Analytic Hierarchy Process as a Tool to Explore the Success Factors of BIM Deployment in Construction Firms

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Abstract –

In the past ten years, more and more construction companies have adopted and implemented the Building Information Modelling (BIM). Government agencies have addressed the relevant technologies because the application of BIM has brought a lot of benefits to engineering. However, many companies today have neither deployed BIM technology nor confirmed their intention(s) to adopt BIM technology. This is perhaps subject to the limited knowledge about successful BIM deployments. Based on the literature and the experience of an expert, in this study, the influencing factors and a decision hierarchy are identified and developed by using Delphi method. The priority over and the relative importance of these factors and over/of those upper constructs were analysed using the analytic hierarchy process (AHP). These findings are key to enhance the decision-making process of a construction firm which wishes to introduce a BIM system.

Keywords –

Building Information Modelling; Delphi Method; Analytic Hierarchy Process (AHP); System Adoption Factors (SAF)

1 Introduction

Adopting BIM technology in an architecture, engineering, or construction (AEC) project may improve the performance of the project and bring benefit to the project. Establishing an effective BIM evaluation standard can help new users of BIM systems during deployment [1]. However, as the studied case in Taiwan, at this stage, most of the companies that have adopted BIM technology are the construction firms.

This paper studies the influencing factors which may affect a construction firm’s decision on the adoption of BIM technologies for deployment and implementation. Except for analysing the priority and the relative importance of these factors, these factors are mounted under four constructs, namely, BIM system integration, BIM use, organisation (organizational factors), and project execution. The relative importance of these constructs, which is also the key knowledge that is to be explored, is also assessed.

This study progresses as follows. First, from a literature study and the expert discussions, the set of initial system adoption factors (SAFs) for BIM were determined. These SAFs are organised as a ‘decision hierarchy’ [2] [3]. It is a tree which includes a layer of constructs and another layer of factors, while the root of this hierarchical tree is the total decision goal (i.e., the deployment and implementation of a BIM system). Delphi Method, which is also known as the expert survey method, is used confirm the form of the decision hierarchy, with expert discussions polled.

Next, using the analytic hierarchy process (AHP), a questionnaire is designed and the expert opinions are investigated in terms of the pairwise comparison matrices. To facilitate this survey process, Expert-Choice, a computerised tool, is used as an assistant tool to validate the consistency in the data (i.e., polled opinions) and to obtain the weights (relative importance) of the factors/constructs. Finally, these factors are prioritized according to their associated weights. The key factors that influenced BIM system adoption, which is the key knowledge as desired by the decision makers (DMs), are identified. Together with other findings, the set of knowledge can serve as an important guide for any construction firm which is willing to adopt, deploy and implement the relevant technologies of BIM.

2 The Determination of the Influencing Factors Using Delphi Method

Figure 1 shows the way in which this study has applied the Delphi Method.

First, in the literature study phase, the influencing factors of BIM on BIM adoption are identified from the literature, using materials in the research field. The literature and the collected materials are also used as the important references for subsequent study. A number of influencing factors (i.e., SAFs) are collected in this process. For example, but not limited to, Badrinath summarised a set of 454 initial SAFs [4]. Tsai et al. identified the other set of 123 SAFs, considering the whole life cycle of the building as the research subject [5][6], while in general, the life cycle of a building is mainly divided into four general stages: planning, design, construction, and operation/maintenance.

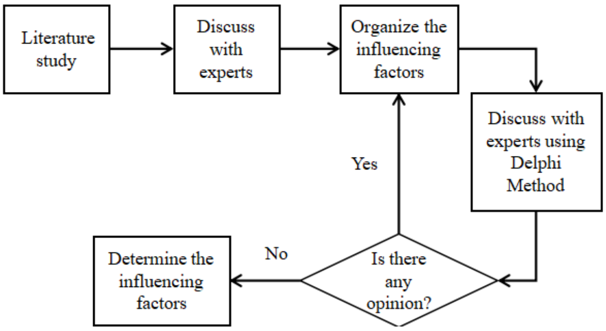

Figure 1. Determining the influencing factors

Second, it is the 'discussion with the expert' phase. The SAFs which are summarized from the literature are given by a BIM researcher in Taiwan. She is in charge of filtering the SAFs and reduce the size of the set of SAFs so that only those factors which are regarded as important for the construction firms in Taiwan are included. So after the discussions, this phase obtains a set of only 25 'initial SAFs'.

Third, the Delphi method (see the right loop in the figure) is used to confirm the obtained set of SAFs, while any addition of a new SAF or removal of an included SAF in the set is possible. The Delphi method, also known as the 'expert survey method', mainly uses communication methods to send questions that are to be discussed to the experts for consultation, to collect the opinions of all the experts, to understand these opinions by discussions and to aggregate the opinions. These aggregated opinions are once again fed back to the experts for further consultation, so their opinions are collected and aggregated more accurately. This approach gradually produces more consistent results for making a precise decision. It uses an anonymous way where the aggregated opinion maintains a general representativeness and is thus a reliable decision-making method.

In this study, through the use of the Delphi method with the experts help, eventually, two new SAFs, i.e., BIM system expansion capability and BIM technology cooperation between the construction firm and downstream subcontractors, are added to the set, but no SAF in the initial set is removed. In the opinion of the expert, the system scalability of BIM technology is very important. In addition, most of the downstream subcontractors of the construction firm will affect the performance of the BIM system owned by the construction firm itself. Therefore, finally, a total number of 27 SAFs are included and studied in this study.

3 AHP Questionnaires and Surveys

In this study, a tree-like hierarchical diagram is established, as to organise the SAFs. This is usually called a 'decision hierarchy'. This decision hierarchy includes not only a bottom layer of the SAFs, but also a middle layer of constructs, where each SAF is mounted under some construct. Thus, a decision construct may have several SAFs mounted. And, all of these constructs are further mounted under the total decision goal, which is BIM adoption.

However, as this decision hierarchy is established by the researchers of this study (see *phase 1* in Figure 2), it requires further confirmation. In this study, this is confirmed by also using the Delphi Method (see *phase 2* in Figure 2). Fortunately, the established decision hierarchy is approved by the expert when it was first established.

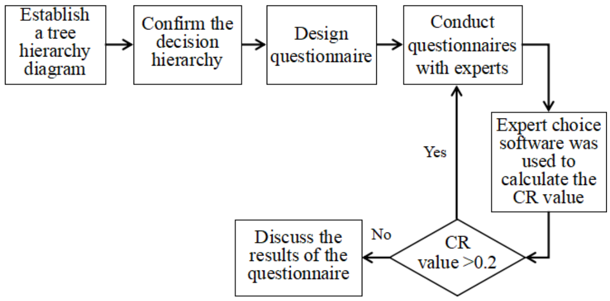

Figure 2. The workflow of AHP processes

Therefore, the confirmed decision hierarchy is used as the basis to design the questionnaires for the pairwise comparisons in the style of AHP. In the confirmed hierarchy, since there are four constructs w.r.t. the goal and there are different numbers of SAFs w.r.t. each construct, there are five questionnaires. This is exactly *phase 3* in Figure 2.

After the questionnaires are designed, they are used for the survey wherein the DM expresses his preferences in terms of pairwise comparisons. The DM is asked for more rounds of interview if the result does not pass the consistency check. This survey process is as shown in the *right part* of Figure 2.

The Analytic Hierarchy Process (AHP) [7] is mainly used for decision problems with multiple evaluation criteria. The purpose is to divide the considerations for a complex decision problem system into several smaller parts (i.e., the constructs), where each of these smaller parts includes the observable factors (i.e., the SAFs). A decision hierarchy can help a DM to fully understand the influencing factors during decision-making, and the analysis of AHP is a method to assess the (relative) importance of these factors in terms of the results from the pairwise comparisons performed by the DM.

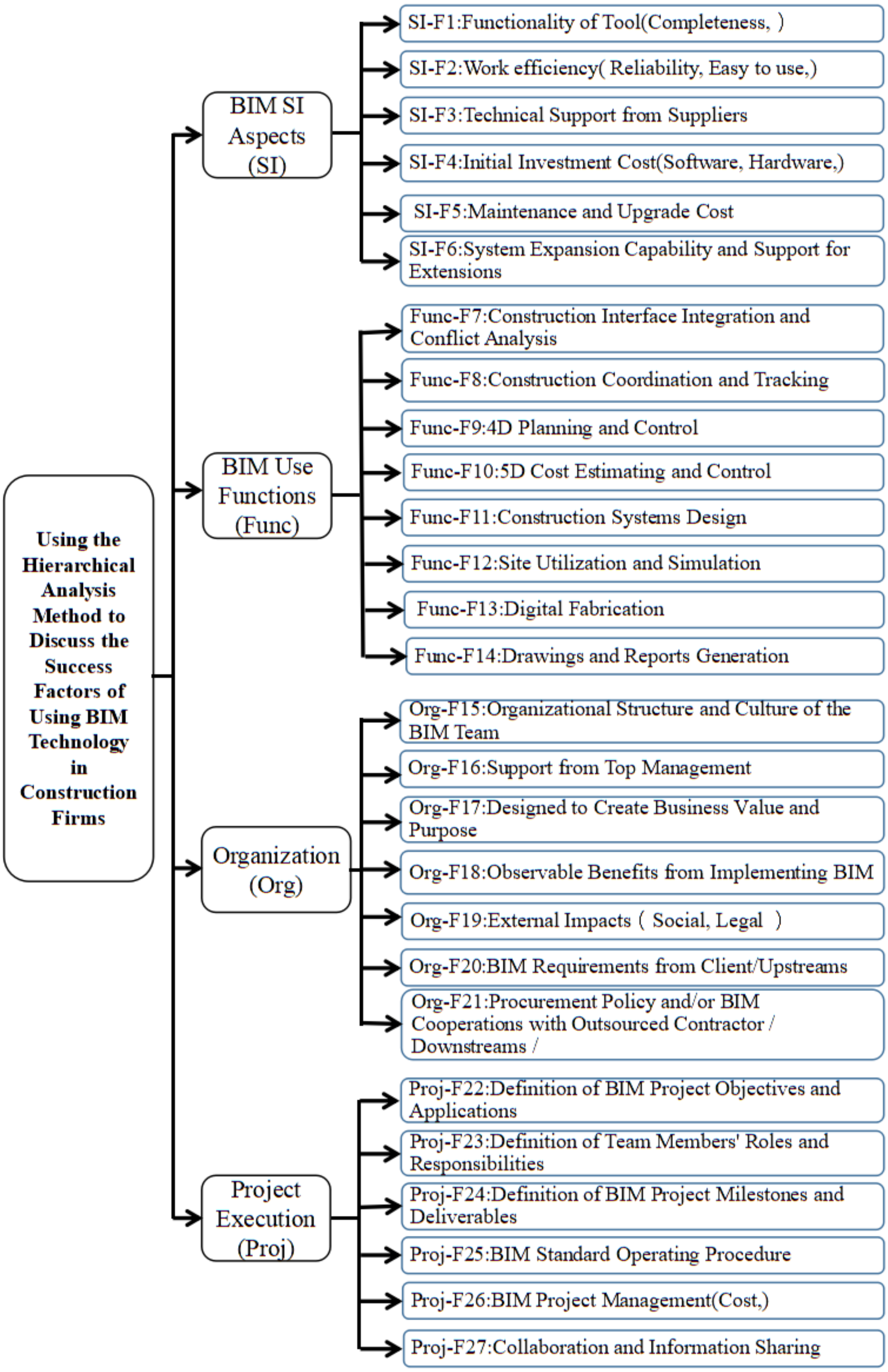

Figure 3. The decision hierarchy diagram

In this study, the decision hierarchy that is confirmed is shown in Figure 3. This hierarchy details what are to be compared pair-wisely.

For the constructs w.r.t. the total BIM adoption decision goal or the SAFs w.r.t. some construct, results from the pairwise comparisons are recorded in a 'pairwise comparison matrix'. Each element in the matrix is recorded as a level revealing the relative importance of a criterion (i.e., a construct or a SAF), C_x, against another criterion, C_y. This is a quantitative measure because the evaluation values in the matrix state the following facts (in the DM's mind): C_x is equal strong (1:1), weakly strong (3:1), strong (5:1), very strong (7:1), and absolutely strong (9:1) than C_y, so the corresponding measured values are 1, 3, 5, 7 and 9, whilst 1, 1/3, 1/5, 1/7 and 1/9 are recorded for the cases vice versa.

The survey work of this study obtain several pairwise comparison matrices in this manner, as the questionnaires that were designed based on the decision hierarchy and were answered the BIM expert had provided data to fill up these matrices. During the survey, the interviewed expert DM specified the relative importance of each pair of two criteria in the questionnaire, and such information became the data source to compose (fill in) each pairwise comparison matrix.

To validate the collected source data, Expert Choice (i.e., a decision analysis software) was used to receive the input, to compose the decision matrix, to validate the answers in terms of consistency ratio (C.R.) and as to calculate the weights of the constructs or the SAFs.

In the consistency analysis, if the C.R. value of the questionnaire was greater than 0.2, the DM was asked to fill the questionnaire once again until the C.R. of the questionnaire yielded a value less than the standard of the inconsistency threshold (C.R. value < 0.2). As in other engineering fields, Zhuang et al. [8], Schmidt et al. [9] and other scholars believe that an AHP questionnaire is acceptable when the C.R. value of a pairwise comparison matrix it infers is less than 0.2.

In this study, actually, the DM was interviewed twice (i.e., the DM was re-interviewed only once as to meet the above data validation requirement). So finally, the relative weight of each construct (w.r.t. the total BIM adoption decision goal) and the relative weight of each SAF (w.r.t. some construct) was obtained and sorted. Based on the information, eventually, the absolute weights of all SAFs were calculated and prioritised. Such knowledge is both critical and significant for a DM to understand the priority over the evaluation criteria of BIM system adoption, as to mitigate the risk of decision-making mistakes.

A mathematical review to AHP (including the data validation process based on C.R. and the determination of the weights) is provided in the subsequent subsection. Readers who are familiar with this method can skip this subsection.

3.1 A Review to AHP's Mathematical Process

In this subsection, the data validation method used based on the pairwise comparison matrix data and the determination of the SAF weights in AHP are introduced. First, the survey process of AHP compared n SAFs pair-wisely. Each of the results is the relative importance between the i-th and j-th SAFs, which can be connoted as: m_{ij}. The matrix $M=\left(m_{ij}\right)$ is the comparison matrix obtained by comparing the n SAFs pair-wisely.

By calculating the eigenvector and finding the maximum eigenvalue $\lambda_{\max}$, they are then used to evaluate whether the respondents' judgments on the pairwise comparison matrix are inconsistent, according to the following equations:

$$v_i = (\textstyle\sum_{j=1}^{n} w_j m_{ij})/w_i, \text{ for all } i = 1, 2, \ldots, n \tag{1-1}$$

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} v_i}{n} \tag{1-2}$$

$$C.I. = \frac{\lambda_{\max} - n}{n} \tag{2}$$

$$C.R. = \frac{C.I.}{\text{R.I.}} \tag{3}$$

where n is the number of criteria for the given decision context; the weight for the i-th criterion, w_i, has been assessed according to a known method (e.g., the following Eqs. (4)-(7)); v_i is the temporary eigenvector element used for calculating the eigenvalue, $\lambda_{\max}$; $C.I.$ is the consistency index for M as can be evaluated based on $\lambda_{\max}$ and n; C.R. is the final result which is the consistency ratio that is used to assess the consistency in the pairwise relationships as revealed in M; however, the necessary denominator of Eq. (3), which is the R.I. value, is a value determined (and can be looked up in Table 1) by the dimension of square matrix, which is M; the matrix elements, m_{ij}, are the source data in matrix M, as defined previously.

Table 1. The random index (R.I.)

n	1	2	3	4	5	6	7	8
R.I.	0	0	0.58	0.9	1.12	1.24	1.32	1.41

As can be seen, when the respondent's judgment in the pairwise comparison matrix is not consistent, the values in M will produce a larger value of λ_{max}. Then, the consistency index (C.I.) grows larger. So when C.I. is further divided R.I., which is the Random Index (R.I.) that can be looked up in the Table 1, the C.R. ratio will exceed the threshold that is set in the decision context (e.g., 0.2 in our study). The entire consistency analysis process presented here, which validates the source data for AHP, was proposed and proved by Saaty [7].

Second, the criterion weight vector (CWV) of the factors can be obtained, so it is possible to judge the relative importance of them by prioritizing them [8] [3]. Following from the matrix $M=\left(m_{ij}\right)$, which is the source pairwise comparison matrix that has passed the above consistency check, M is expanded as the following:

$$M = \begin{bmatrix} m_{11} = 1 & \cdots & m_{1n} \\ \vdots & \ddots & \vdots \\ m_{n1} & \cdots & m_{nn} = 1 \end{bmatrix} \quad (4)$$

The column-sums vector, V, of the matrix M is thus:

$$V = \left[\sum_{i=1}^{n} m_{i1} \quad \sum_{i=1}^{n} m_{i2} \cdots \sum_{i=1}^{n} m_{in}\right] \quad (5)$$

Dividing the elements in matrix M by the column-sums vector, V, another square matrix, M', is obtained, as:

$$M' = \begin{bmatrix} m'_{11} = 1/\sum_{i=1}^{n} m_{i1} & \cdots & m'_{1n} = m_{1n}/\sum_{i=1}^{n} m_{in} \\ \vdots & \ddots & \vdots \\ m'_{n1} = m_{n1}/\sum_{i=1}^{n} m_{i1} & \cdots & m'_{nn} = m_{nn}/\sum_{i=1}^{n} m_{in} \end{bmatrix} \quad (6)$$

So the row-sums vector of M is exactly the CWV:

$$CWV = \left[\sum_{j=1}^{n} m'_{1j} \quad \sum_{j=2}^{n} m'_{2j} \cdots \sum_{j=n}^{n} m'_{nj}\right]^{T} \quad (7)$$

The main results that are further analysed in the next section are assessed using the abovementioned mathematical process.

4 Results and Discussion

As discussed in Section 3, the questionnaire that was filled out by the DM in the second interview round passed the consistency check (i.e., the CR values of the five pairwise comparison matrices, 0.0975, 0.1805, 0.0884,0.186 and 0.0574, were all less than 0.2). In the first round of interview, because the number of SAFs w.r.t. each construct was close to 7 (i.e., human's psychological limit to make pairwise comparisons over items [10]), the difficulty of filling in the questionnaire increased and led to logical errors by the interviewees.

As shown in the Figure 4, we conclude that the DM believed that a construction firm needs to address the matters about the execution of a BIM project (43.19%) and the organisational factors (38.01%) that may influence the deployment of BIM technologies. The various aspects about the system integration (SI) matters of BIM and the BIM functions that are used can be placed in a secondary position (i.e., 14.68% and 4.13%, respectively).

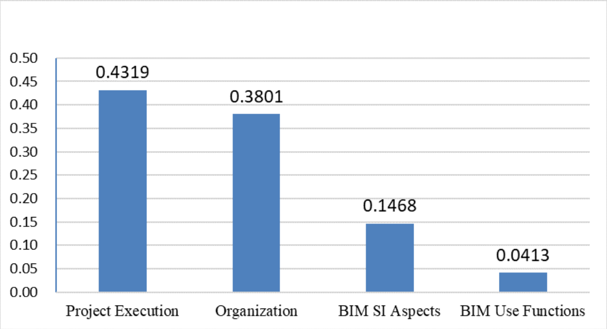

Figure 4. Relative importance of the constructs for BIM system/technologies adoption decision in a construction firm

As shown in Figure 5 to Figure 8, the SAFs for the BIM adoption decision w.r.t. the four constructs are visualised, while their ranks are also sorted according to their relative importance.

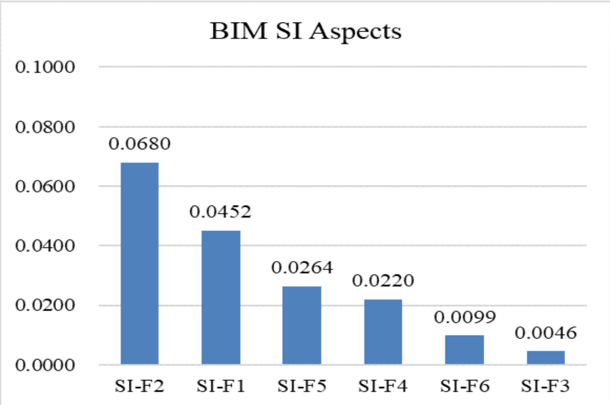

Figure 5. The weights of SAFs w.r.t the 'BIM SI' construct

The top three SAFs w.r.t the constructs are easily observed in these figures. These SAFs are not only the major factors which should be put into consideration when a construct is solely addressed during the introduction of BIM, but also the topics worthy of note in this study.

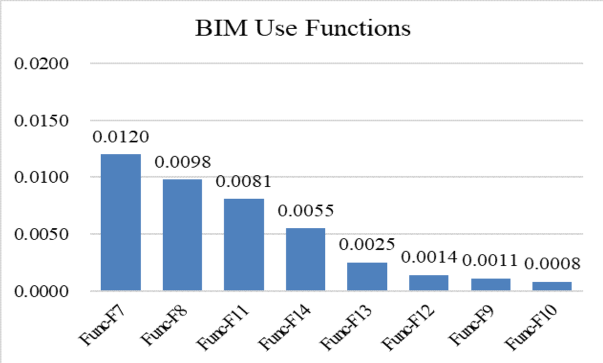

Figure 6. The weights of SAFs w.r.t. the 'BIM use functions' construct

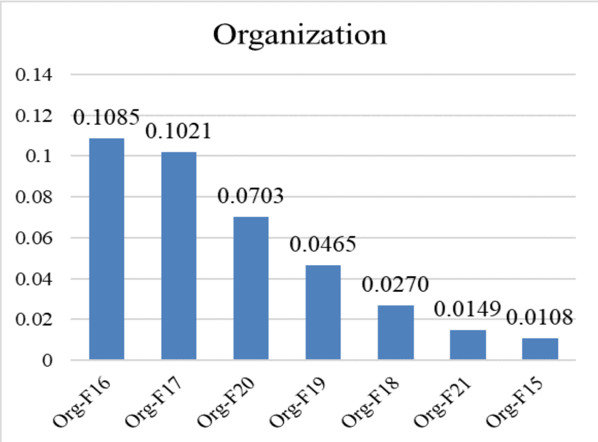

Figure 7. The weights of SAFs w.r.t. the 'organization' construct

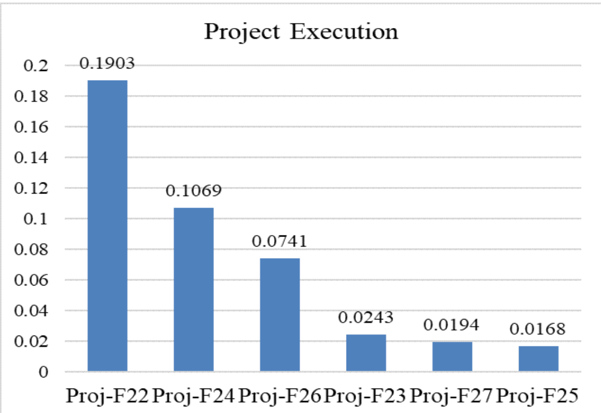

Figure 8. The weights of SAFs w.r.t. the 'project execution' construct

For example, according to the analysis, it is clearly understood that the DM believes that the three most important SAFs w.r.t. the 'BIM SI aspects' construct are the 'efficiency of BIM technology', 'software functions', and 'maintenance and upgrade costs'.

Since there are still other interesting observations which can be made for the 'top three SAFs' w.r.t. other constructs in these figures, relevant discussions are omitted here because of the space reason.

Another significant observation can also be made based on the absolute weights, rather than on the relative weights. For this sake, all of the 27 SAFs that have been confirmed using the Delphi Method are sorted and ranked all together in Table 2. Figure 9 provides a visualisation for Table 2.

It can thus be found that the top five SAFs with the highest absolute weight values are 'Proj-F22', 'Org-F16', 'Proj-F24', 'Org-F17' and 'Proj-F26' (i.e, definition of BIM project objectives and applications, supports from the top management, specification of BIM project milestones and deliverables, whether the design creates and fits business value and purpose, and finally, the BIM project management matters).

Table 2. Weight rankings for all factors

Ranking	SAFs	Weights
1	Proj-F22	0.1903
2	Org-F16	0.1085
3	Proj-F24	0.1069
4	Org-F17	0.1021
5	Proj-F26	0.0741
6	Org-F20	0.0703
7	SI-F4	0.0499
8	SI-F5	0.0465
9	SI-F2	0.0387
10	Org-F18	0.0270
11	Proj-F23	0.0243
12	SI-F1	0.0236
13	Proj-F27	0.0194
14	SI-F3	0.0186
15	Proj-F24	0.0168
16	Org-F21	0.0149
17	Func-F7	0.0120
18	SI-F5	0.0118
19	Org-F15	0.0108
20	Func-F8	0.0098
21	Func-F11	0.0081
22	Func-F14	0.0055
23	SI-F6	0.0041
24	Func-F13	0.0025
25	Func-F12	0.0014
26	Func-F9	0.0011
27	Func-F10	0.0008
Total		1.0000

In other words, the DM believes that these five SAFs play a role of impact when a decision for BIM adoption is made by the construction firms. This is the key knowledge that is discovered by this study: construction firms should give priority to these five SAFs. When introducing a BIM system or relevant BIM technologies. The results as mentioned above are also verified and confirmed by another expert in the construction industry (than the interviewed DM during AHP investigation or the experts selected for confirming the SAFs set and the decision hierarchy during the use of the Delphi method). In this sense, in this study, works for data validation have been performed not only for the dataset itself (i.e., the C.R.-based consistency analysis), but also for the various empirical aspects from the results.

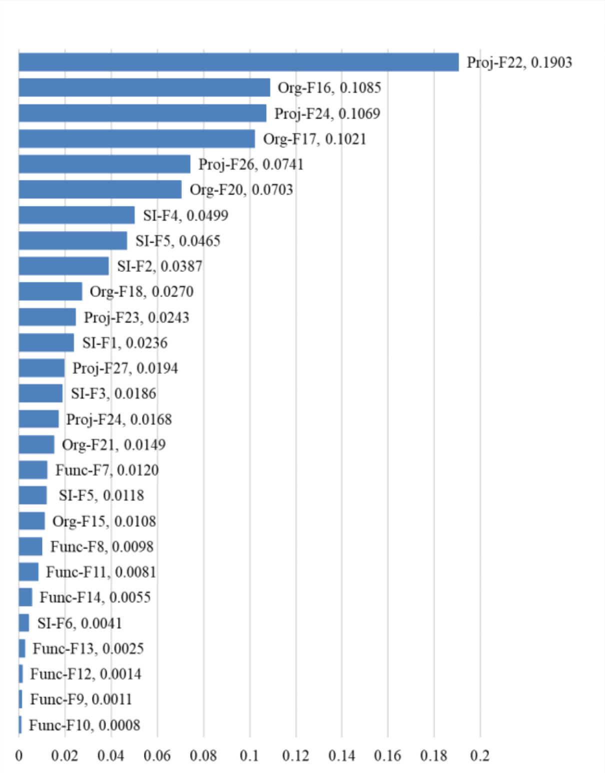

Figure 9. Prioritising the absolute weights of all SAFs

5 Conclusion

This study identified the key SAFs for the adoption of relevant BIM system and technologies and examined the relative importance of them. The initial set of SAFs deemed as important by the authors through literature study is further modified and confirmed by the expert in the construction domain of AEC, using the Delphi Method. In other words, the obtained set of the 27 SAFs consists of the major factors that are to be considered for the adoption of BIM. Given the thoroughness of the original literature review process (see also the reviewed articles [13-25]), this knowledge (i.e., the identified and confirmed set of SAFs) is important for construction firms whenever one such BIM-adoption decision is to be made.

In order to conduct the research for the influence of each SAF on the BIM-adoption decision systematically, a decision hierarchy which introduces an additional layer of constructs and organises the SAFs in a suitable manner is developed and further confirmed by also using the Delphi Method. Such knowledge (i.e., the decision hierarchy) is also a significant sub-product of this study.

The importance of the constructs and the SAFs is then assessed using AHP. The relative importance of each construct w.r.t. the total BIM-adoption decision goal is assessed and ranked. The relative importance of each SAF w.r.t. the construct on which it is mounted is also assessed and ranked. The absolute weight of each SAF is further calculated, and all absolute weights are ranked so that the relation (i.e., the absolute priority) among these SAFs is observed. These have formed another important set of knowledge for BIM-adoption in that the weights are quantitatively assessed. Since preference relations among the SAFs have been easily ordered, some interesting observations are made and the practical implications for the adoption of BIM or the decision to adopt BIM are drawn. For example, from the analysis of this study it is understood that the DM believes the most critical constructs for BIM adoption/introduction include the project execution factors and the organisational factors, which are closely related to the support from the top management. For another example, through the final absolute ranking analysis, it is understood that among the 27 SAFs, the (top five) most influential factors that may affect the expected success of BIM adoption/deployment are the objective of the BIM project, BIM project milestones, BIM project management, and whether BIM can create enterprise value and competitive advantage are important SAFs. These factors form a set of empirical knowledge which can serve as a reference for construction firms in deciding whether to deploy BIM technology or how to implement a BIM project more successfully.

Despite the fact that the results from this study are subject to the interviewee (i.e., a DM of a construction firm in Taiwan) during AHP investigations, the research framework can be generalised to surveys in other AEC domains (e.g., architecture and engineering) and/or in other countries. Not only the survey works themselves but also the possible comparisons that can be made based on the future available data across the nations would draw further more fruitful yet more insightful implications for the whole civil engineering industry.

Moreover, despite the fact that the study has successfully identified a set of SAFs which a construction firm may think important for the 'successful deployment' of BIM, in the opposite sense, these results can also be used to understand the reasons for why there is 'reluctance' for BIM adoption, which is a fact that is often observed in the industry (to the authors' knowledge). This is also another future knowledge discovery topic worth of exploration.

Finally, given the confident results in this study, more in-depth future researches can also be expected. For example, the number of interviewees may be increased so the knowledge can be explored on a group basis, while the group/subgroup analytical methods can be introduced [2] [3], as the group-based mind-mining process [11] is a focused cognitive topic in the recent development of data-driven decision-making (DDM, or D^3M) [12]. In this sense, this study is a pilot work for subsequent studies which pertain to the decision of BIM system adoption.

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