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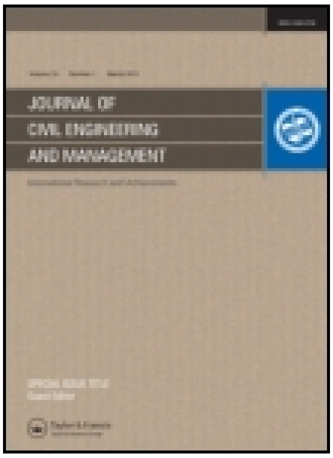

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Application of importance-satisfaction analysis and influence-relations map to evaluate design delay factors

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APPLICATION OF IMPORTANCE-SATISFACTION ANALYSIS AND INFLUENCE-RELATIONS MAP TO EVALUATE DESIGN DELAY FACTORS

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Abstract. Design delays can negatively influence the total completion time of a facility construction project. Knowing the factors to which design delays are most sensitive supports the time management of designs. However, factors that cause design delays are several and interrelated. This study proposes a new model to identify key factors that drive design delays. The core of the model integrates importance-satisfaction analysis (ISA) and an influence-relations map (IRM). The ISA evaluates the performance of each delay factor, while the IRM captures the causal relationships among factors. Additionally, the IRM is generated using a decision making trial and evaluation laboratory technique (DEMATEL). The model is applied to a real-world high-tech facility construction project to indicate the strengths of the model. In this investigation, four first-level delay factors and 17 second-level delay sub-factors are derived. The factor of "organization's decision making and budget constraints" is identified as the key driver of design delays in the project of interest. The results support management in determining which problem factors should be given priority attention. The proposed model can be employed in other decision-making situations that involve interrelated factors.

Keywords: design delays, importance-satisfaction analysis (ISA), influence-relations map (IRM), decision making trial and evaluation laboratory technique (DEMATEL), high-tech facility construction project.

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Introduction

The design of a facility construction project involves conceptual design, schematic design and detailed design. During the conceptual and schematic design phases, a prime designer (architect/engineer or A/E) seeks to consider information from a wide range of disciplines; represent candidate solutions, and generate new states of design from the current states to fulfil the requirements of the project client (or owner), including for example, the budget and spatial arrangements (Baldwin *et al.* 1999; Rivard, Fenves 2000). These two early phases ensure that the design deliverables satisfy the general needs of the project client. In the detailed design phase, the required design work is explicated; the design deliverables must be delivered in a timely fashion to prevent delays to future construction work.

When a design delay occurs, the completion time of the entire project may be postponed. Identifying design delay factors for improvement is critical to managing design duration (Yang, Wei 2010). However, many interrelated factors affect the design duration. These include, for example, the clarity of user needs, the timing of decisions made by the client, the design capabilities of A/E, and the management abilities of project management. When user needs are not clearly specified or client's decisions change frequently, the design deliverables are likely to be determined by trial and error. As time passes, the A/E begins to lose patience and spends less time on design. Consequently, the project client is unsatisfied with the design deliverables. Each factor influences each other factor. Finally, project participants (including facility users, decision makers, project management, and A/E) complain to each other, exacerbating delays. If key factors that drive design delays can be identified, and attention paid to them, then such delays can be eliminated or, at least, prevented from being increased. Nevertheless, identifying the cause-effect relationships among delay factors is difficult when a project involves numerous project participants and includes specialty knowledge (such as concerning a clean room or special mechanical/electrical/plumbing layout requirements).

This study proposes a new model to help identify the key factors that govern design delays. Correcting the key factors that most strongly affect delays is effective in preventing design delays. A real-world high-tech facility

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construction project in northern Taiwan is considered to demonstrate the advantages of the proposed model.

The rest of this paper is organized as follows. Section 1 reviews recent related studies. Section 2 presents details of the proposed model. Section 3 illustrates a case study of the proposed model. The final section draws conclusions and provides recommendations for future research.

1. Literature review

This section reviews past studies related to duration management design and delay factor identification for construction projects.

1.1. Management of design duration

The importance of efficient design management in ensuring the smooth running of a project is being increasingly appreciated (Chua *et al.* 2003; Senthilkumar *et al.* 2010). Much research has been undertaken to control design processes, and thereby increase the effectiveness of the management of design duration. For example, Sanvido and Norton (1994) proposed a building design process model that indicates the tasks on which a successful design depends. Bogus *et al.* (2005) developed a concurrent engineering approach that involved overlapping sequential design activities to reduce design duration.

Several researchers have directly dealt with design schedule management (Chua, Hossain 2011). For example, considering the uncertainty in the number of iterations of design activities, Luh *et al.* (1999) developed an optimization-based method to schedule the design process in a manufacturing project. Considering design iterations and information dependency, Austin *et al.* (2000) presented a model to schedule a building design project. Taking the uncertainty in the number of iterations and the number of design participants into account, and considering the possibility of conducting multiple design projects simultaneously, Wang *et al.* (2006) devised a simulation-based model to produce design schedules for a design firm.

1.2. Identification of delay factors

An increasing number of construction projects have experienced extensive delays (Odeh, Bataineh 2002). Causes of delays (i.e. delay factors) arise in all project phases. Research on delay factor identification has received considerable attention in the past several decades because timely identification is the basis for resolving delays (Baldwin, Manthei 1971; Yang, Wei 2010). Practitioners should foresee potential delay factors likely to confront their current and future projects and avoid or reduce these delays in a timely manner (Long *et al.* 2004; Sweis *et al.* 2008).

Past research studies may be broadly divided into two types: identifying delay factors in general and evaluating specific delay factors in detail:

1) In the first type of research, for instance, a survey conducted by Sweis *et al.* (2008) found that the financial difficulties faced by the contractor and an excess of change orders made by the project client are the two factors that most responsible for construction delays. Delay factors arising in international countries have been explored, such as Vietnam (Long *et al.* 2004), Nigeria (Aibinu, Odeyinka 2006), Malaysia (Sambasivan, Soon 2007), Jordan (Odeh, Bataineh 2002; Sweis *et al.* 2008), Saudi Arabia (Assaf, Al-Hejji 2006; Al-Kharashi, Skitmore 2009), Thailand (Ogunlana *et al.* 1996; Toor, Ogunlana 2008), Egypt (El-Razek *et al.* 2008), Zambia (Kaliba *et al.* 2009), Gaza Strip (Enshassi *et al.* 2009), Ghana (Fugar, Agyakwah-Baah 2010), Taiwan (Yang, Wei 2010), and India (Doloi *et al.* 2011).
2) In the second type of research, researchers assessed specific delay factors to find solutions to mitigate the delay impact. These specific delay factors include labor productivity (Alinaitwe *et al.* 2007), weather-related factor (Apipattanavis *et al.* 2010), and order variations (Enshassi *et al.* 2010). For example, Apipattanavis *et al.* (2010) identified the weather attributes (such as temperature and rain) that cause construction delays and developed a weather prediction model for mitigating disputes arising from weather-related delays.

Ramanathan *et al.* (2012) recently reviewed 113 construction delay factors from 41 studies around the world. Their analyses concluded several findings, including:

1) All 41 studies conducted semi- or full-structured expert interviews and performed questionnaire surveys to analyse the data obtained from the responses. Various indices such as importance index, frequency index and severity indices were then used to evaluate the factors.
2) Delay factors are specific to various countries (developed versus developing countries), project sizes (project contract price amount) and project types (such as housing, industrial and commercial projects) and that no root causes can be generalized. This finding is agreed by some researchers (Sweis *et al.* 2008).
3) None of these studies can be generalized and directly applicable "as is". This critical review presented a strong case against opinion surveys and suggested conducting statistical analyses of actual projects to generate meaningful results.

Existing studies are too numerous to describe in detail. Summaries are available in Toor and Ogunlana (2008) and Ramanathan *et al.* (2012). Table 1 compares some of recent studies and this work for indicating the significances of this study, including:

1) This study focuses on the design phase, while most past studies focused on the construction phase. Only very few studies discussed the delay factors occurring in the design phase (Wei 2005; Yang, Wei 2010; Yang *et al.* 2010). For instance, based on 95 valid responses from consultant engineers, Yang and Wei (2010) found that "changes in the client's requirements" are the main causes of both planning and design phase delays. Focusing on public con-

struction projects under the build-operate-transfer contract model, Yang *et al.* (2010) indicated several design delay causes, such as change in client's needs, wrong client's needs recognized by the design team, inexperienced design team and improper plans and schedule developed by the design team. These design delay factors are applied for general projects.

2) Past studies identified delay factors for general projects. This study focuses on developing a model to identify factors and evaluate their cause-effect relationships. The identified delay factors are for a particular project (and are not intended to apply to general projects), although they may serve as references for other projects.
3) The proposed model here assesses the cause-effect relationships among factors to identify the key driving factors. Only a few past studies considered the correlations among factors and used different correlation analyses. For instance, several researchers used the Spearman rank correlation coefficient to analyse the agreement/disagreement between project parties or survey respondents (El-Razek *et al.* 2008; Al-Kharashi, Skitmore 2009). Their studies indicated that the clients and contractors often have opposing views. Doloi *et al.* (2011) used factor analysis to assess the correlations among delay attributes and grouped the highly correlated attributes into factors (such as lack of commitment and inefficient site management). They also developed a regression model to indicate that slow decisions from the owner and rework due to mistakes in construction had the greatest impact on construction delays in Indian construction projects.

In summary, this study has three major significances: it focuses on the design phase; it develops an evaluation model for a specific project and it evaluates causal relationships among factors for finding driving delay factors.

2. Proposed model

Delay factors may vary greatly with the characteristics of the project (including the participants of the project, management style, project complexity, and project type). Accordingly, a model that can help management find delay factors in a step by step manner is preferred. Figure 1 presents the steps in the proposed model for identifying the factors and sub-factors that govern design delays in a project. The steps in the model are as follows, and steps 1–3 are elucidated in greater detail in subsequent subsections.

Step 1: Defining the factors and sub-factors that influence the time taken to design a facility construction project. In this step, available studies can assist in generating a long list of possible factors. Expert interviews are conducted to assess the relevance of these factors to the project in question.

Step 2: Using the "importance-satisfaction analysis (ISA)" to evaluate the degree of importance and the degree of satisfaction of each identified factor. A factor that results in a delay is considered to be unsatisfactory.

Step 3: Applying the "decision making trial and evaluation laboratory technique (DEMATEL)" to construct a cause-effect influence-relations map or impact-relations map (IRM) among factors.

Step 4: Integrating the ISA and IRM. The ISA specifies factors that are important and highly unsatisfactory to design delays. Meanwhile, the IRM traces the key factors that govern design delays.

Steps 2–4 are repeated to find the problematic subfactors of the key factors. Management can attend to them to improve the design time.

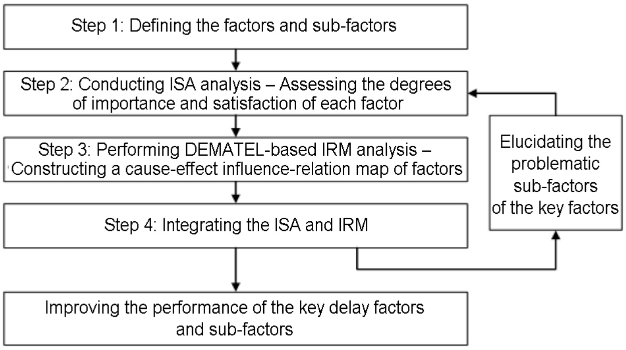


Fig. 1. Steps of proposed model

2.1. Step 1: defining the factors and sub-factors

In defining the design delay factors and sub-factors, the following sub-steps are suggested:

1) Reviewing past studies (although most concern construction delays) to identify potential delay factors and sub-factors. Prior research showed that grouping delay factors helped to understand the factors systematically; but, no consensus existed on how factors should be grouped. For example, Odeh and Battaineh (2002) used seven groupings, such as client-, contractor-, consultant-, materials-, labour-, contract-, and contractual-related groups. Ramanathan *et al.* (2012) divided factors into 18 categories.
2) Conducting expert interviews to indentify suitable delay factors from the aforementioned potential delay factors.

2.2. Step 2: conducting ISA

The ISA method was based on the importance-performance analysis that was proposed by Martilla and James (1977), but "satisfaction" replaced "performance" (Tonge, Moore 2007). In the ISA, the input data (degree of satisfaction and degree of importance of each factor and sub-factor) collected from the questionnaires are normalized to a single measuring scale. Eqns (1) and (2) yield the initial degree of satisfaction (IDS) and standardized satisfaction value (SS):

$$\mathrm{IDS} = \frac{\mathrm{SumDS}}{\mathrm{N}}; \qquad (1)$$

$$\text{SS} = \frac{(\text{IDS} - \text{Average of IDS in all factors})}{\text{Standard deviation of IDS in all factors}}, \quad (2)$$

where: N is the number of respondents; and $SumDS$ is the sum of degrees of satisfaction from all respondents.

Eqns (3) and (4) calculate the initial degree of importance (IDI) and the standardized importance value (SI). The number of respondents in the case study was 36.

$$\text{IDI} = \frac{\text{SumDI}}{\text{N}}; \quad (3)$$

$$\text{SI} = \frac{(\text{IDI} - \text{Average of IDI in all factors})}{\text{Standard deviation of IDI in all factors}}, \quad (4)$$

where $SumDI$ is the sum of degrees of importance from all respondents.

The ISA evaluations are classified under the following four categories (SS, SI): (1) ○(+,+): a factor with high satisfaction and high importance; (2) ●(+,–): a factor with high satisfaction and low importance; (3) ▼(–,–): a factor with low satisfaction and low importance, and (4) x(–,+): a factor with low satisfaction and high importance. The fourth category, x(–,+), should attract the most attention.

Table 1. Comparisons of recent studies in identifying delay factors for construction projects

Authors	Focused project phase	Studied countries	Significances	Major delay factors
Toor and Ogunlana 2008	Construction	Thailand	For general projects	(1) Lack of standardization in design; (2) Lack of contract's experience; (3) Inadequate experience of consultant staff; (4) confusing/ambiguous requirements.
Sweis *et al.* 2008	Construction	Jordan	For general projects	(1) Financial difficulties faced by the contractor; (2) too many change orders by the owner; (3) contractor's poor planning and scheduling; (4) shortage of manpower.
El-Razek *et al.* 2008	Construction	Egypt	For general projects	(1) Financing by contractor; (2) delays in payment by owner; (3) design changes by owner.
Al-Kharashi and Skitmore 2009	Construction	Saudi Arabia	For general projects	(1) Shortage of experienced manpower; (2) lack of finance by the client; (3) contractor experience; (4) late in reviewing / approving design documents by consultant.
Enshassi *et al.* 2009	Construction	Gaza Strip	For general projects	(1) Delay because of closures leading to materials shortage; (2) unavailability of resources; (3) delay in regular payments.
Kaliba *et al.* 2009	Construction	Zambia	For general projects	(1) Delayed payments; (2) financial difficulties; (3) contract modification; (4) materials procurement; (5) changes in drawings.
Fugar and Agyakwah-Baah 2010	Construction	Ghana	For general projects	(1) Delay in honoring payment certificates; (2) underestimation of project cost; (3) underestimation of project complexity; (4) difficulty in assessing bank credit.
Yang *et al.* 2010	All phases	Taiwan	For general BOT projects	(1) Change of client's needs; (2) wrong client's needs recognized by design team; (3) inexperienced design team; (4) improper plans and schedule developed by design team.
Yang and Wei 2010	Design	Taiwan	For general projects	(1) Changes in client's requirement; (2) client's complicated administration process; (3) insufficient or ill-integrated basic project data; (4) inadequate integration on project interfaces; (5) change orders caused by deficiency design.
Doloi *et al.* 2011	Construction	India	For general projects	(1) Lack of commitment, inefficient site management, and poor site coordination are the most critical factors of construction delays; (2) Owner's slow decision and rework due to errors in execution have the greatest impact on delay duration.
Ramanathan *et al.* 2012	Construction	All the world	For general projects; reviewing 41 past studies	Among the 18 factor groups, the following groups fall into the first five categories: (1) owner; (2) contractor; (3) design related and plant and equipment; (4) labor; and (5) consultant and contractual relationships.
Current study	Design	Taiwan	For a specific project; building an evaluation model; assessing causal relationships	(1) User needs and specification requirements; (2) organization's decision making and budget constraints; (3) project control and review management; and (4) design execution and interface management.

2.3. Step 3: performing DEMATEL-based IRM analysis

In the proposed model, the end product of the DEMATEL process is an IRM that is a visual representation of the interdependences of factors. The Battelle Memorial Institute of Geneva developed the DEMATEL method for a Science and Human Affairs Program to solve complex and interrelated problems (Gabus, Fontela 1973; Li 2009; Lin, Tzeng 2009). The DEMATEL method enables management to solve problems visually and divide the related factors (or variables) into cause and effect groups to improve understanding of causal relationships among factors (Li 2009; Wu, Tsai 2011; Hu *et al.* 2011; Wang *et al.* 2012). This method has been employed in numerous fields, including the development of global managers' competencies (Wu, Lee 2007), the assessment of value-creating industrial clusters in a science park (Lin, Tzeng 2009), and the capture of the causal relationships between strategic criteria in an organization (Jassbi *et al.* 2011).

The steps in the DEMATEL method are as follows (Lin, Tzeng 2009; Wang *et al.* 2012): (1) Step D1 – finding the average matrix; (2) Step D2 – calculating the direct influence matrix; (3) Step D3 – calculating the indirect influence matrix; (4) Step D4 – deriving the total influence matrix; and (5) Step D5 – obtaining the influence-relations map.

Step D1: Finding the average matrix

Suppose h experts are available to solve a complex problem and n factors are considered. The scores assigned by each expert yield an $n \times n$ non-negative answer matrix $\overset{k}{\boldsymbol{X}}$, with $1 \le k \le h$. Hence, $\overset{1}{\boldsymbol{X}}, \overset{2}{\boldsymbol{X}}, \ldots, \overset{h}{\boldsymbol{X}}$ are the answer matrices for each of the h experts, and each element of $\overset{k}{\boldsymbol{X}}$ is an integer, denoted x_{ij}^{k}. The diagonal elements of each answer matrix $\overset{k}{\boldsymbol{X}}$ are all set to zero. The $n \times n$ average matrix $\boldsymbol{A}$ can then be computed by averaging the h experts' value (or score) matrices. The (i, j) element of the average matrix $\boldsymbol{A}$ is denoted a_{ij} (average influence):

$$a_{ij} = \frac{1}{h} \sum_{k=1}^{h} x_{ij}^{k} . \quad (5)$$

Step D2: Calculating the direct influence matrix

A direct influence matrix $\boldsymbol{D}$ is obtained by normalizing the average matrix $\boldsymbol{A}$. That is:

$$\boldsymbol{D} = s\,\boldsymbol{A}, \quad (6)$$

where s is a constant, which is calculated as follows (Li 2009):

$$s = \mathrm{Min}\left[\frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} \left|a_{ij}\right|}, \frac{1}{\max\limits_{1 \le j \le n} \sum_{i=1}^{n} \left|a_{ij}\right|}\right], \; i, j = 1, 2, \ldots, n. \quad (7)$$

Notably, suppose the (i, j) element of matrix $\boldsymbol{D}$ (denoted d_{ij}) is the direct influence of factor i on factor j. Then, $\lim\limits_{n \to \infty} \boldsymbol{D}^{m} = [0]_{n \times n}$, where $\boldsymbol{D} = [d_{ij}]_{n \times n}$ (Goodman 1988). Additionally, $0 < \sum_{j=1}^{n} d_{ij}, \sum_{i=1}^{n} d_{ij} \le 1$, and the sum of only one row or column equals one.

Step D3: Calculating the indirect influence matrix

The indirect influence of factor i on factor j declines as the power of the matrix increases, as in $\boldsymbol{D}^{2}$, $\boldsymbol{D}^{3}, \ldots$, $\boldsymbol{D}^{\infty}$ (Lin, Tzeng 2009). This fact guarantees convergent solutions to the matrix inversion, similar to an absorbing Markov chain matrix. The indirect influence matrix $\boldsymbol{ID}$ is obtained from the values in the direct influence matrix $\boldsymbol{D}$. That is:

$$\boldsymbol{ID} = \boldsymbol{D}^{2} + \boldsymbol{D}^{3} + \ldots = \sum_{i=2}^{\infty} \boldsymbol{D}^{i} = \boldsymbol{D}^{2}(\boldsymbol{I} - \boldsymbol{D})^{-1}, \quad (8)$$

where $\boldsymbol{I}$ is the identity matrix.

Step D4: Deriving the total influence matrix

The total influence matrix $\boldsymbol{T}$ is also an $n \times n$ matrix, and is given by (Li 2009):

$$\boldsymbol{T} = \boldsymbol{D} + \boldsymbol{ID} = \boldsymbol{D} + \boldsymbol{D}^{2} + \boldsymbol{D}^{3} + \ldots = \sum_{i=1}^{\infty} \boldsymbol{D}^{i} = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{D})^{-1} . \quad (9)$$

Let t_{ij} be the (i, j) element of matrix $\boldsymbol{T}$; the sum of the i-th rows and the sum of the j-th columns, d_i and r_j, respectively, are obtained as follows:

$$d_i = \sum_{i=1}^{n} t_{\mathrm{ij}} \quad (i = 1, 2, 3\ldots, n); \quad (10)$$

$$r_j = \sum_{j=1}^{n} t_{\mathrm{ij}} \quad (j = 1, 2, 3\ldots, n). \quad (11)$$

Notably, d_i represents the sum of the direct and indirect influences of factor i on the other factors, and r_j denotes the sum of direct and indirect influences on factor j by the other factors. When $j = i$, $d_i + r_i$ is an index of the strength of influences by and on a factor, and is a measure of the importance of that factor. The term $d_i - r_i$ (also called "Relation") divides factors into the "cause group" and the "effect group". If $d_i - r_i$ is positive, then factor i influences other factors more than it is influenced by, and so belongs to the cause group. Conversely, if $d_i - r_i$ is negative, then factor i is influenced by more factors than it influences and it belongs to the effect group (Li 2009).

Step D5: Obtaining the influence-relations map

To visualize the complex causal relationships among factors using a visible structural model, an IRM is developed from the values of $d+r$ and $d-r$, represented on the x axis and the y axis, respectively, of a graph (Lin, Tzeng 2009). Furthermore, the net influence matrix $\boldsymbol{N}$ is provided to evaluate the strength of the effect of one factor on another:

$$N = Net_{ij} = t_{ij} - t_{ji}. \qquad (12)$$

3. Case study

This section presents the results of applying the proposed model to a case project. The project background is presented; factors and sub-factors are defined; input data are collected, the ISA and IRM methods are evaluated, and the results are discussed.

3.1. Project background

The case project is the construction of a high-tech facility of a national research centre located in northern Taiwan. The total floor area of the facility is approximately 53,000 m^2. The case project comprises three main components: (1) civil and building construction (Civil); (2) mechanical, electrical and plumbing (MEP) works; and (3) special equipment construction (SPE). The Civil and MEP design is contracted out to an A/E. However, the SPE is designed by an internal team of the project client, because the SPE depends on particular domain knowledge, such as synchrotron accelerators and resistance against micro-vibrations. The planned design and construction durations of the Civil and MEP components of the facility are about one year and 2.5 years, respectively. The consultant fee for the A/E is around US $3.3 million, while the budget for construction (Civil and MEP) is approximately US $77.4 million.

The project client establishes a task force to manage the design of the Civil and MEP components, which represent the scope of this case study. The researchers of this study have worked closely with this task force. Four major groups of participants are involved in the design phase of this project (Fig. 2). They are: (1) facility users, who determine the requirements of the facility; (2) decision makers, who are the top management of the project client; (3) the project management team, which is the aforementioned task force; and (4) the A/E. The facility users, decision makers and project managers are all the colleagues of the project client, and they interact with the A/E both directly and indirectly. The facility users, from 11 departments of the research centre, have various specialties and needs.

After approximately 1.5 years, the design had not been completed, and the design was thus significantly delayed. The project client claimed that poor execution by the A/E as responsible for the delays, while the A/E claimed compensation for reworking and costs incurred by the late decisions and frequent change orders of the project client. Since several external factors (associated with governmental agencies) and internal factors affect the progress of the project, no one could convincingly present the causes of the delays. The relationship among the parties in the project was therefore very tense. In the midst of this situation, the research team began to implement the proposed model to help identify the design delay factors to resolve the dispute and hopefully prevent further delays. The research team members included practitioners with expertise in construction project management and researchers familiar with performing ISA and IRM.

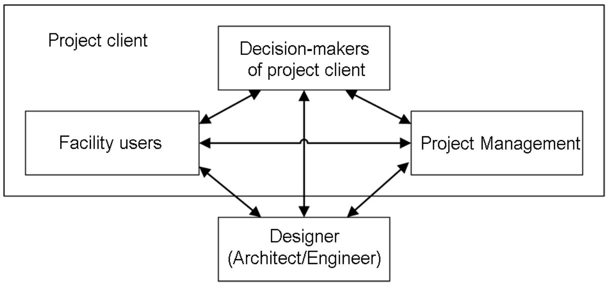


Fig. 2. Interactions among four project participants in the case project

3.2. Definitions of design delay factors and sub-factors

The research team first defined the factors and subfactors that affect the design duration of the case project. Some studies were reviewed and factors were grouped based on project participants, because the team was asked to identify "who" caused the most delays. This study then identified four first-level delay factors, corresponding to the four groups of project participants (facility users, decision makers, project management, and A/E). Additionally, after referring to the work of Wei (2005) that focused on the design phase, a long list of possible factors was reserved for this case project. These factors included changes in the client's requirements, poor scope definition, client change orders, the client's complicated administration process, the client's financial problems and inadequate A/E experience.

Three project engineers and one project manager for the case project were then invited to join with the research team to further identify delay factors suitable for this specific project. During the factor indication process, each of the aforementioned possible factors was included, revised or deleted.

Table 2 summarises the identified 17 second-level sub-factors under the four first-level factors. These factors and sub-factors are described as follows:

1) User needs and specification requirements (US) – In this case project, the facility users needed high technical requirements on the resistance standards against micro-vibrations and several vertical/horizontal precisions of construction. Because this facility (i.e. accelerator) was only the second kind in Taiwan, none of the project participants (including the users) had sufficient experience in ascertaining a need (i.e. sub-factor US1) or clarifying a need (US2). Sometimes, governmental regulations (US4, such as building codes) and technical specifications (US5) prevented the full description of user needs. Moreover, many user needs were difficult to

meet in design or in construction (US2). Each factor could cause a delay. For example, if the user needs were unclear (US2), then A/E would have problems in comprehensively translating these needs into design deliverables, leading to a design delay.

2) Organization's decision making and budget constraints (OB) – This OB factor was mainly involved the project client's decision-making and management abilities. Two top managers fully supervised the whole project and made most decisions, such as user needs, budget allocation, building architecture and layout. Consequently, whether or not their decisions were made timely (OB1), their supervising methods were appropriate (OB2) and their budget allocation was efficient (OB4) could impact design duration. Additionally, the project client was responsible for the effects of external factors, such as the project budget approved by governmental agencies (OB3). If part of budget was not available (OB3) or budget was allocated too much to certain components (such as the accelerator MEP systems, OB4), user needs might be altered and budget would be insufficient for other parts of the facility, leading to a redesign.

3) Project control and review management (PM) – This factor related to the effectiveness of project management, in terms of both communication and experience. The project client formed a project management team. Although most PM members had expertise in construction projects (PM2), they basically managed this high-tech facility construction project in a conventional way. For instance, no advanced management tools for scheduling were used (PM1) and no standard design review operating procedures were strictly implemented (PM4). Furthermore, the PM's communication with other participants was not effective (PM3). Overall, it was considered that the PM managed the project reactively.

4) Design execution and interface management (DM) – Although this A/E had plenty of experience in designing high-tech facilities, he tended to be overconfident and neglected the demands of this project. This factor concerned the A/E's abilities in drawing and design (DM1), estimating costs (DM2), and allocating design man-hours (DM4). Moreover, this project's MEP design involved numerous complicated systems developed by A/E subcontractors. A/E's ability to manage his subcontractors became crucial to timely design deliverables (DM3).

Most of the design delay factors and sub-factors identified here are similar but more specific than those suggested by past studies. For example, prior research often categorized these factors into two broader groups (i.e. client and consultant), while this study further divided the client group into two groups (i.e. facility users and decision makers) and divided the consultant group into two groups (i.e. project management and A/E). A few factors here were unique because of the characteristics of the case project. For instance, sub-factors US3, US4 and US5 (related to facility users) occurred due to the high technical micro-vibration resistance and construction precision requirements for this case project. Sub-factor OB4 (decision makers' budget allocation management) and sub-factor DM3 (A/E's subcontractor management) might not be common to other projects.

Table 2. Factors and sub-factors that affect design delays

First-level factors / second-level sub-factors	Description
1. User needs and specification requirements (US)	
1.1 Uncertainty of user needs (US1)	Whether or not to include a user need is uncertain.
1.2 Clarity of user needs (US2)	User needs are not clearly defined.
1.3 Difficulty of meeting user needs (US3)	User requirements are too strict or difficult to meet.
1.4 Limitations imposed by regulations (US4)	Governmental regulations prevent user needs from being met.
1.5 Limitations imposed by specifications (US5)	Technical specifications do not suffice to meet user needs.
2. Organization's decision making and budget constraints (OB)	
2.1 DM's decision making (OB1)	Decisions made by decision makers are not timely or definite.
2.2 DM's supervising ability (OB2)	DM's supervision methods are inefficient.
2.3 Budget availability (OB3)	Project budgets are tight, so DM must change user needs.
2.4 DM's resource allocation (OB4)	DM's budget allocation is inefficient.
3. Project control and review management (PM)	
3.1 PM's management method (PM1)	PM's project control methods are inefficient.
3.2 PM's experience (PM2)	PM's experience and professionalism are insufficient.
3.3 PM's communications (PM3)	PM's communications with other parties are inefficient.
3.4 PM's reviews (PM4)	PM's reviews of design deliverables are inefficient.
4. Design execution and interface management (DM)	
4.1 Design ability (DM1)	A/E's ability in drawings and design is poor.
4.2 Designer's cost estimations (DM2)	A/E's experience of estimating costs is poor.
4.3 Subcontractor management (DM3)	A/E manages his design subcontractors ineffectively.
4.4 A/E's resource allocation (DM4)	A/E allocates designers to design jobs ineffectively.

3.3. Collection of input data

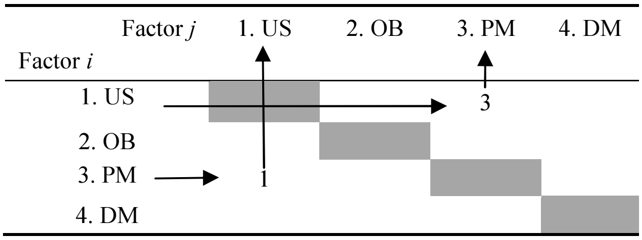
The required input data for the ISA and (DEMATEL-based) IRM are obtained using a set of questionnaires. Thirty-six experts (engineers, section managers or managers who were involved in this case project) were asked to fill out each questionnaire. Table 3 shows an example of the response from the questionnaire for executing ISA. In Table 3, the degree of importance and the degree of satisfaction range between ten (highest importance or satisfaction) and zero (lowest importance or satisfaction).

Table 3. Example of the response from the ISA questionnaire

Factors and sub-factors	Degree of importance	Degree of satisfaction
1. US		
1.1 US1	8	5
1.2 US2	8	5
1.3 US3	7	5
1.4 US4	9	4
1.5 US5	8	8
2. OB		
2.1 OB1	8	5
2.2 OB2	7	5
2.3 OB3	7	6
2.4 OB4	7	6
3. PM		
3.1 PM1	9	7
3.2 PM2	8	8
3.3 PM3	8	8
3.4 PM4	7	8
4. DM		
4.1 DM1	8	7
4.2 DM2	8	7
4.3 DM3	8	7
4.4 DM4	7	6

Note: Degrees of importance and satisfaction range between ten (highest importance or satisfaction) and zero (lowest importance or satisfaction).

Table 4. Example of the response from the IRM questionnaire



Factor *i* \ Factor *j*	1. US	2. OB	3. PM	4. DM
1. US	▨		3	
2. OB		▨		
3. PM	1		▨	
4. DM				▨

Note: 0: no influence; 1: weak direct influence; 2: moderate direct influence; 3: strong direct influence; 4: very strong direct influence.

Table 4 presents an example of the response from the questionnaire for generating IRM. Each respondent was asked to evaluate the strength of the direct influence (effect) of a factor on each of the other factors using an integer scale (from zero to four). In Table 4, for example, suppose factor *i* (PM) has a weak direct influence on factor *j* (US): a score of “1” is given to represent this weak influence. Conversely, if the US factor has a strong direct influence on the PM factor, a score of “3” is assigned. A high score represents the belief that an improvement in the PM factor relies strongly on an improvement in the US factor.

The research team held several meetings to illustrate the details of the questionnaire to the experts in order to ensure that the questionnaires could respond effectively. Cronbach’s α is utilized to test the reliability of data collected from the questionnaires in this case project. The test results reveal that these questionnaires used in the ISA and IRM analyses are reliable (as α exceeds 0.7) (Table 5).

Table 5. Reliability tests on questionnaires

Reliability tests	Cronbach’s alpha	Results
In ISA analysis:		
Data on degree of importance	0.899	High
Data on degree of satisfaction	0.908	High
In IRM analysis:		
Data on first-level factors	0.849	High
Data on sub-factors under each factor		
1. Data on second-level sub-factor under US factor	0.834	High
2. Data on second-level sub-factor under OB factor	0.858	High
3. Data on second-level sub-factor under PM factor	0.896	High
4. Data on second-level sub-factor under DM factor	0.881	High

Table 6. Degrees of satisfaction and importance of factors

	Degree of satisfaction		Degree of importance		
Factors	Initial value	SS	Initial value	SI	(SS, SI)
1. US	6.233	0.217	7.772	–1.209	● (+,–)
2. OB	5.583	–1.415	8.153	1.128	x (–,+)
3. PM	6.521	0.939	8.035	0.403	○ (+,+)
4. DM	6.250	0.259	7.917	–0.322	● (+,–)

3.4. Evaluation of ISA

Table 6 shows the evaluations made using ISA in the case study. As indicated earlier, the fourth category, x (–,+), should attract the most attention. In this case study, the OB factor (organization’s decision making and budget constraints) falls under the fourth category: the OB factor is considered to be highly important, but with a low degree of satisfaction. Therefore, this OB factor should be improved immediately. Figure 3 graphically represents the results of the ISA evaluation. Factors (including the OB factor herein) that are in the second quadrant are easily identified for improvement.

3.5. Generation of IRM

The research team then carried out the steps of the DEMATEL method, as follows.

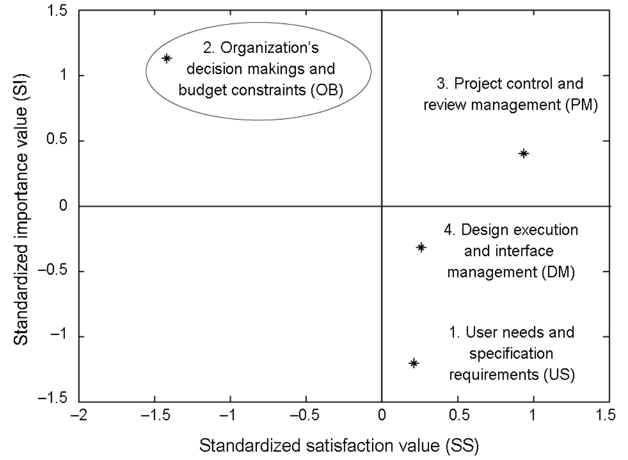


Fig. 3. ISA analysis of first-level factors

Step D1: Finding the average matrix – Table 7 presents an initial average matrix (average matrix A) of the factors in the case project. The value of h in Eqn (5) is 36 (36 respondents). For example, the initial average value of the effect of the US factor on the OB factor (US→OB) is calculated to be 3.111, indicating a high direct influence (as 4.0 is the highest value).

Table 7. Initial average matrix ***A*** of factors

Factors	US	OB	PM	DM	Sum
1. US	0	**3.111**	2.972	2.861	8.944
2. OB	3.167	0	3.056	2.750	8.973
3. PM	2.500	2.361	0	2.861	7.722
4. DM	2.583	2.361	2.778	0	7.722
Sum	8.250	7.833	8.806	8.472	

Step D2: Calculating the direct influence matrix – In Table 7, the sum of the second row is the maximum value (8.973) of $\max\limits_{1\le i\le n}\sum_{j=1}^{n}\left|a_{ij}\right|$ and $\max\limits_{1\le j\le n}\sum_{i=1}^{n}\left|a_{ij}\right|$. Therefore, the value of s equals 1/8.973. Accordingly, based on Eqn (6) and the values of the average matrix ***A*** (Table 7), a direct influence matrix ***D*** is obtained and presented in Table 8. For instance, the value of direct influence US→OB is calculated to be around 0.347 (= 3.111/8.973).

Table 8. Direct influence matrix ***D*** of factors

Factors	US	OB	PM	DM	Sum
1. US	0	0.347	0.331	0.319	0.997
2. OB	0.353	0	0.341	0.307	1.000
3. PM	0.279	0.263	0	0.319	0.861
4. DM	0.288	0.263	0.310	0	0.861
Sum	0.920	0.873	0.982	0.945	

Step D3: Calculating the indirect influence matrix – Table 9 shows the calculated indirect influence matrix ***ID*** of factors in the case project, using the calculation functions in MATLAB (2009).

Table 9. Indirect influence matrix ***ID*** of factors

Factors	US	OB	PM	DM	Sum
1. US	3.196	2.984	3.283	3.195	12.658
2. OB	3.115	3.083	3.290	3.211	12.699
3. PM	2.783	2.680	2.995	2.836	11.294
4. DM	2.782	2.682	2.924	2.915	11.303
Sum	11.876	11.429	12.492	12.157	

Step D4: Deriving the total influence matrix – Table 10 presents the total influence matrix obtained using Eqn (9). The table also provides the values of d_i and r_j. Table 11 displays the values of d_i+r_i and d_i-r_i for each factor. The results demonstrate that the values of d_i-r_i are positive for the US and OB factors, which therefore fall into the cause group. If management wishes to improve the effect group factors to exhibit satisfactory duration performance, they must take great care to control the cause group factors.

Table 10. Total influence matrix ***T*** of factors

Factors	US	OB	PM	DM	Sum (*d*)
1. US	3.196	3.331	3.614	3.514	13.654
2. OB	3.468	3.083	3.631	3.518	13.700
3. PM	3.062	2.943	2.995	3.155	12.154
4. DM	3.070	2.945	3.234	2.915	12.164
Sum (*r*)	12.795	12.302	13.474	13.101	

Table 11. Degree of total influence of factors

Factors	*d*	*r*	*d*+*r*	*d*–*r*
1. US	13.654	12.795	26.449	**0.859**
2. OB	13.700	12.302	26.002	**1.398**
3. PM	12.154	13.474	25.627	–1.320
4. DM	12.164	13.101	25.266	–0.937

Step D5: Obtaining the influence-relations map (IRM) – Figure 4 presents the IRM of the first-level factors in the case project. Using the map, management can visualize the difference between cause factors (OB and US) and effect factors (PM and DM). Table 12 shows the net influence matrix of factors using Eqn (12). For example, the net influence of the OB factor on the US factor is 0.137 (= 3.468–3.331; Table 10).

Table 12. Net influence matrix ***N*** of factors

Factors	US	OB	PM	DM
1. US	–			
2. OB	0.137	–		
3. PM	–0.552	–0.688	–	
4. DM	–0.444	–0.573	0.080	–

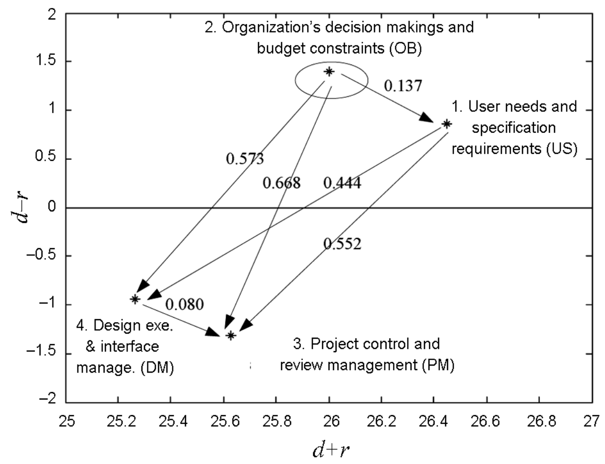


Fig. 4. Influence-relations map of first-level factors

3.6. Integration of ISA and IRM

Table 13 presents the evaluation obtained using ISA and IRM. In the ISA analysis, only the OB factor (with positive importance; SI > 0) has unfavourable design duration performance (negative satisfaction; SS < 0). Therefore, the OB factor must be improved. Moreover, IRM analysis reveals that the US and OB factors are in the cause group, while the other two factors, PM and DM, are in the effect group. Overall, management strategy A (which requires no further improvement) can be applied to US, PM, and DM (SS > 0). Management strategy B (which requires direct improvements) should be applied to OB (SS < 0 and $d - r > 0$).

Figure 5 represents the evaluation in visually. The left of the figure presents the ISA analysis, whereas the right shows the IRM analysis. In the figure, the OB factor affects all other factors.

3.7. Identification of the key second-level sub-factors

Improving the OB factor depends on identifying the key sub-factors that are responsible for the delays. The input data collected from the aforementioned questionnaires and the same modelling steps as used in applying the ISA and IRM methods yield the following results:

- The performance of all four sub-factors (OB1~OB4) is not satisfactory;
- Sub-factors OB1 (DM's decision making), OB2 (DM's supervising ability), and OB3 (budget availability) are in the cause group, and they must be improved directly (strategy B; SS < 0 and $d - r > 0$);
- Sub-factor OB4 (DM's resource allocation) is in the effect group; it must be improved indirectly (strategy C; SS < 0 and $d - r < 0$). That is, sub-factor OB4 is improved by improving other sub-factors (OB1~OB3).

Table 14 shows the suggested strategies for improving the second-level delay sub-factors under the OB factor. Figure 6 represents the evaluation results of the ISA and IRM analyses of these sub-factors.

Table 13. Suggested strategies for improving delay factors

	ISA			IRM			
Factors	SS	SI	(SS , SI)	$d+r$	$d-r$	Group	Strategies
1. US	0.217	–1.209	● (+,–)	26.449	0.859	Cause	A
2. OB	–1.415	1.128	X (–,+)	26.002	1.398	Cause	B
3. PM	0.939	0.403	○ (+,+)	25.627	–1.320	Effect	A
4. DM	0.259	–0.322	● (+,–)	25.266	–0.937	Effect	A

Note: Strategy A: factor requires no further improvement (SS > 0); Strategy B: factor must be improved directly (SS < 0 and $d - r > 0$).

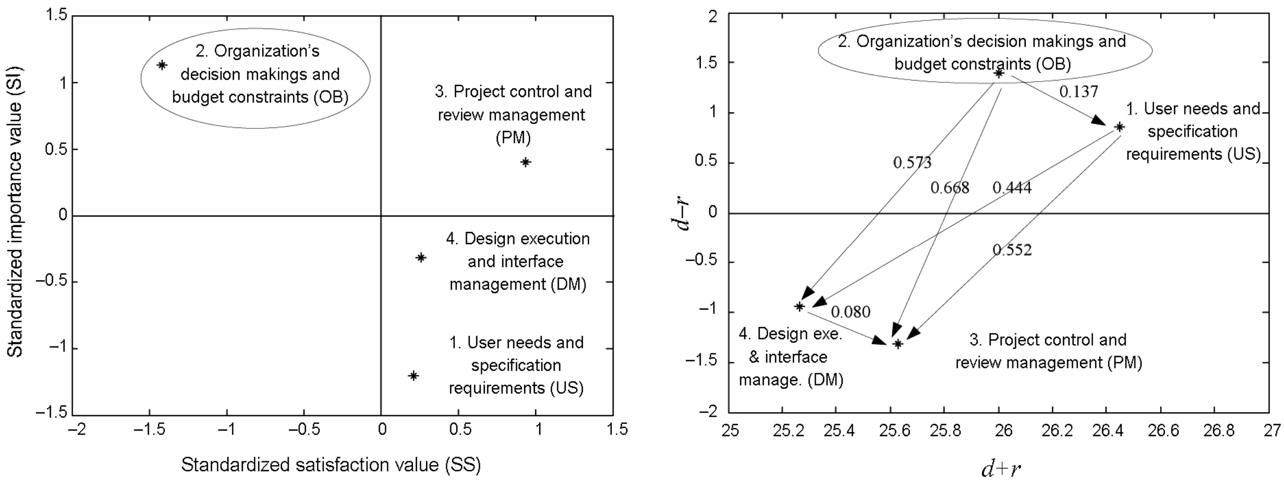


Fig. 5. Integration of ISA and IRM for first-level factors

Table 14. Strategies for improving second-level delay factors under OB factor

	ISA			IRM			
	SS	SI	(SS , SI)	*d*+*r*	*d*–*r*	Group	Strategies
2.1 DM's decision makings (OB1)	–2.245	1.967	X (–,+)	13.138	0.860	Cause	B
2.2 DM's supervising ability (OB2)	–1.383	1.093	X (–,+)	12.657	0.367	Cause	B
2.3 Budget availability (OB3)	–1.014	–0.154	▼ (–,–)	12.133	0.037	Cause	B
2.4 DM's resource allocation (OB4)	–0.398	–1.152	▼ (–,–)	12.095	–1.264	Effect	C

Note: Strategy B: factor must be improved directly (SS < 0 and $d - r > 0$); Strategy C: factor must be improved indirectly (SS < 0 and $d - r < 0$).

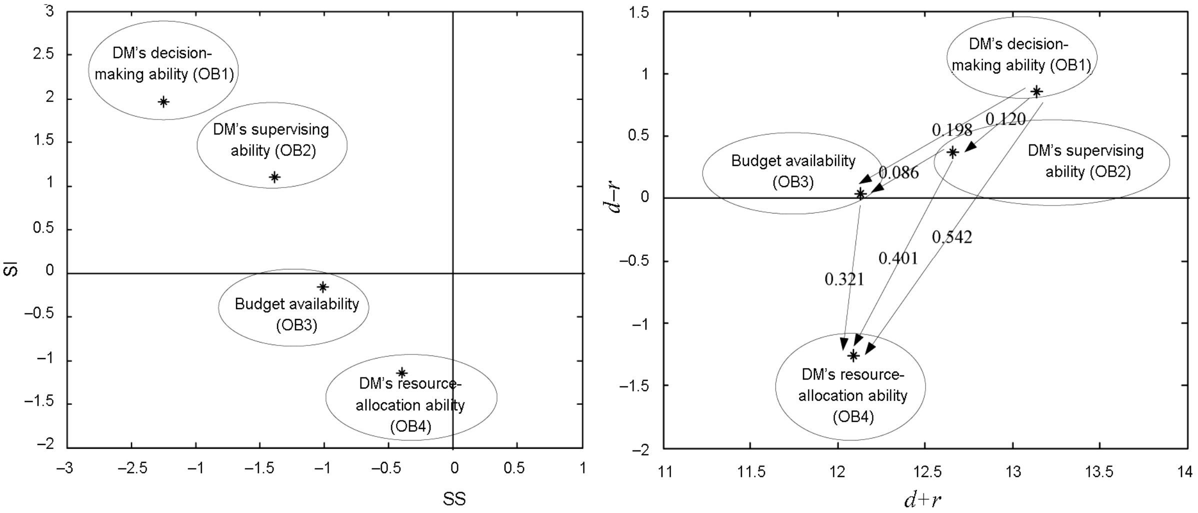


Fig. 6. Integration of ISA and IRM for sub-factors under OB factor

3.8. Discussion

The research team took around one month to collect the required questionnaires and conduct the analyses. The major evaluations in this case study are as follows:

- The ISA analysis reveals that the OB factor that is related to decision makers is the only unsatisfactory factor;
- The IRM analysis demonstrates that the OB and US factors are in the cause group (meaning that they influence other factors more than they are affected), whereas the PM and DM factors are in the effect group. The decision makers (related to the OB factors) and facility users (related to the US factors) should have higher responsibilities for the delays (if any) than the other two project participants (project management and A/E) in this case project;
- In the cause group, the US factor with the highest value of $d + r$ is the most important factor (meaning that it most strongly influences, and is most strongly influenced by other factors) in preventing design delays, whereas the OB factor, with the highest value of $d - r$, has the greatest effect on the other factors;
- In the effect group, an improvement in the PM factor (with the lowest value of $d - r$) depends strongly on the improvements in other factors;
- The decision makers (related to the OB factor) should take more responsibility for the design delays than does the A/E (related to the DM factor);
- Improving the OB factor depends on the improvement of sub-factors OB1, OB2 and OB3.

The above evaluation results were presented to a top manager of the project client and some project management team members. Their main feedback was as follows:

- A visual diagram (Fig. 5) is useful for clearly communicating the cause-effect relationships among factors;
- The modeling results are useful in providing two types of information for managing design delays – (1) factors or sub-factors to which delays are most sensitive, and (2) project participants who are most responsible for delays;
- Obtained management information should be provided as soon as possible to enable corrections to be made in a timely fashion. Regularly updating of the evaluation of the model is preferred;
- The modelling results are useful in supporting the design duration management. However, they are not useful as legal evidence in the resolution of disputes;
- The top manager appreciated the evaluation results even though the project' decision-makers were considered to have the most responsibility for the delays. However, he thought that the project client organization should take responsibility and that blame should not lie only with its top managers because many of their late decisions and inefficiencies were

caused by an ineffective organizational structure. He also indicated that some of the delay factors (related to client's needs) were caused by offering an excess of conflicting opinions by facility users and the scientific spirit of the organization, which always seeks perfect solutions to problems. Nevertheless, he would pay attention to improving the two driving delay factors, that is, the DM's decision making (OB1) and DM's supervising ability (OB2).

Conclusions

Factors that affect delays in design projects are complex and interrelated. Controlling key delay factors is an efficient means of managing the duration of design work. This study proposes an innovative model that helps identify the performance and cause-effect relationships among delay factors. The ISA method is adopted to evaluate the performance of each factor and sub-factor. A DEMATEL-based IRM analysis is employed to analyse the cause-effect interrelationships among factors. The ISA and IRM are then combined to trace the key factors that most strongly affect design delays. In the case study, of the four first-level delay factors and the 17 second-level delay sub-factors, the OB factor (organization's decision making and budget constraints) was found to be the key driver. The top manager should pay more attention to this factor to improve design duration.

Notably, specialist knowledge may be required to implement the proposed model successfully. For instance, in the case study, the research team members possessed expertise in construction project management, allowing them to search for relevant studies efficiently and communicate with project participants smoothly to identify appropriate design delay factors. Furthermore, the team members familiarized itself with the steps of performing the ISA and IRM, allowing them to not only clearly present the proposed model to the experts in order to gather the required questionnaires, but also to perform the modelling calculations and interpret the modelling results easily.

For facilitating the implementation of the proposed model, we recommend that future research computerize the proposed model to expedite the evaluation steps. Computerization also supports management to act appropriately and timely. Second, as implied by Ramanathan *et al.* (2012), analyses of the management solutions of delay factors for additional specific projects are needed. Third, comparing the practical meanings of delay causes in various countries is also valuable. Fourth, ISA and IRM schemes may be applied to solve different decision-making problems, which involve various interrelated factors.

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