeat procedure as in "Category k" to get α
w1 < - Within.cat.weights1%*% d[1,53] ## Category 1 weights * α 1
w2 < - Within.cat.weights2%*% d[2,53] ## Category 2 weights * α 2
w3 < - Within.cat.weights3%*% d[3,53] ## Category 3 weights * α 3
w4 < - Within.cat.weights4%*% d[4,53] ## Category 4 weights * α 4
w < - as.matrix(rbind(w1,w2,w3,w4)) ## Report Final Overall Weights
```