Journal of Asian Architecture and Building Engineering

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tabe20

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**To cite this article:** Seoung-Wook Whang, Sohrab Donyavi, Roger Flanagan & Sangyong Kim (2023) Contractor-led design risk management in international large project: Korean contractor's perspective, Journal of Asian Architecture and Building Engineering, 22:3, 1387-1398, DOI: 10.1080/13467581.2022.2085718

**To link to this article:** https://doi.org/10.1080/13467581.2022.2085718

JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING
2023, VOL. 22, NO. 3, 1387–1398
https://doi.org/10.1080/13467581.2022.2085718

CONSTRUCTION MANAGEMENT

# Contractor-led design risk management in international large project: Korean contractor's perspective

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**ABSTRACT**

In contemporary international large-scale projects (LSPs), where heavy responsibilities are placed on the contractor, the contractor needs to manage all design-related issues for production activities, unlike traditional design management. To mitigate the contractor's design-related risks from the bid stage, this study identifies the design risk management (DRM) factors and analyzes them in terms of importance weight and application preference. Through the questionnaire survey and statistical analysis using SPSS, "Integrated design management team on-site [F11]", "BIM application/ simulation [F27]", and "Design-related value engineering [F04]" are recognized as the most important factors with over the 4.00 mean value and their application preferences are ranked 6th, 4th, and 17th, respectively. And then, the factor interrelationship analysis is carried with 18 high-rank DRM factors in order to investigate the structural features of design-related project elements. Overall, high application preference factors have diverse relationships with other factors, whereas high importance weight factors show a strong and direct relationship. Factor interrelationships of the high-rank application preference factor (5.16) show more than twice of the average factor relationship (2.29). Finally, a causal loop diagram is generated using System dynamics based on factor interrelationships to verify the interrelationship structure among DRM factors. With the awareness of detailed DRM factors and their interrelationship structure, the contractor can understand how the design-related risk issues are interconnected with various production activities on site and prepare suitable management methods according to the project's situation from an early project stage.

**ARTICLE HISTORY**
Received 11 December 2021
Accepted 28 May 2022

**Keywords**
international project; design risk management; contractor's perspective

## 1. Introduction

This study focused on how contractor-led design risk management (DRM) can assist in a systematic process of international large-scale projects (LSPs), where the contractor has generally been responsible for not only production, but also design-related issues occurred throughout the project (Sha'ar et al. 2016). Formulating a bid is a complex process involving interdependence, risk, uncertainty, and complexity. Moreover, having an international design team involved in the design process adds another layer of complexity that the contractor must manage. LSPs incorporate many design elements that require unique and innovative structural, mechanical, lighting, electrical, and even environmental systems (Aminmansour and Moon 2010). These are complex and interconnected with all types of production activities and supply chains on-site. LSPs have been problematic for contractors who have underestimated the time and cost of project delivery from the early project stage. Moreover, LSPs have normally used international design teams to produce the concept and scheme design, which has resulted in a complex arrangement for the delivery of design information (Whang, Flanagan, and Kim 2017). Because all these project elements should be implemented sufficiently as a single process, contractors have difficulties in the integration of complex elements during production phases. In practice, time and cost overrun in LSP is tremendous compared to regular building projects if the contractor fails to integrate these complex elements efficiently (Othman et al. 2016).

In addition, LSP accounts for a large portion of the Korean construction industry. Since 2015 winning new orders has been flat, the Korean contractor's revenue from overseas were around 40% of Korea annual construction output as seen in Figure 1. Almost all oversea projects carried out from Korean contractors are LSPs including industrial plants, refinery, petrochemical plants, infrastructure, and complex high-rise building project. From the standpoint of a contractor that carries out such large and complex projects oversea as well as in Korea, it is clear that project success will be greatly affected if the project risks are not identified early and managed quickly.

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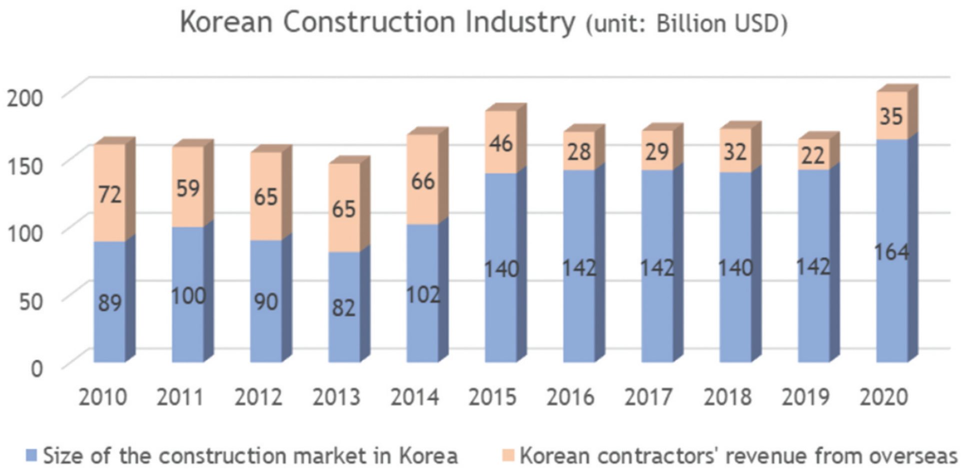

**Figure 1.** Korea annual construction output. Source*: Construction Association of Korea (CAK) and International Contractors Association of Korea (ICAK)*

Traditionally, design management is an established process for a design team at the design stage to coordinate and manage the various disciplines engaged in the design process. On the other hand, because of the unique nature of an LSP, design management needs to be supplemented using a systematic process, which ensures the sequencing, interaction, and flow of information from the design stage into production activities. Designers and design engineers focus on the aesthetics, form, function, and structural and environmental integrity, whereas contractors focus on the resources, production methods, process, and sequence (Emmitt, Pasquire, and Merita 2011). Projects are continuously increasing in size, and most importantly, they are increasing in complexity. In order to implement these large and complex projects, new procurements which eliminate boundaries between design and production such as Design-Build or EPC (Engineering, Procurement, and Construction), are increasingly being applied to contemporary LSPs, where a contractor-led DRM concentrates more on the design-related issues for production or assembly. Therefore, DRM is an important tool for the contractor to deal with the design information for managing resources effectively from the early project stage. Han, Love, and Pena-Mora (2013) showed empirically that more than 50% of the cost overrun on sites were as the result of poor design management. Because many design elements and construction technologies are interconnected in contemporary construction project, design-related risks are inevitably such as design errors and omissions (Mohamed, Khoury, and Hafez 2011; Whang and Flanagan 2015). These can become severe causes of design changes and subsequent reworks throughout the production stages, and these iterative works result in negative influences on not only the overall project quality but also the contractor's profit. Early contractor involvement for managing of design-related risk elements could be a critical condition in reducing the project uncertainty and in promoting production efficiency because a contractor has specialized technologies, in-depth knowledge of construction materials and methods, and sufficient practical experiences.

The bid stage is crucial to the contractor, who operates the enterprise to deliver the project to calculate a bid price and construction duration. In the bid stage, the project team cannot review all the design information on how much and closely they are interrelated with the production activities directly or indirectly. Within a short period of the bid stage, it is difficult for the contractor to produce an accurate bid and choose the suitable construction methods. This means that during the bid stage, many critical elements regarding design and production are overlooked (Mohamed, Khoury, and Hafez 2011; Chou, Pham, and Wang 2013; Kalan and Ozbek 2020). In addition, because contractors are more exposed to unexpected risks such as geopolitical or supply chain issues rather than other project stakeholders in LSP due to a lack of clear and accurate information, practical management methods should be prepared to respond to any design and information related risks. However, insufficient attention has been paid to the use of design information and effective management of design-related issues on site. Research on design management has focused previously on the management of design information from the perspective of the design team to ensure timely and relevant information through the design process (Galloway 2009).

## 2. Literature review

### *2.1. Changed role of design risk management*

The role of design management needs to shift fundamentally to control the complex risks interconnected between the design information and productions that match it. The trends in the international construction market are shifting to globalization, enlargement, and complexification. According to Whyte, Stasis, and Lindkvist (2016), there are increasing changes in the basic patterns: form, function, and fit to conduct modern complex construction project. Form relates to style, function concerns engineering, and fit is the link between form and function. Despite the increasing complexity of modern construction projects in all respect, less time and effort are being allocated in the early project stage (Hastie, Sutrisna, and Egbu 2017). The contractor cannot fully appreciate the design assurance in the early project stage, while designers tend to avoid their responsibility after handing the design output over to the contractor. In addition, the international design team tends to shift their design responsibilities on to the contractor or local partners with the excuse of immediate responses to unexpected design-related issues during the production stage. In many international LSPs, the contractor plays a role not only as the construction manager but also as the design manager. This is far from the concept of traditional design management which focuses on only how to plan and design the building aesthetically with less consideration on other issues that design causes. Contractor-led DRM inevitably involves different disciplines, including innovative design, building materials, construction engineering, and supply chain. However, over the past few decades, various researches have been carried out for changing concepts of design management, the majority focuses on the contractor's early involvement or new procurement system such as Design-Build, where all design processes are carried out by the contractor or the design firm that has made a contract with the contractor. There have still been limited researches for the contractor's decision making on whether to bid or not or practical production strategies by managing design information from an early project stage. Contractor-led DRM can show the highest performance when applied from an early project stage, where different important decisions should be made, including the bid price or the erection method. Early involved DRM aims to control the various issues of production activities systematically by understanding from the project outline to the budget availability. From this, the contractor can identify the design-related risks and produce a suitable implementation plan. Therefore, this can finally result in avoiding unnecessary time and cost overrun (Larsen et al. 2016; Pankaj 2016). Moreover, with the changing trend in LSP where contractors are required to manage the design-related issues such as omission or minor alterations by unavailable materials on site, accurate recognition of the shifted role of design management, which focuses more on the integration between design and production elements, is critical (Tzortzopoulos and Cooper 2007). The production stage is dynamic, constantly changing, and defined subjectively. In accordance with the changing trend of international LSPs, an integrated managing approach is required between design and production to deal with the complicated construction stages.

## 3. Contractor's perspective

Design manager, who was assigned mainly from an architect, designer, or consultants, was interested in the uniqueness of the building form and functional conveniences. Recently, however, the design manager considers the feasibility and erection process more instead of only the design aspects. The contractor's design management understands the coordination and regulation of the building design process on-site, resulting in the delivery of a high-quality project that the client wants. The explicit functions of design management are less well defined, and there has been little empirical research from the contractor's perspective. And such researches do not affect the entire production stage but emphasize a very limited role. There are studies on the early intervention of contractors to determine the bid price or procurement, but only a few researches focus on design management encompassing the entire project. Wang et al. (2016) reported that while there was growing interest in design management within the AEC sector, there are several barriers to applying the design management practically during the production stage. They insisted that these barriers are related to the responsibility of who is in charge of the design process and output and who dominantly leads the design management during the production stage. Tzortzopoulos and Cooper (2007) also argued that there are still diverse issues relating to the lack of clarity and understanding of the role of design management within the construction industry.

The research of design management from the contractor's perspective was started as procurement shifted in favor of design-building procurement from the 1990s. Gray, Hughes, and Bennett (1994) pointed out the growing importance of the contractor's design management by the seminal report and the resultant book. To date, however, design management has not been emphasized sufficiently regarding how contractors can manage the design information for the production stage, what their role is in the design process, and what barriers they face. In addition, researchers on contractor's design management (Song, Mohamed, and Abourizk 2009; White and Marasini 2014; Nibbelink, Sutrisna, and Zaman 2017) have pointed out that even if specialized design professionals and construction trades have made the delivery of many complex LSPs, they also decouple the design process from contractor's work scope. This separation hinders the integration of design and construction knowledge and reduces the opportunity for contractors to influence the design output. Recently, several grounded studies on contractor-led DRM have been carried. Various researchers argued that due to the complexity of contemporary construction projects, the managing responsibility of the contractor has risen, even in the design aspects (Emmitt 2010; Minchin et al. 2014). Different studies (Zhou and Zhang 2010; Gransberg 2013; Sutrisna and Goulding 2019) are indicating that importance of the contractor's design management on site is drawing attention and the method is also becoming systematic. They explained that contractors are in the best position to provide well-balanced management because they have empirical data on the project availability and resource allocation, which can be integrated with design aspects in the production stages. With the similar context of managing the design-related issues, Walker and Walker (2012) examined the importance of contractor's early involvement. They argued that because the contractor is accumulating various project experiences regarding design-related problems occurring on previous projects, the contractor is ultimately responsible for the actual coordination between the construction and design process. Song, Mohamed, and Abourizk (2009) also emphasized the importance of early contractor involvement in the design process with the simulation of a construction schedule, which was conducted on four different construction stages. However, research on the application or practical performance of full-scale contractor-led design management is very limited, and there are more superficial arguments about the need for an introduction. In addition, most design management researches tend to cover only peripheral events such as design changes or value engineering, however rare researches have been conducted to encompass the entire project. More specific and practical researches are needed, such as application method or integrated management with production activities. Then, these academic achievements could be applied to actual LSPs. And the benefits from the involvement of a contractor's design management will be more expanded by the improved managing solutions covering schedule, cost, safety, and quality performance.

## 4. Research methods

This study uses an empirical approach, focusing on understanding the existing problems and practical ideas from the collected and analyzed data. Figure 1 presents the methodological approach of this study, which shows the summarized research flow carried out. The study is divided into five parts. On the other hand, the main research flow is structured into three stages: data identification stage, data collection and analysis stage, and DRM process (causal loop diagram) based on system dynamics.

The data identification stage is comprised of an investigation of existing problems, a literature review, and potential factor identification. In this stage, difficulties of the contractor in evaluating the accurate bid price and practical design-related project risks are reviewed. Based on the underlying complexity theory, the potential DRM factors are obtained from the literature and industrial reports. In the data collection and analysis stage, a survey questionnaire is formulated, reflecting the results of pilot interviews. In questionnaire, the degree of importance and application preference of individual DRM factors are evaluated using a Likert 5-point scale. Values of one to five are assigned to the responses for the "importance weight and application preference" of the DRM factors, with one as "negligible," two as "less important or applicable," three as "normal," four as "important and applicable," and five as "extremely important or applicable." Research data collected by questionnaire surveys are reassessed and analyzed using a computationally statistical method (SPSS 26) to ensure greater consistency and objectivity. Importance and application preference ranking, and interrelationships among different DRM factors are analyzed together. In addition, because the aim of this study is understanding the complex relationships among DRM factors not just the recognition of the importance of individual factors, every single DRM factors are allowed to indicate the multiple interconnections with all 31 factors. And, the interrelations of 18 high ranked DRM factors are presented later (Seen in Figure 2). Finally, using system dynamics (causal loop diagram), the structural features of DRM factor relationships is verified.

## 5. Data identification and collection

For identification of substantial DRM factors, 48 potential DRM factors are obtained from the initial factor collection and reconsidered and revised by four pilot interviews. All interviewees are in high positions in their organizations including senior managers or directors having at least 25 years of working experience in the international construction sector. The interviewees were asked to evaluate the appropriateness of the selected factors and add any additional DRM factors if they need. Finally, the survey questionnaire was designed in three parts, and 31 factors were determined to constitute the survey questionnaire. Factors what have similar context were merged, and some other factors that were not related to the design-related issue directly were excluded by the pilot interview. Instead, two factors were added newly according to the interviewee's recommendations. Through the questionnaire part 1, the personal information of the respondents and general perspective for international LSPs were acquired. Part 2 comprises of detailed questions to evaluate the degree of importance and

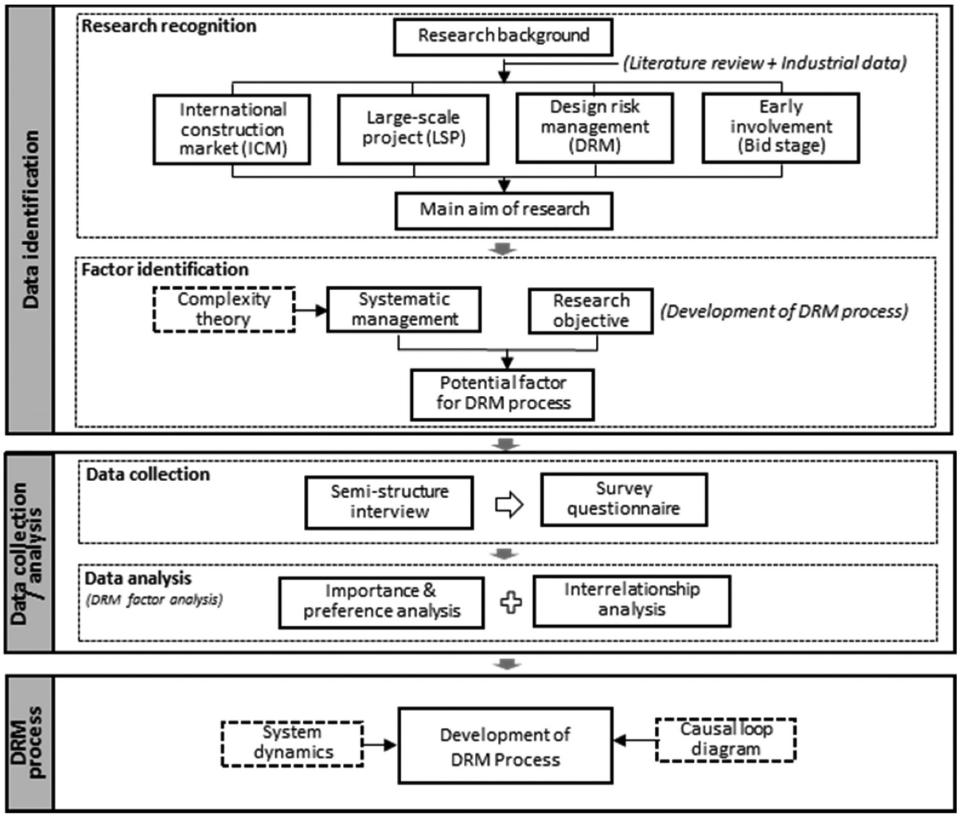

Figure 2. Research flow.

application preference of each DRM factor. In part 3, the respondents were asked to select multiple DRM factors which have a specific relationship against the DRM factor that they graded in part 2. In order to analyze the interrelationships in detail between factors, the plural chosen DRM factors were also evaluated using a Likert 5-point scale like the Part 2 questions.

Survey questionnaires were issued to the Korean construction professionals who are registered in the International Contractors Association of Korea (ICAK), and their companies are in Korean Grade 1 contracting and engineering firms. A total of 284 questionnaires were distributed, and 106 valid responses were received, representing a response rate of 37%. Among the 106 valid responses, 24 respondents (22.6%) are project managers, 32 (30.1%) are site managers, 31 (29.2%) are project engineers, 11 (10.3%) are design managers, and 8 (7.5%) are other project participants. As listed in Table 1, the majority of the respondents (84.9%) have more than 10 years of working experience with their organizations. They are positioned professionally at the middle or higher management level, which implies a high level of accuracy and credibility of the response. Because this study tries to understand not only the importance and application preference of DRM factors, but also interrelationships between them, all factor interrelationships are evaluated using computational statistical analysis (SPSS) and presented how strong and close the relationships are between DRM factors.

## 6. Data analysis and discussion

### 6.1. Importance weight and application preference

Using the statistical analysis tool, SPSS (26.0), the mean values and standard deviation of each factor were derived to determine the importance and application preference. The DRM factors with mean values that are greater than the average value of all

Table 1. Survey respondents.

| Experience (Years) | Project Managing | Site Managing | Project Engineering | Design Managing | OtherRoles | Total Responses |
|---|---|---|---|---|---|---|
| Under 10 | 3 | 5 | 7 | 1 | -2 | 16 |
| 11–15 | 10 | 12 | 5 | 6 | 3 | 35 |
| 16-20 | 7 | 8 | 10 | 2 | 1 | 30 |
| 21–30 | 3 | 5 | 7 | 2- | 2 | 18 |
| Over 30 | 1 | 2 | 2 |  |  | 7 |
| Total | 24 | 32 | 31 | 11 | 8 | 106 |

mean value (3.16) were recognized as important. Finally, 18 out of 31 DRM factors were recognized as critical research data according to their importance weight and application preference rates as seen in The mean value of the responses was 3.16 for the importance weight and 2.67 for the application preference rate. The standard deviations were 1.01 and 1.04, respectively. These 18 critical factors are used for Factor interrelationship analysis later on.

For reliable analysis of DRM factors, the Bartlett test of sphericity and the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy were tested. As shown in Table 2, the result of the Bartlett test was 637.095, and the associated significance level was 0.000 which allows researchers to verify the existence of significant correlation between the variables. All variables (DRM factors) had a significant correlation of at least 5 percent, which implies that all factors can be analyzed as variables. The value obtained from the sample adequacy measure of Kaiser-Meyer-Olkin (KMO) is 0.707, which is an acceptable value (Norusis 2012).

**Table 2.** Results of Bartlett's test and KMO measure.

| | | |
|---|---|---|
| Sampling adaptation measure of Kaiser–Meyer–Olkin (KMO) | | ,707 |
| Bartlett's sphericity test | Approximate Chi-square | 637,095 |
| | Df. | 210 |
| | Sig. | ,000 |

Spearman's rho was also tested to measure the degree of agreement on the ranking between the importance weight and application preference rate using the following formula (Schmid and Schmidt 2007; Hauke and Kossowski 2011).

$$\rho = 1 - \frac{6\Sigma D^2}{N(N^2 - 1)} \tag{1}$$

where D is the difference between the importance and application preference ranking for each Table 3. DRM factor. N is the total number of ranked variables. Subsequently, a t-test was used to analyze the variance between the two criteria for every single factor, such that a decision could be made as to whether the two samples come from the same population or not at the 95% confidence level.

As shown in Table 3, F11 (Integrated design management team on-site), F27 (BIM application/ simulation), and F04 (Design-related value engineering) are ranked as the top-three importance factors with a higher mean value above 4.00. Among the 31 DRM factors, only three factors show a remarkably high mean value and a relatively low standard deviation. This means that regardless of the work position and experience, most respondents recognized these three factors are essential for contractor-led design management. These top-three high importance factors are also ranked 6th, 4th, and 17th, respectively, in application preference. This finding shows that the factors that are expected to have direct and immediate effects on

**Table 3.** Importance weight and application preference rate.

| | | Importance weight | | | Application preference | | |
|---|---|---|---|---|---|---|---|
| No | Design Risk Management Factor | Lank | Mean | Standard Deviation | Lank | Mean | Standard Deviation |
| F01 | Design/ Changed-design checklist in life cycle | 14 | 3.239 | 1.128 | 27 | 1.809 | 0.985 |
| F02 | Clear scope of design and construction work/ responsibility | 7 | 3.440 | 1.134 | 21 | 2.122 | 0.929 |
| F03 | Awareness of local regulations | 26 | 2.540 | 1.223 | 9 | 3.133 | 1.136 |
| F04 | Design-related value engineering | 3 | 4.181 | 1.037 | 17 | 2.462 | 0.937 |
| F05 | Involving the design manager from bid stage | 16 | 3.210 | 0.932 | 22 | 2.081 | 0.936 |
| F06 | Design quality assurance practices | 5 | 3.609 | 0.925 | 23 | 2.063 | 1.107 |
| F07 | Pre-construction study and review of design documents | 8 | 3.436 | 1.161 | 16 | 2.470 | 0.977 |
| F08 | Structural grid planning review (over design, omission) | 24 | 2.729 | 1.304 | 13 | 2.941 | 0.899 |
| F09 | Reasonable design fee structure | 6 | 3.592 | 0.931 | 29 | 1.788 | 1.015 |
| F10 | Regular design meeting with supply chain | 12 | 3.388 | 0.882 | 26 | 1.846 | 0.993 |
| F11 | Integrated design management team on-site | 1 | 4.652 | 0.927 | 6 | 3.452 | 1.118 |
| F12 | Establishment of a project management information system (PMIS) | 9 | 3.428 | 1.077 | 14 | 2.932 | 1.106 |
| F13 | Analysis of impact around the site (noise, hazard, vibration, dust) | 28 | 2.319 | 1.232 | 10 | 3.126 | 1.022 |
| F14 | Establishment of shop drawing master schedule | 21 | 3.098 | 1.220 | 15 | 2.483 | 0.963 |
| F15 | Standardization of different types of drawings and documents | 13 | 3.364 | 0.903 | 7 | 3.448 | 1.114 |
| F16 | Standardisation of the pre-assembly/ Off-site | 4 | 3.876 | 1.043 | 24 | 2.041 | 0.976 |
| F17 | Analysis of site conditions (site topography/ underground condition) | 23 | 2.863 | 0.941 | 1 | 4.166 | 1.107 |
| F18 | Cooperation with interior design team | 30 | 1.980 | 1.094 | 28 | 1.791 | 1.211 |
| F19 | Project documents review | 15 | 3.231 | 1.089 | 2 | 4.132 | 1.102 |
| F20 | Awareness of international procurement (FEDIC/JCT) | 17 | 3.178 | 0.899 | 12 | 3.097 | 0.973 |
| F21 | Technical support for sustainable design | 10 | 3.423 | 1.148 | 30 | 1.692 | 0.998 |
| F22 | Lifecycle cost analysis (maintenance cost/ energy use) | 27 | 2.537 | 0.934 | 18 | 2.254 | 0.957 |
| F23 | Simulation of environmental impact | 29 | 2.015 | 1.187 | 20 | 2.135 | 1.144 |
| F24 | Previous projects case study | 18 | 3.171 | 1.117 | 19 | 2.216 | 0.983 |
| F25 | Review of the design level compared to the project budget | 25 | 2.558 | 1.066 | 8 | 3.179 | 1.125 |
| F26 | Approval working drawing and material samples | 19 | 3.167 | 0.933 | 5 | 3.467 | 0.872 |
| F27 | BIM application/ simulation | 2 | 4.403 | 0.917 | 4 | 4.039 | 1.105 |
| F28 | Pre-construction study and review of design documents | 22 | 3.063 | 0.972 | 3 | 4.073 | 1.038 |
| F29 | Support for an environmental building certification | 31 | 1.731 | 1.083 | 31 | 1.281 | 1.129 |
| F30 | Management of client's design change requirements | 20 | 3.152 | 1.094 | 11 | 3.101 | 0.931 |
| F31 | Design-related risk register | 11 | 3.397 | 1.089 | 25 | 1.955 | 0.982 |

Shading 18 factors are used for Factor interrelationship analysis the project performance are recognized as important from the contractor's perspective. For example, during the production stage, the contractor can expect clear and specific managing solutions by application of high importance factors such as practical simulation results from F27, the reduction of unwanted time and cost overrun from F04, Off-site criteria from F16, or efficient project information system from F12. The other remarkable finding is that some factors show unique characteristics of Korean contractors (F05, F06, F07, and F10), which operates a design team or design managing team within their organization. Whilst using their own design managing team, they can analyze inaccurate design information, potential design change elements, and their impact on the actual production stage early in the project and prepare appropriate design solutions in advance (Wang et al. 2016). Therefore, it is analyzed that Korean construction experts recognize the F06 (Design quality assurance practices) and F07 (Pre-construction study and review of design documents) as an important factor; they are ranked 5th and 8th in importance weight.However, not all-important factors are intended to be applied first during the production stage. Interestingly, many high importance weight factors such as F04 (3rd), F16 (4th), F06 (5th), F09 (6th), and F02 (7th) are ranked very low in the application preference, 17th, 24th, 23th, 28th, and 21th, respectively. Thus, it can be interpreted that the high importance factors should be considered first, but there may be other determinants to apply DRM factors to a project with the consideration of different production stages and situations. Some high ranked application preference factors such as F15 (Standardization of different types of drawings and documents) or F19 (Project documents review) are also ranked not high in importance weight with 13th and 15th. At the same, they have various inter-relationships with other RDM factors. This finding also can be interpreted that application preference factors can be applied not only to mitigate specific design-related issues, but also to manage the general conflicts between the design elements and production activities (Aminmansour and Moon 2010; Al-Qady and Kandil 2013).

### *6.2. Factor interrelationship analysis*

The factor inter-relationship can be recognized as more critical than importance weight or application preference for contractor-led design risk management. Unlike mean values of importance weight and application preference, the degree of factor relationships is presented not in a Table 3, but in a separate graph (Seen in Figure 2), where interrelationships are indicated with a more clear and intuitive way than numerical value. A certain high ranked DRM factor may be critical in itself having direct and specific influence on design-related issues. In contrast, some factors, even those not high ranked, can give a wide range of impacts on the whole production stages when they are cooperated or integrated with other relevant DRM factors appropriately (Wang et al. 2016; Demirkesen and Ozorhon 2017). Every project is unique and one-off according to the situation each faces due to the involvement of multinational architect-firms, highly complex construction, inexperienced design teams, geopolitical factors, which is the biggest feature of the construction project. Therefore, the DRM factor cannot be applied to the project in an important order. When applying an important factor, the effects of other DRM factors that may be related should be analyzed in advance. The interrelationships of every DRM factor are analyzed and presented separately in different ways. By understanding the relationship between various DRM factors at a glance, contractors can not only reduce design-related decision-making, but also effectively utilize limited project resources.

In Figure 2, all DRM factors are positioned based on the importance and application preference weight. In order to analyze the entire interrelationship structure, relationships between DRM factors are expressed intuitively using bold lines. In accordance with the result of the questionnaire (part 3), the more respondents are selected, the wider the line is expressed, and the higher the weight in relationship, the darker the color is expressed. Overall, high application preference factors have diverse connections with other DRM factors, whereas high importance weight factors show a strong relationship comparatively. This finding indicates that the high importance factors play a crucial role in the direct and specific relationships. For example, F27 (BIM application/ simulation) is one of the most important factors, but it can have a great effect on project performance with indirect support of other related DRM factors rather than alone. By the application of F12 (Establishment of a project management information system), simulated BIM data can be efficiently analyzed, shared, and used throughout the project. On the other hand, high application preference factors can cooperate with a wide range of production activities; F19, F15, and F12 have connections with diverse RDM factors. The average factor relationships of these three factors is 5.16, which is 80% higher than the average of the top three important factors (2.78) and more than twice the average of 18 DRM factors (2.29).

Another interesting finding is that some RDM factors which are neither perceived as important nor preferable, play a role as hubs cooperating with other critical (high ranked) RDM factors. For example, even if F02 (Clear scope of design and construction work/

responsibility) and F31 (Design-related risk register) are ranked low on the importance weight and application preference rate, they are linked not only with the average 4.35 RDM factors, but directly with the top-ranked importance factors, such as F27 and F11. In contemporary international LSPs, in which enormous design and production elements are interconnected complicatedly, the effective operation with integrated factors is more critical than only focusing on the critical factors (Demirkesen and Ozorhon 2017; Liu et al. 2017).

### *6.3. Research finding (Causal loop diagram)*

Traditional management approach tends to assume that if each project element can be subdivided and understood, then the entire project can be controlled (Sha'ar et al. 2016; Cerezo-Narváez et al. 2020). However, in contemporary LSPs, the interrelationships between the project's components are becoming more complex, where the entire project structure is incomprehensible with a traditional approach (linear thinking system). A new thinking system has been invented as a new framework of thinking to replace the existing linear thinking mechanism. System dynamics is a practical method used to indicate the complex phenomena or whole system by describing the correlations which cause changes of systems in reality (Forrester 1961). System dynamics integrates individual components into the entire structure, where the individual subordinate layers or elements have their own rules to implement when responding to complexity. A causal loop diagram is a type of analysis method in system dynamics. It has been used to analyze the structural features of the social phenomena or system (Yearworth and White 2013; Loosemore and Cheung 2015; Bala, Arshad, and Noh 2017). Causal loop diagrams consist of arrows, signs, and feedback loops. Relationships between selected components are expressed by arrows. In system dynamics model, causality is not statistical but practical and intuitive, because it often arises from specific experiences.

With the causal loop diagram, contractors can understand not only the overall project structure, but also when and how a certain DRM factor affects other factors and entire project performance (Time, Cost, Quality) before commencing the construction stage. The factor interrelationship analysis only explains that there is a relationship between factors, but the casual loop diagram could analyze the causal relationship between factors and their direction. It is possible to explain what and how much a factor affects the other factor, and finally, the effect on project performance can be verified (Sterman 2018). Even if causal loop diagram itself may not be able to provide a specific decision-making such as construction schedule or actual cost planning, it can improve the understanding of the project structure which is created by the causal relationship between DRM factors and make the contractors respond to unexpected design-related issues during the production stage. Furthermore, it can also be used as a basic input data for system dynamics simulation by which the contractor can achieve more practical and detailed information (simulated graph and figures); how many project resources are needed for a specific factor, exactly how much that factor affects other factors or project performances, and when the effects of the factors work (Schaffernicht 2010).

Figure 3 shows the entire structure of the project performance, which is generated in the context of cost, time, and quality performance during the production stage. All DRM factors directly or indirectly affect one or more project performances (time, cost, and quality) at the same time, and this impact would be positive and/or negative in accordance with the production stage. As the project progresses, positive effects can be changed to negative, and vice versa. For example, the F27 (BIM application/ simulation) can have a negative influence on the cost performance by forcing to purchase BIM related software such as Revit, Cost-X, or Navisworks, contact with a third-party BIM technician for modelling, and train all project team for operation and simulation using BIM. Furthermore, extra costs may be requirable to store on-site BIM data into the company's information system such as PMIS and to make it compatible with each other digital and information system. Oppositely, it has a positive impact on the quality of the entire production with clash detection, building simulations, or various visual analysis, throughout the production stages (Doumbouya, Gao, and Guan 2016; CAO, LI, and WANG 2017).

In addition, using this causal loop diagram as shown in Figure 4, the contractor can implement the most well-timed DRM factor according to the project conditions or situations. For example, if the most critical performance target is cost reduction at a certain production stage, the contractor can first consider applying the F04 (Design-related value engineering) referring to the causal loop diagram. This is because the factor has not only a direct influence on the time and cost performance but also various indirect influences via other DRM factors including F31 (Design-related risk register) or F11 (Integrated design management team on-site). Before applying F04, not only the importance and preference weight but also other related factors can be comprehensively considered to determine the direct impact and response to possible subsequent side effects in advance. On the contrary, if there is no specific performance target, the contractor may consider applying the F02 (Clear scope of design and construction work/ responsibility). It has connections with diverse DRM factors and although the effect

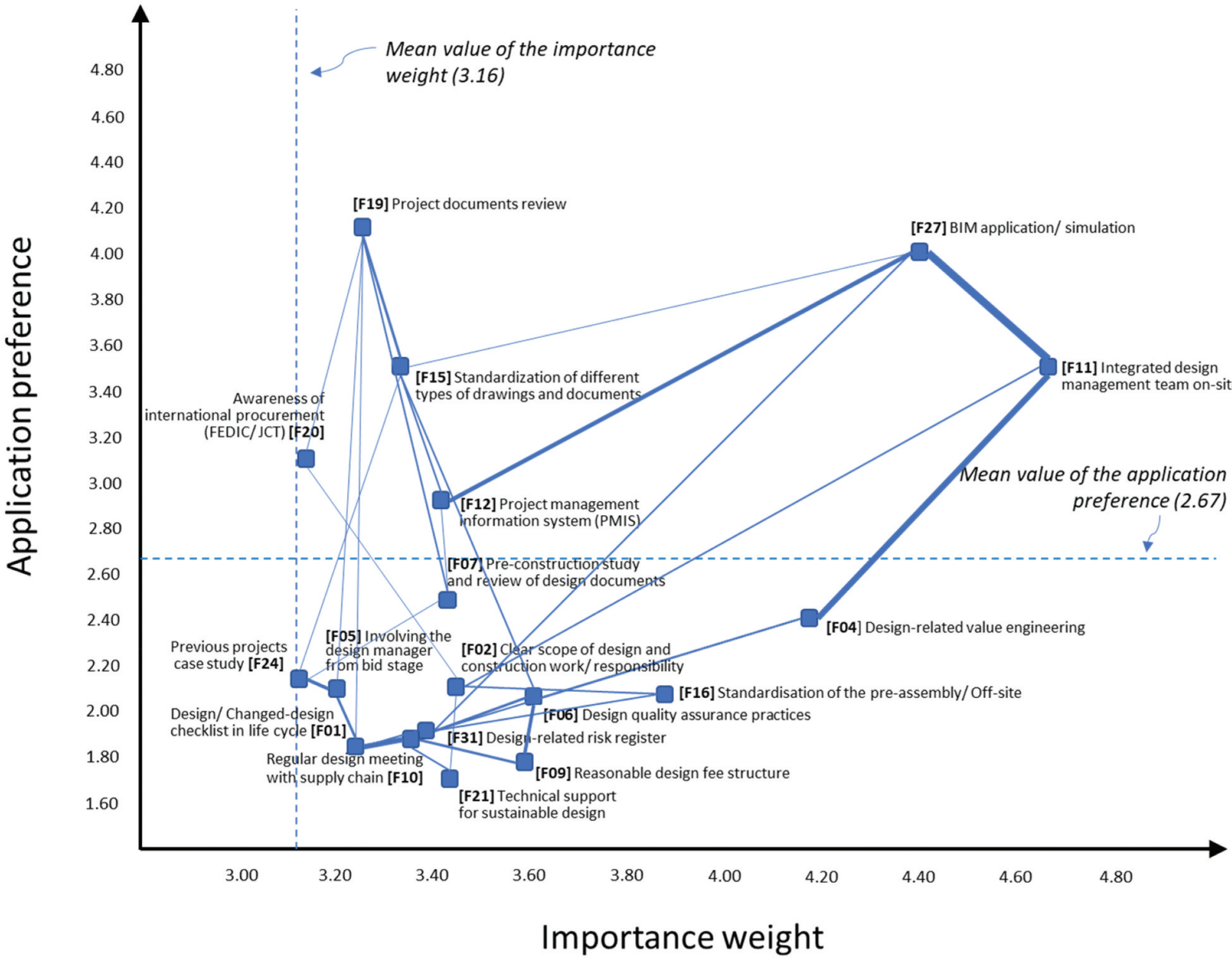

**Figure 3.** Interrelationship between the DRM factors.

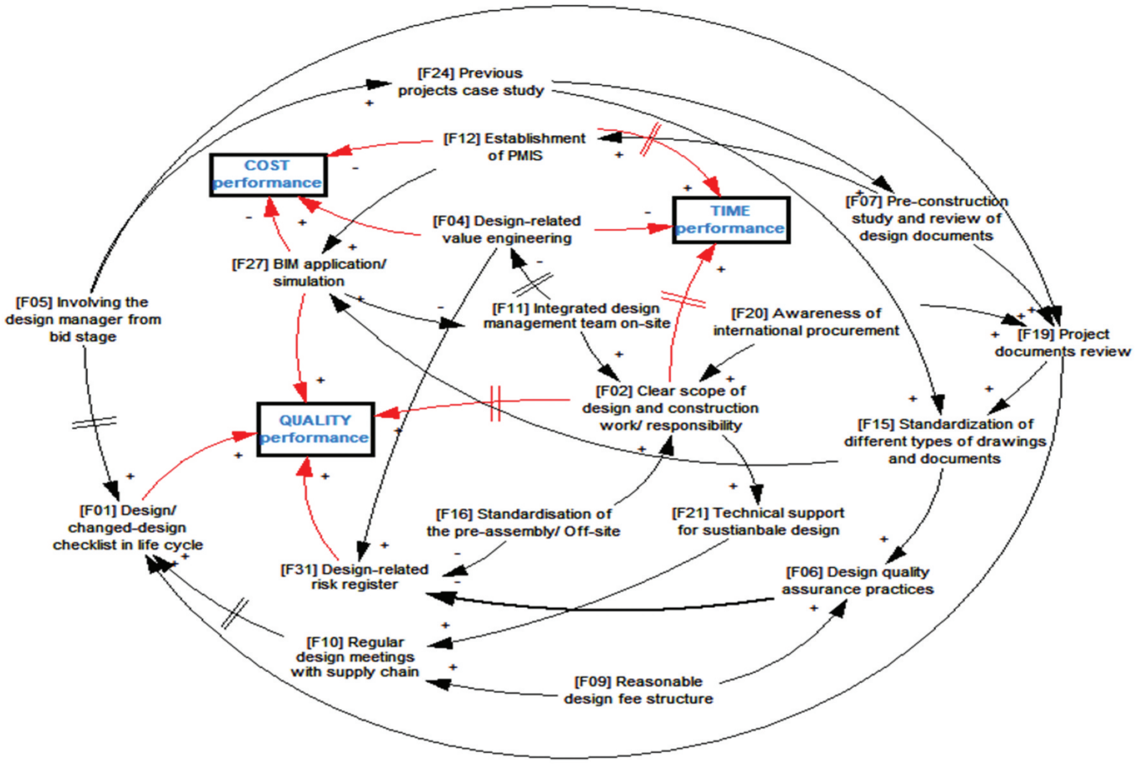

**Figure 4.** DRM factor causal loop.

is delayed, it directly affects time and quality performance at the same time. By applying relatively general DRM factors such as F02 or F19 (Project documents review), the contractor would manage the different production stages stably.

## 7. Conclusion

With the increasing project scale and complexity, contractors are facing increased design-related risk. Moreover, in contemporary international LSPs, the contractor should manage all the latent design-related issues and prepare a suitable design management strategy within a very short period. To mitigate such design-related risks in the production stage, this study focused on the contractor-led DRM. Through the questionnaire survey and social statistical analysis, the collected DRM factors were expressed by the importance weight and application preference rate. "Integrated design management team on-site [F11]", "BIM application/simulation [F27]", and "Design-related value engineering [F04]" were found as the most important factors with outstanding importance weight (over 4.00 mean value) and their application preference rankings are 6th, 4th, and 17th, respectively. This study focused more on the causal relationship between DRM factors and the entire structure. In complex LSPs, because only one critical factor could not have a profound effect on the project performance independently, research was approached as a comprehensive thinking. Thus, a factor interrelationship analysis was conducted with 18 high ranked DRM factors. Overall, high application preference factors have diverse relationships with other factors, whereas high importance weight factors show a strong relationship. The Interrelationship rate of top three high application preference factors (F19, F15, and F12) is 5.16, which is more than twice the average relationship rate (2.29).

Finally, using the system dynamics, a causal loop diagram was generated to understand the structural features of the entire project and manage the design-related issues that have managed fragmentarily with traditional linear thinking approach. In general, system dynamics were mainly used to explain logistics or peripheral processes, but this study may be able to contribute to another theoretical approach by analyzing the entire structure of the LSP. Viewing such an interrelationship structure of a causal loop diagram can help the contractor develop deeper insight into the fundamental dynamics of an international LSP. With such insight, contractors can recognize what DRM factor is urgently needed for specific issues and what influences may happen with the implementation of that factor at the same time. In addition, such information can help contractors to estimate an accurate bid and establish a suitable implementation plan from an early project stage. In further research, this causal loop diagram can be embodied in a system dynamics simulation because the numerical value by the simulations can be a more reliable and practical verification. Through system dynamics simulations with different variables (DRM factors) and constants (amount of input project resources such as cost, labour, and equipment), the optimal and balanced contractor-led design risk management plan can be established reflecting the different project conditions and situations.

## Acknowledgments

This work was supported by the 2021 Yeungnam University Research Grant.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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