CONCEPTUAL COST ESTIMATION FRAMEWORK FOR MODULAR PROJECTS: A CASE STUDY ON PETROCHEMICAL PLANT CONSTRUCTION

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Abstract. Modularization, which allows for pre-assembly away from a construction site, has been known to be more cost-effective than stick-built; however, contractors have difficulty ascertaining the benefits and adopting it. Calculating the benefits and costs of adopting modularization precedes decision making. However, modular cost estimation is challenging since relevant information in the early stages of a project and historical data about industrial modularization both have limited availability. To solve this problem, this study developed a conceptual cost estimation framework for industrial modular projects by converting stick-built project information. The framework is composed of eight steps based on two approaches. This study conducted a case study to demonstrate the applicability of the framework, which compared the project cost of modularization scenarios 1 and 2 with that of the stick-built version of the ongoing project. In addition, the estimated modular cost was compared with the engineers' estimation to verify the accuracy of the framework. The contributions of this study are in identifying and quantifying the factors influencing the differences in cost between the modularization and stick-built versions, and developing the conceptual cost estimation framework for an industrial modular project. This framework is expected to support deciding on adopting modularization, budgeting, and project viability.

Keywords: modularization, industrial modular projects, conceptual cost estimation, quantity-based estimation, Monte-Carlo simulation.

Introduction

Modularization allows for pre-assembly away from a construction site and includes a process of transporting and installing complete systems to the site (Haas et al., 2000). Modularization receives the widespread support from contractors since it can reduce project duration, accident rates, and project risk, and improve labor productivity, the work environment, and management capabilities (Choi & Song, 2014; Choi et al., 2019b; O'Connor et al., 2014). Over the course of decades, some of advanced contractors have tried to apply modularization to their projects in order to improve profits. However, despite this growing attention to modularization, most contractors have difficulty ascertaining the benefits and adopting it for their projects because of a lack of experience and knowledge (Wuni et al., 2020). Many contractors have attempted to do modular project execution using a trial-and-error approach.

Industry practitioners have to make several initial decisions in order to have a successful project. Cost estimation is crucial to making major decisions such as budget al.ocation, alternative selection and the modularization decision in the early stages (Kinney & Soubiran, 2004; Oberlender & Trost, 2001). Cost estimation in the early stages is difficult due to the low level of available information and the typically limited project definition (Choi et al., 2014). The project scope easily can change from the initial plan because detailed information is not yet determined (Choi, 2014). Moreover, due to insufficient experience with modular projects, historical data is scant to accurately estimate the cost of the modularization decision (Mao et al., 2016).

In this context, several studies have investigated the cost of modular construction compared with stick-built construction (Construction Industry Institute [CII], 2002;

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O'Connor et al., 2013; Pan et al., 2012). Various studies have investigated the way to apply the modularization method and help practitioners increase the efficiency of modular construction (Choi & Song, 2014). To date, most of those studies have assessed the problems at the strategic level, but an economic approach for estimating the cost of modularization is missing. Decisions about adopting modularization are complex problems (Wuni et al., 2019). Both practitioners and researchers need to understand the cost variances underlying the construction method decisions (i.e., the differences between modular and stick-built construction) prior to establishing the strategies for a project. Thus, this study aims to develop a conceptual cost estimation framework to support decision-making toward adopting the modularization approach.

To achieve this aim, this study sets out a conceptual cost estimation framework that converts the stick-built cost (which has relatively plentiful historical data to modularization cost (which does not have such data). Two main research activities were used to develop the cost estimation framework: (1) the factors affecting the differences in cost between stick-built and modularization were identified by literature review, and (2) the magnitude of those differences was quantified into probability and impact factors by a survey and interview of experts' knowledge and experience. The cost estimation framework was established based on these two approaches: (1) quantity-based estimation (QBE) and (2) Monte-Carlo simulation (MCS). A detailed description and the methodology of the framework are discussed in the following sections.

This study proceeded via four research steps: (1) reviewing the literature to understand the state of the art of research and set up the research problems; (2) capturing experts' knowledge and experience and developing the cost estimation framework based on two approaches; (3) conducting a case study to verify the functionality of the developed framework; and (4) discussing the results and findings of the case study.

1. Research background

1.1. Overview of industrial modular project research

Several studies have been conducted to improve the performance of modularization from the perspective of construction management. Studies on the construction management approach can be divided into two branches: (1) applicability of modularization and (2) optimization of the modular process.

In the first area, determining a proper construction method for a project at an early stage is critical to improving project performance (Naqvi et al., 2014). In order to the need to meet the changing market environment, as well as improving performance, the adoption of modularization in industrial projects is expected to grow (CII, 2002). However, many researchers have emphasized that unconditional use of modularization can have negative impacts. It is important to understand modularization in the context of the characteristics of individual projects and environmental conditions (Choi et al., 2019a; CII, 2002). Therefore, previous studies have focused on deriving critical factors affecting the applicability of modularization (Choi & Song, 2014; O'Connor et al., 2013, 2014). These studies classified the project characteristics relevant to adopting modularization and developed the decision-making criteria to examine the feasibility of such adoption. Although conceptual cost estimation and changes in total project cost have greater impact on decision-making, previous studies were limited in that they focused only on the constructability and applicability of modularization.

In the second area, many researchers have studied optimizing the benefits of modularization such that they are maximized (Chowdhury, 2016; Hsu et al., 2018; O'Connor et al., 2015; Taghaddos et al., 2010). Modularization can benefit by having parallel work done simultaneously at the construction site and in fabrication shops. Also, work in fabrication shops can reduce risks existing at the construction site and improve productivity (Jameson, 2007). To maximize these types of benefit, several studies have sought to optimize resource allocation and the supply chain from a logistics perspective (Hsu et al., 2018; Taghaddos et al., 2010). Other studies have focused on the interface between the fabrication shops and the construction site (Chowdhury, 2016). These studies are important because modularization includes additional phases (i.e., fabrication, transportation, and installation) compared to the stick-built process. However, there is a lack of understanding of cost variation and changes in the total project cost due to these additional phases.

The existing studies have widely discussed the applicability and optimization associated with the use of a modular method in industrial projects compared with traditional construction method. Despite advantage of modularization, the industry has not yet been able to fully apply modularization (Abdul Nabi & El-adaway, 2020; O'Connor et al., 2014). Decisions about adopting modularization are complex problems (Wuni et al., 2019). Both practitioners and researchers need to understand the cost variances according to construction method decisions (i.e., the differences between modular and stick-built construction) prior to establishing the strategies for a project. However, existing studies lacked consideration of cost aspects during modularization decision.

1.2. Review of cost estimation in construction industry research

For conceptual cost estimation at an early stage of a project, many studies have developed a cost estimation model by using various techniques. Table 1 summarizes previous studies on construction industry. These studies emphasized that the cost estimation model and framework should be simple, quick to use and provide trustworthy results, even if an accurate prediction is difficult due to a lack of available information (Oberlender & Trost, 2001).

Table 1. Overview of project estimation methods

Estimation method	Description and features	References
Artificial intelligence	Plays an innovative role in the cost estimation by performing thinking and learning from considerable input data, e.g., artificial neural networks	Dursun and Stoy (2016); Hashemi et al. (2019); Petroutsatou et al. (2012)
Parametric estimation	A statistical technique that estimates and optimizes the cost of a system as a parameter that constitutes the system and applies the factors to the cost drivers as empirical coefficients with the other characteristics	Chou et al. (2006); Kwak and Watson (2005); Yu (2006)
Regression estimation	A statistical analysis method for modeling the relations among several variables as a functional formula and indicating a single dependent variable as a linear function with one or more independent variables	Kim et al. (2004); Sonmez et al. (2007)
Case-based reasoning	An inference method that can solve new problems by reusing relevant information and knowledge based on previous similar cases	Choi et al. (2014); Koo et al. (2011)
Quantity-based Estimation	The estimate using limited information by deriving representative work for each project and calculating the quantity and cost for each work item separately	Kim et al. (2009); Smith et al. (2018)
Simulation estimation	A technique to predict the actual results by modeling a phenomenon or an event, using a systematic tool	Chou et al. (2009); Kang and Kim (2018); Zhu et al. (2016)
Activity-based estimation	Focuses on calculating the cost of each unit of the activities by dividing the performing business into discrete pieces of work	Kim and Cho (2013); Staub-French et al. (2003)
BIM-integrated estimation	An estimation which enables to consider various attribute of design aspect and to change the estimates automatically according to design	Cheung et al. (2012); Fazeli et al. (2020)

Since related information is insufficient in the early stages of projects (Chou et al., 2009), efforts have been made to increase accuracy by using available construction cost data (Smith et al., 2018).

Although these studies contribute to the body of knowledge of cost estimation for various structures, they rarely consider industrial modular projects in conceptual planning (Choi et al., 2019a). Cost estimation for the industrial modular project is challenging due to the additional processes involved. Capturing the cost variation associated with the use of modularization requires the consideration of factors influencing the cost (Bertram et al., 2019). In this sense, the characteristics of modular projects should be considered adequately to conceptually estimate the project cost in early stage. This research aims to establish framework associated with additional modularization process applying quantity-based estimation and simulation methods among various cost estimation methods. Since these methods do not require large amount of data, framework developed can overcome the lack of industrial modular projects information and seeks to identify a means to make decisions in early stage of the project.

1.3. Research objectives

Most previous studies which identified the characteristics of modular construction projects sought to determine the advantages and disadvantages of modularization (Abdul Nabi & El-adaway, 2021; O'Connor et al., 2014). Various factors and decision-making criteria were provided for successful projects. Despite their contributions, previous studies have several limitations for practical use. First, little effort was made to quantitatively grasp the comprehensive impact of modularization. It is important to

quantify the impact of modularization in an early stage of each project in order to capture relevant cost reductions. However, previous studies have not presented appropriate approaches for the industrial modular sector. As an industrial modular project is carried out, the total project cost changes depending on the additional processes needed for modularization. Second, previous studies have not been able to fill the knowledge gap between academia and practice, as mentioned above. Practitioners tend to wonder how much profit will be made when adopting the construction method for their projects. If the approximate cost of a modular construction can be estimated, contractors can be helped toward selecting that construction method compared with the stick-built approach. Therefore, this study aimed to develop a conceptual cost estimation framework for industrial modular projects that could be applied by inexperienced contractors at an early stage of projects.

2. Research method

2.1. Concepts of cost estimation framework

The authors designed the structure of the framework based on practitioners' practical or academic knowledge and relevant experience. There are three key elements that critically influence cost for industrial modular projects. The author interviewed industry practitioners about how to effectively estimate the cost for such projects.

Previous studies attempted to use many similar completed cases to predict total project cost. However, industry practitioners claimed that, when estimating industrial modular projects, it is difficult to find several modular project cases to use for a basis. Thus, it was recommended

that estimation would be conducted based on the quantity and cost using the stick-built method, for which there is sufficient information in the early stages. The concept of our cost estimation method is set to calculate project cost changes based on the quantity changes of work items used when modularization is adopted.

Another key issue regarding estimation for industrial modular projects from some practitioners was estimating the cost of additional phases (i.e., fabrication, transportation, and installation costs), which is the most important factor in such a project. The work items are converted to modules and moved from fabrication shops to the construction site. To overcome the limitations of a lack of industrial modular project case data, some practitioners suggested the use of the construction cost database, which provides reliable information updated annually (such as all-in-rate, location factor, and productivity factors). In construction research, several attempts have been made to estimate total project cost in an early stage (Smith et al., 2018), which helps reduce the chance of discrepancies due to lack of information and a limited project definition.

Furthermore, there was a recommendation for identifying the modularization effects in order to revise the initial estimates. Some industry experts recommended quantifying and reflecting industry-specific influencing factors, which would show negative and positive effects on modular projects compared to stick-built projects. After an extensive literature review, this study adopted the probability and impact of factors based on previous industrial modular projects. To calculate the cost impact, the Monte-Carlo simulation method was used based on the assumed distribution of each factor.

Approach 1: Quantity-based estimation

Quantity based estimation (QBE) has several advantages as a tool for calculating the cost using the type of work item and the approximate cost per quantity of work. First, QBE allows semi-detailed cost estimates according to the project cost structure, so that an effective cost estimation can be conducted (Chou et al., 2006; Soutos & Lowe, 2005). Second, QBE can be applied in a limited time for decision-making or alternative selection (Kim & Cho, 2013). Once the unit quantity of the work items is determined, the cost estimation can be approximated using the construction cost database, which provides potential costs associated with each work item (Bell & Kaminsky, 1987). Such a database comprises the national averages and construction information updated annually; such information provides costs of labor, materials, general overhead, and profit.

In this study, QBE is used to identify the quantity changes in work items and to calculate the required weight of the modules. Then, this study calculated not only the fabrication cost but also the related transportation and installation costs, by using the construction cost database (Compass International Inc., 2016a, 2016b; Smith et al., 2018).

Approach 2: Monte-Carlo simulation

Monte-Carlo simulation (MCS) is a probabilistic statistical method that overcomes the limitations of deterministic methods (Touran & Wiser, 1992). MCS is suitable for solving problems in the construction industry with limited cases because relatively few data points can be defined as probability distributions and run through several simulations (Zhu et al., 2016). Since a range of values is derived from MCS, rather than a single value, decision-makers can choose the appropriate value corresponding to the desired probability distribution for their project (Touran & Wiser, 1992). Since it is usually helpful to analyze the uncertainty of cost changes, many contractors have attempted to apply MCS to evaluate project cost variation (Zhu et al., 2016).

To perform MCS, it is necessary to assume that uncertain variables take the form of probability distributions. If considerable data are available, a statistical analysis can be used for a normal distribution. However, if there are few data, the uniform distribution or triangular distribution should be used (Touran, 1993). The triangular distribution is suitable for a construction project for which it is difficult to analyze and extract reliable cost data (Back et al., 2000). In addition, the Bernoulli distribution is a discrete probability distribution of a random variable that shows only two possible outcomes (Uspensky, 1937) and is used to indicate whether an event occurs. Therefore, this study uses the triangular distribution to quantify the impact of the factors and the Bernoulli distribution to set their probability of occurrence.

2.2. Framework formulation

The framework comprises nine steps according to the availability of the contractors' module information. The QBE approach (Approach 1) is addressed in Steps 1 to 6, which inform the estimating process using the unit cost of work items. The MCS approach (Approach 2) is addressed in Steps 7 and 8 to quantify the impact of cost factors and present the total project cost as a probabilistic range. Figure 1 shows the procedures of the developed framework to support the reader in understanding the logical links between each sequential step. This framework can be used once the conceptual design for the stick-built approach to the project has been completed, so that the quantity and cost of the work items can be determined. To determine which of the national averages in construction cost data should be used, the expected location of the construction site and fabrication shops must be decided. A detailed demonstration of the framework is described in the next section through a case study.

Step 1: Customizing work items

The purpose of Step 1 is to define the cost structure of the work items that can be accessed in the early stages. Industrial projects have a complex structure wherein various elements, such as civil, architectural, chemical, mechanical, and electrical, are combined. The cost structure of the work items cannot be generalized with one clas-

sification system due to the characteristics of the projects and contractors and the requirements of the owner and organizational environment. Thus, the user must define the cost structure of the work items that can represent the particular projects.

Generally, 20% of work items with high volume normally take more than 80% of the total project cost (Kim et al., 2009). Therefore, it is possible to estimate the total project cost by selecting the representative work items. After the classification of each work item into the appropriate project phase, the user identifies the proportion of each work item's cost to the total project cost. Then, the user lists them in order by their proportion of cost (in descending order, highest first), and finally, defines a cost structure of work items that together combine to cover more than 95% of the total project cost. Finally, the additional phases (i.e., fabrication, transportation, and installation) are added to the breakdown of the work items to reflect the modular construction process.
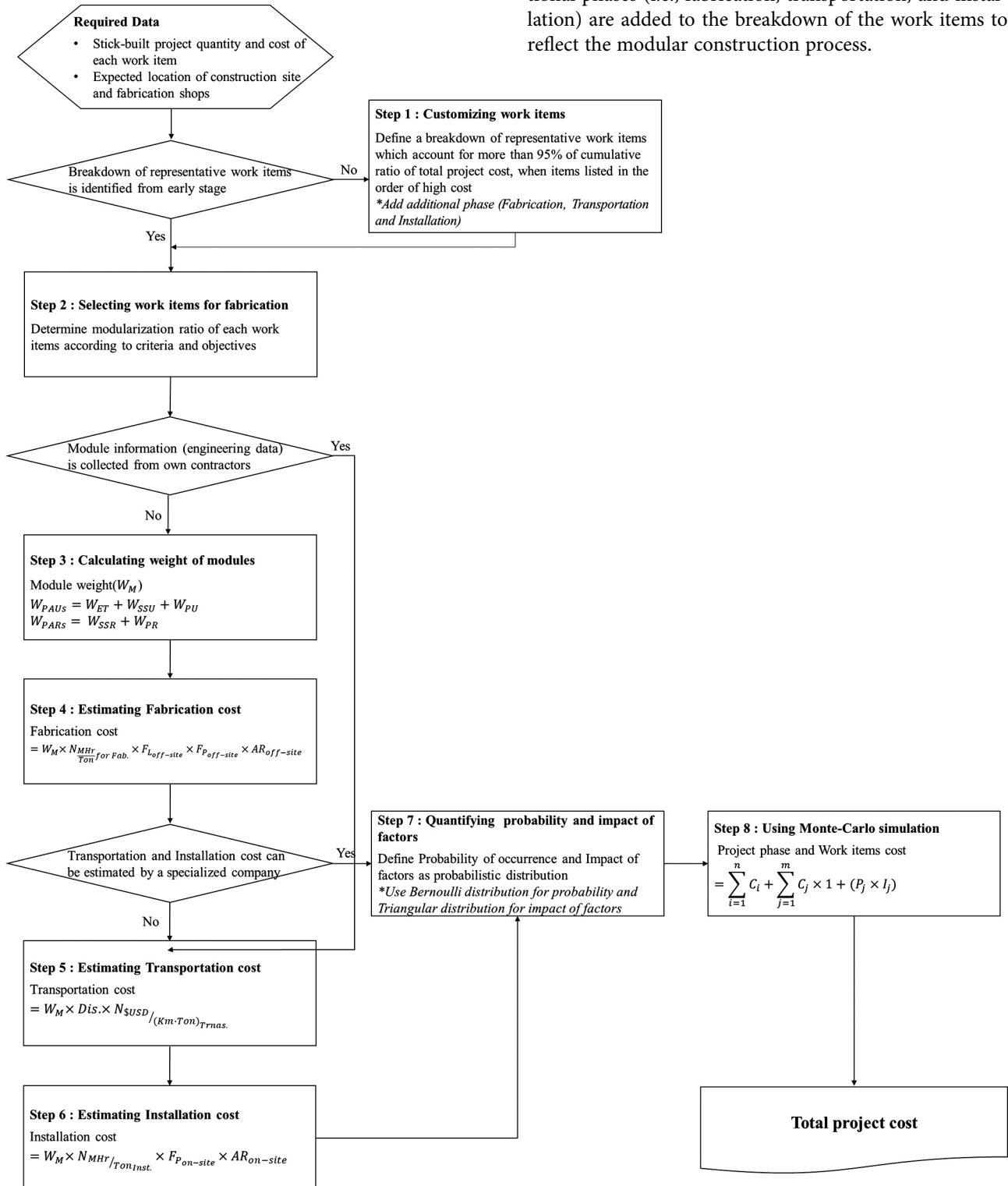

Figure 1. The Process of modular cost estimation framework

Step 2: Selecting work items for modularization

Step 2 aims to select work items that are transferred from the construction site to the fabrication shops. Since a module is a completed system that is assembled in the fabrication shops (Haas et al., 2000), it should be assembled with a certain percentage of each work item included. In addition, each project requires a different modularization application area, and thus corresponds to a different transfer ratio for each work item. According to industry practitioners, there are some objectives and criteria for adopting modularization. The objectives include: (1) owner's requirements, (2) environment damage minimization, (3) cost reduction, (4) duration reduction, and (5) improvement in quality. The criteria for applying the modularization area include: (1) the construction process plan, (2) an impossible stick-built construction area, (3) repeatability of work, (4) limitation of transport because of module size, and (5) existence of special equipment. The user selects work items of fabrication parts regarding different criteria and objectives for adopting the modularization.

The user sets the modular application area for the main elements composing an industrial project approximately. Then, based on user experience, the user determines the transfer ratio of each work item, which is defined in Step 1, to calculate the quantities of the work items for each module. Once the quantities are determined, they are converted to modules to be manufactured in the fabrication shops.

Step 3: Calculating weight of modules

If contractors have module configuration information, they can calculate the weight given to each of the modules easily. However, most contractors lack such experience and cannot attempt to calculate the weight of modules. Thus, the weight of modules is approximately calculated from the quantity of major work items in this step. According to practitioners, the assembled modules are divided into pre-assembled units (PAUs) and pre-assembled racks (PARs):

$$W_M = W_{PAUs} + W_{PARs} , \qquad (1)$$

where W_M is the summation of the weights of PAUs and PARs (in tons), W_{PAUs} is the total weight of PAUs (in tons), and W_{PARs} is the total weight of PARs (in tons).

Even though the elements of the modules comprise many work items, the weights of PAUs and PARs can be calculated from the major work items. First, the majority of the weight of PAUs is comprised of (1) 20% in equipment work, (2) 50% in structural steel work, and (3) 30% in piping work (Compass International Inc., 2016b). Therefore, the weight of structural steel work and piping work can be calculated using that of the equipment work. Thus, this study first assigned the weight of total equipment, and then added the weight of structural steel work and piping work with the ratio mentioned above for PAUs:

$$W_{PAUs} = W_{ET} + W_{SSU} + W_{PU}, \qquad (2)$$

where W_{ET} is the total weight of the equipment transferred into fabrication (in tons), W_{SSU} is the partial weight of the structural steel work for PAUs [$=5/2\ W_{ET}$] (in tons), and W_{PU} is the partial weight of the piping work for PAUs [$=3/2\ W_{ET}$] (in tons).

Second, the majority of the weight of PARs is comprised of (1) structural steel work and (2) piping work (Compass International Inc., 2016b). PARs are calculated with the leftover weight of the structural steel work and piping work after allocating the partial weight of structural steel work (WSSU) and piping work (WPU) for PAUs:

$$W_{PARs} = W_{SSR} + W_{PR} , \qquad (3)$$

where W_{SSR} is the partial weight of structural steel for PARs [$= W_{SST} - W_{SSU}$] (in tons), W_{SST} is the total weight of structural steel work transferred into fabrication (in tons), W_{PR} is the partial weight of the pipe for PARs [$= W_{PT} - W_{PU}$] (in tons), and W_{PT} is the total weight of piping work transferred into fabrication (in tons).

Step 4: Estimating fabrication cost

Once the weight of the modules is calculated, the fabrication cost can be estimated by using the construction cost database. Before developing the estimation equation, it is important to reflect the characteristics of the fabrication shops. According to previous studies, the modularization can expect better productivity with all necessary facilities and use cheaper labor than at the construction site (CII, 2002; Mao et al., 2016; Compass International Inc., 2016b). To grasp the entirety of modularization effects, the fabrication cost must reflect this advantage.

For estimating the fabrication cost, this study combined several national factors and values based on practitioners' opinions. The national averages and annual values are listed in the construction cost database. The user selects the values with the corresponding location of the fabrication shops (Step 4). The fabrication cost is derived as:

Fabrication Cost =

$$W_M \times N_{MHr/Ton_{Fab.}} \times F_{L_{off-site}} \times F_{P_{off-site}} \times AR_{off-site}, \quad (4)$$

where $N_{MHr/Ton_{Fab.}}$ is the approximate MHr/Ton using the U.S. Gulf Coast basis for stick-built work (in Mhr/ton); $F_{L_{off-site}}$ is a country-applicable labor productivity factor applicable to fabrication shops for process facility, offshore work, and modules; $F_{P_{off-site}}$ is the country productivity factor applicable to fabrication shops compared against a U.S. basis; and $AR_{off-site}$ is the all-in hourly labor rate for skilled and unskilled construction workers corresponding to fabrication shops (in USD/hr).

The remaining quantity excluded from the fabrication is estimated by interpolation using the stick-built quantity and cost:

$$\text{Remaining stick-built cost} = C_W \times \frac{Q_{Fab.}}{Q_T} , \qquad (5)$$

where C_W is the original stick-built cost of each work item, Q_T is the total quantity of each work item, and $Q_{Fab.}$ is the quantity of each work item transferred into modular fabrication.

Step 5 and 6: Estimating transportation and installation costs

Costs for the extra processes for modular construction are high, not only the transportation cost from the fabrication shops to the construction site, but also the installation cost for the modules. Of course, these costs do not apply to the stick-built process (Choi & Song, 2014; CII, 2002; Jameson, 2007). The transportation and installation for the modules are carried out by specialized companies. However, if the estimates cannot be provided by a professional company, the costs should be approximately estimated by using a simple equation.

This study combined several national factors and values based on practitioners' opinions to calculate the transportation and installation costs, which are similar to those shown in Eqn (4). The transportation cost can be calculated as:

$$\text{Transportation cost} = W_M \times Dis. \times N_{USD/(km*ton)}, \quad (6)$$

where $Dis.$ approximates the maritime and land distance between the construction site and the fabrication shops and $N_{USD/(km*ton)}$ is the shipping cost per ton of the module per kilometer (in USD/km*ton).

The installation cost can be calculated using Eqn (7), where the user selects the national averages and annual values which correspond with the location of the construction site:

$$\text{Installation cost} =$$
$$W_M \times N_{MHr/Ton_{inst.}} \times F_{P_{on-site}} \times AR_{on-site}, \quad (7)$$

where $N_{Mhr/ton_{inst.}}$ is an approximate Mhr/ton using the U.S. Gulf Coast basis for module installation (in Mhr/ton); $F_{P_{on-site}}$ indicates the country productivity factor corresponding to the construction site compared against a U.S. basis; and $AR_{on-site}$ is the all-in hourly labor rate for skilled and unskilled construction workers corresponding to the construction site (in USD/hr).

Step 7: Identifying and quantifying the factors influencing the cost variance

This step aims to identify the influencing factors on cost, which have caused variation in estimating cost. This study conducted comprehensive literature reviews and expert interview to identify the factors. In the related literature and reports, major consideration and lessons learned from previously completed modular construction projects have been presented. This study categorized them as negative factors due to the application of modularization. On the contrary, the benefits and advantages of modular construction were presented. The author categorized them as positive factors due to the application of modularization. The factors indicated negative and positive effects compared to stick-built projects. Finally, 10 cost factors that affect each work item and phase in industrial modular projects were identified (Table 2). The factors were reviewed by industry practitioners, and they were modified and selected from a cost perspective.

Step 8: Monte-Carlo simulation

In the last step, the user calculates the total project cost using MCS. There are different probabilities and impacts of each factor on the work items and phases. The quantitative method used in this study has been traditionally estimated by two values, as suggested previously (CII, 2003; Renn, 1998). For example, let the influencing factor 1 = F1, the probability of factor 1 = P1, and the impact of factor 1 = I1. F1 affects certain work items (e.g., piping work and structural steel work), P1 equals an occurrence percentage from Bernoulli distribution (e.g., occurrence of 30% and non-occurrence of 70%), and I1 equals a percentage from the triangular distribution (e.g., a lower limit of 5%, a mode of 10%, and an upper limit of 15%). In addition, if the influencing factor affects a certain phase, then each work item in the phase is affected.

The objective function is a summation of the non-influenced and influenced costs, which are multiplied by the probability and impact of factors. Since the costs are presented as a range, the user selects a certain value. The following Eqn (8) shows the objective function:

$$\text{Total Project Cost} = \sum_{i=1}^{n} C_i + \sum_{j=1}^{m} C_j \times \left(1 + P_j \times I_j\right), \quad (8)$$

where C_i and C_j are the cost items that are not influenced by the factors (expressed in USD) and that are influenced by the factors (also expressed in USD), respectively; P_j is the probability of occurrence for the factors (%); and I_j is the impact of the factors (%).

2.3. Data collection

This paper proposes an approximate probability and impact of the factors to help practitioners enter appropriate values (Step 7). These values were obtained by expert survey to reflect their experience from previous projects (Appendix). Seven projects conducted by four Korean contractors in seven countries were selected and the survey collecting the information was distributed. The project costs for each of the seven were between 300 million USD and 6 billion USD. The locations of the projects were in the Middle East, North America, and Asia; 70% of all respondents had more than 15 years of industrial project experience and 50% were responsible for project management on their projects. Table 3 and 4 shows the profile of the previously completed projects that we used in this study.

Table 5 provides a list of the 11 probability and impact factors quantified from the survey. The probability values are defined as the number of occurrences in the seven surveyed projects and respondents. For example, let us assume that an influencing factor occurred in 8 out of 10 of the previous projects; then probability of the factor was assumed conservatively to be conservatively 80%. The impact was estimated based on the results of the respondents' experience and expertise. This study used an interval scale in accordance with the factor's degree of affecting the cost estimates, using based on the question number 4 in Appendix. Even if the interval scale cannot express the

exact impact value that affected the project cost, the respondents can distinguish the approximate range of impact value (Jung & Han, 2017). In the case of sufficient raw data (from more than five of the projects), the impact values were selected based on fitment into the triangular distribution. On the other hand, in the case of insufficient raw data (from fewer than five of the projects), the average value of the available data was used. However, it was noted that the relationship between the probability and impact values and the influencing factors can be changed and modified by the users for other new projects, which is required for proper analysis.

Table 2. Factors influencing the cost variance in industrial modular projects

Category	Factors	Factor description	Source
Negative	Additional use of materials	Use of stiffeners for modular logistics transportation	Abdul Nabi & El-adaway (2020); Choi and Song (2014); O'Connor et al. (2013); Shelley (1990)
	Need for inspection and supervision	Large amount of supervision required for assembling the modules	De La Torre (1994); O'Connor et al. (2013)
	Additional fabrication yard and machine arrangement	Additional machines and space for module installation	Abdul Nabi & El-adaway (2020); CII (2002)
	Need for additional coordination	The need for communication and control between activities	Sharafi et al. (2018); Stubbs and Emes (1990)
	Increased design and engineering costs	Additional home office and engineering cost due to modular design	Abdul Nabi & El-adaway (2020); Choi and Song (2014); CII (2002)
Positive	Reduction in project management manpower	Lower requirement for supervision and technical requirement	Gibb and Isack (2003); Hesler (1990); Stubbs and Emes (1990)
	Reduction in construction machine operations	Shortening operation duration and early sequencing for construction machines	Jameson (2007); Stubbs and Emes (1990)
	Reduction in on-site labor operations	Reduction in input construction labor and training of available manpower	Choi and Song (2014); Gibb and Isack (2003); O'Connor et al. (2013)
	Reduction in construction risk	Reduction in construction expense, such as insurance and Health, Safety, and Environment (HSE) costs	Choi and Song (2014); CII (2002); Gibb and Isack (2003)
	Increase in field efficiency	Lower requirement for temporary facilities, major equipment, camp, and supervision	Gibb and Isack (2003); Jameson (2007); O'Connor et al. (2013)
	Reduction in project duration	Fast construction termination due to simultaneous work	Choi and Song (2014); Gibb and Isack (2003); Stubbs and Emes (1990)

Table 3. Project profile

No.	Product	Region	Price (in billions of USD)	Duration (in Months)
1	Petrochemical	Middle East	Price > 5	49 < Dur. < 60
2	Petrochemical	Middle East	0.5 < Price < 0.6	49 < Dur. < 60
3	Petrochemical	North America	0.3 < Price < 0.4	25 < Dur. < 36
4	Petrochemical	North America	0.3 < Price < 0.4	25 < Dur. < 36
5	Petrochemical	Asia	0.7 < Price < 0.8	25 < Dur. < 36
6	LNG	Middle East	0.7 < Price < 0.8	37 < Dur. < 48
7	LNG	Middle East	Price > 5	61 < Dur. < 72

Table 4. Respondent profile

No.	Position	Experience (in number of modular projects)	Project participation experience (in Years)	Total experience (in Years)
1	PM	3	1~2	20~25
2	PM	2	3~4	20~25
3	PM	2	1~2	20~25
4	PM	2	3~4	25~30
5	PM	2	1~2	25~30
6	Eng.	1	1~2	10~15
7	Eng.	1	1~2	20~25
8	Eng.	1	3~4	15~30
9	Eng.	2	3~4	10~15
10	Eng.	2	3~4	10~15

Table 5. Probability and impact of the factors influencing differences in cost

Category	Factors	Influenced phase or work items	Prob. (%)	Triangular distribution of cost impact		
				Lower limit (%)	Mode (%)	Upper limit (%)
Negative	Additional use of materials	Structural steel	80	2.0	9.4	24.1
		Module transportation	80	2.0	7.2	10.8
	Need for inspection and supervision	Project management	70	2.0	4.3	8.9
		Fabrication	60	2.0	6.0	14.0
		Construction	50	2.0	3.4	6.3
	Additional fabrication yard and machine arrangement	Project management	40	1.5	3.5	5.0
		Modules installation	70	2.0	3.3	5.8
	Need for additional coordination	Project management	50	2.0	3.2	5.6
	Increase in design and engineering man-hour	Basic design	80	1.2	3.7	5.0
		Detailed design	80	2.0	7.2	17.7
Positive	Reduction in project management manpower	Project management	30	−8.0	−6.5	−3.5
		Fabrication	50	−8.0	−6.8	−4.3
		Construction	40	−15.0	−10.7	−2.1
	Reduction in construction machine operations	Fabrication	30	−15.5	−6.5	−2.0
		Construction	50	−12.0	−10.7	−8.2
	Reduction in on-site labour operations	Construction	80	−18.0	−10.1	−2.0
	Reduction in construction risk	Construction	50	−12.0	−9.2	−3.5
	Increase in field efficiency	Project management	20	−8.0	−6.5	−5.0
		Construction	40	−13.5	−8.0	−5.0
	Reduction in project duration	Fabrication	30	−17.0	−11.0	−.8.0
		Construction	50	−18.9	−7.6	−2.0

3. Case study

This section presents the application of the framework developed. To demonstrate the cost estimation practices, a case study was carried out for an ongoing industrial project. As discussed, the cost estimation procedure differs by module information (previous engineering data) and request to a logistics-specialized company. To illustrate the procedure, the selected case covers all distinctive procedures discussed in this study and is expected to help understand the framework. Additionally, the case project is used to verify the framework for the accuracy of estimated cost through a comparison with the detailed engineers' estimate.

3.1. Overview of the project

The case project is to build a petrochemical plant in Kuwait, in which two Korean and one American construction contractors are participating as a joint venture. The initial estimated cost of the project was approximately five billion dollars and the duration was 45 months. The contract covered every character of expense, including profits and incentives, as well as minor penalties for delays. Modularization was discussed between the owner and contractors in an early stage of the project for three reasons. First, there were low oil prices in the international market in 2016 (Mohaddes & Pesaran, 2017). To avoid a deficit from these low oil prices, getting the project into early opera-

tion was the key. Second, since the joint contractors have insufficient connection with any local sub-contractors, the primary contractors ended up making a contract with local sub-contractors at a high price. Third, the project was located in Kuwait, which is known for harsh environments such as high temperature and hurricanes. The location made the supply of labor and equipment difficult for the contractors to handle. In this study, the case project cost was calculated using two modularization scenarios (assuming different locations of the fabrication shop) and one stick-built scenario, and the cost of each scenario was compared.

3.2. Input of required information

Table 6 shows the required information for cost estimation. For both modularization scenarios, the construction site was Kuwait. The fabrication shops' locations included the Philippines and the UAE in the first scenario, and South Korea and Japan in the second scenario. The costs for each scenario were adjusted by the location of the selected fabrication shops. For calculating the distance from the fabrication shops to the construction site, the author first obtained the nautical miles from SeaRates, which provides shippers and cargo agent with the transportation routes, and then converted the distance to kilometers. The construction cost data for both scenarios in 2016 was chosen as the basis because the case project started at that point. Each national value can be provided by the

Table 6. Modularization scenario information
for cost estimation

Category	Scenario 1	Scenario 2
Point of estimation (year)	2016	2016
Construction site location	Kuwait	Kuwait
$F_{P_{on-site}}$	2.10	2.10
$AR_{on-site}$ (USD/hr)	18.00	18.00
Fabrication shop location (PAUs)	Philippines	South Korea
$F_{L_{off-site}}$	0.90	0.95
$F_{P_{off-site}}$	2.33	1.20
$AR_{off-site}$ (USD/hr)	11.50	34.5
Fabrication shop location (PARs)	UAE	Japan
$F_{L_{off-site}}$	0.96	1.04
$F_{P_{off-site}}$	1.45	1.20
$AR_{off-site}$ (USD/Hr)	21.50	55.5
Distance from fabrication shops to construction site (PAUs)	9,527	11,716
Distance from fabrication shops to construction site (PARs)	824	10,142
$N_{MHr/Ton_{Fab.}}$ (Mhr/ton)	80.00	80.00
$N_{\$USD/Km\cdot Ton_{Trans.}}$ (USD/km·ton)	0.15	0.15
$N_{MHr/Ton_{Inst.}}$ (Mhr/ton)	6.00	6.00

construction cost database (Compass International Inc., 2016a), which presents the minimum through maximum range for the values. These values were manually set to an average value in this study.

3.3. Cost estimation of each scenario

The list of work items for the project was sorted in order to select the representative work items (Step 1). The selection process was conducted in the following two stages: According to the identified reverse order (highest first) of that item's portion of the cost, seven phases were selected (management, engineering, procurement, fabrication, construction, transportation, and installation) with a total of 21 detailed work items. The fabrication, transportation, and installation phases were added for adopting modularization; hence, the quantities and costs were not applicable (N/A) to these phases, as shown in Table 7.

It is important to identify the objectives and criteria for adopting modularization in order to select a modular application area in the case project (Step 2). The case project selected the water treatment facilities for the application area, including hydrogen compression, hydrogen production, sulfur recovery, and interconnecting pipe way. Then, the user calculated the approximate quantities of work items. Table 8 describes the transfer ratio of each selected work item (% MOD) and the estimation proce-

dure for scenarios 1 and 2. The table includes the estimation of work items for the corresponding steps illustrated in Figure 1 and the outcomes acquired from the formulas (Steps 2–7). In this study, the constraints of overland transportation, such as road width, tunnels, bridges, and electric lines, were not considered for the estimation of module transportation because that information during the early stage was largely unavailable.

The final step in the framework was the estimation of the total project cost considering the use of MCS and the cost comparison sheet (Step 9). The simulation iteration was set to 1000 trials with an 80% confidence interval for each factor using @Risk, which can analyze the results in a Microsoft Excel spreadsheet. To calculate the total project cost of scenarios 1 and 2 in the comparison, both the probability and impact of factors from Table 5 were used (Step 8).

Table 9 shows the estimated simulation results along with the stick-built estimate and shows the cost difference between the modular construction (scenarios 1 and 2) and stick-built. Overall, the total project cost for scenario 1 was estimated to be USD 2,716,335,695 and that for scenario 2 was estimated to be USD 2,913,765,768. Based on the simulation results, Scenario 1 had approximately a 5.9% lower estimate than the stick-built estimate with an increase in management, engineering, and procurement phases and decrease in construction phase. The project management cost was increased due to the comprehensive effect of the factors, although there are also positive factors that affect project management. In addition, the construction phase costs were decreased because its work items were transferred into the fabrication shops and manufactured as modules. On the other hand, Scenario 2 had approximately 1.0% higher estimate than the stick-built estimate. Scenario 2 tended to estimate similarly to scenario 1, but the higher estimate in fabrication and transportation may result in increasing total project cost. These outcomes can result from a higher all-in labor rate and farther distance from the fabrication shops to the construction site as compared to scenario 1.

To verify the accuracy of cost estimation, this study compared scenario 1 from the framework with the basic and detailed engineer's cost estimate, which is defined under the same conditions as that in scenario 1 for modularization. This study used a level of accuracy that corresponded to the level of project definition at that early stage. This difference is acceptable considering an accuracy range set to –20% to +30% for early cost estimation compared to the detailed design phase (Christensen et al., 2005). The contractor, who was a participant in the joint venture company in the case project, provided the basic and detailed engineer's estimate for the case project. The basic engineer's estimate was USD 2,765,710,156 and the difference from the scenario was –1.8%. In terms of comparing them in the same phase, this result demonstrated the potential of using this framework in practice. In addition, the detailed engineer's estimate was USD 3,114,395,375 and the difference from the scenario was –12.8%.

Table 7. Breakdown of work items for the case project (step 1)

Phase	Classification	Work item	Unit of measure	Quantity	Cost
Management	Common	Project management	Hour	4,680,064	424,158,000
Engineering	Common	Basic design	Hour	800,460	113,969,000
	Common	Detailed design	Hour	3,644,600	287,986,000
Procurement	Common	Equipment	Ton	23,395	538,085,000
	Common	Structure steel	Ton	33,103	69,516,300
	Common	Piping	Ton	27,552	137,760,000
Fabrication	Modularization	Pre-Assembled Units (PAUs)	Ton	N/A	N/A
	Modularization	Pre-Assembled Racks (PARs)	Ton	N/A	N/A
Construction	Common	Site and civil work	Cubic meter	1,760,631	177,173,100
	Common	Concrete work	Cubic meter	393,353	320,412,138
	Common	Building	Square meter	267,085	199,111,981
	Common	Insulation work	Square meter	64,274	26,655,038
	Common	Fireproofing work	Square meter	46,430	3,784,788
	Common	Structural Steel work	Ton	33,103	46,423,163
	Common	Equipment work	Ton	23,395	49,885,225
	Common	Piping work	Ton	27,552	307,038,225
	Common	Control systems work	Each	10,501	14,870,863
	Common	Paint work	Linear meter	586,416	35,846,850
	Common	Electrical work	Linear meter	6,430,444	133,367,650
Transportation	Modularization	Modules transportation	Kilometer-Ton	N/A	N/A
Installation	Modularization	Modules installation	Ton	N/A	N/A

Table 8. Cost estimation for the case project (Steps 2–7) in scenarios 1 and 2 (US Dollars)

Phase	Work item	Step	% MOD	MOD. Quantity	Remaining stick-built Quantity	Outcome
Common						
Construction	Insulation work	2, 3	70	44,992	19,282	7,996,511
	Fireproofing work	2, 3	25	11,608	34,823	2,838,591
	Structural steel work	2, 3	75	24,827	8,276	11,605,791
	Equipment work	2, 3	20	4,679	18,716	39,908,180
	Piping work	2, 3	75	20,664	6,888	76,759,556
	Control systems work	2, 3	30	3,150	7,351	10,409,604
	Paint work	2, 3	60	351,850	234,566	14,338,740
	Electrical work	2, 3	10	643,044	5,787,400	120,030,885
Scenario 1						
Fabrication	Pre-Assembled Units (PAUs)	3, 4, 5	N/A	23,395	N/A	45,134,570
	Pre-Assembled Racks (PARs)	3, 4, 5	N/A	26,775	N/A	64,106,375
Transportation	Module transportation	PAUs 3, 4, 6	N/A	222,884,165	N/A	45,540,707
		PARs 3, 4, 6	N/A	22,062,600	N/A	5,799,519
Installation	Module installation	3, 4, 7	N/A	50,170	N/A	11,378,613
Scenario 2						
Fabrication	Pre-Assembled Units (PAUs)	3, 4, 5	N/A	23,395	N/A	73,610,028
	Pre-Assembled Racks (PARs)	3, 4, 5	N/A	26,775	N/A	148,364,873
Transportation	Module transportation	PAUs 3, 4, 6	N/A	274,095,820	N/A	54,819,164
		PARs 3, 4, 6	N/A	271,552,050	N/A	54,310,917
Installation	Module installation	3, 4, 7	N/A	50,170	N/A	11,378,613

Table 9. Cost comparison sheet for the case project (Steps 8–9))

Phase	Work items	Stick-built (US$)	Scenario 1 (US$)	Variance (%)	Scenario 2 (US$)	Variance (%)
Management	Project management	424,158,000	437,213,941	3.1	437,838,576	3.2
Engineering	Basic design	113,969,000	118,399,140	3.9	118,359,524	3.9
	Detailed design	287,986,000	320,466,961	11.3	320,333,640	11.2
Procurement	Equipment	538,085,000	538,085,000	0.0	538,085,000	0.0
	Structure steel	69,516,300	79,974,376	15.0	79,953,721	15.0
	Piping	137,760,000	137,760,000	0.0	137,760,000	0.0
Fabrication	PAUs	N/A	46,259,393	N/A	75,427,998	N/A
	PARs	N/A	45,920,608	N/A	151,397,521	N/A
Construction	Site work and civil	177,173,100	177,173,100	0.0	177,173,100	0.0
	Concrete work	320,412,138	320,412,138	0.0	320,412,138	0.0
	Building	199,111,981	190,111,981	−4.5	190,111,981	−4.5
	Insulation work	26,655,038	6,673,205	−75.0	6,669,958	−75.0
	Fireproofing work	3,784,788	2,368,845	−37.4	2,352,818	−37.8
	Structural Steel work	46,423,163	9,685,201	−79.1	9,617,580	−79.3
	Equipment work	49,885,225	33,303,955	−33.2	33,137,197	−33.6
	Piping work	307,038,225	64,056,962	−79.1	63,869,317	−79.2
	Control system work	14,870,863	8,686,965	−41.6	8,629,627	−42.0
	Paint work	35,846,850	11,965,886	−66.6	11,949,711	−66.7
	Electrical work	133,367,650	100,167,512	−24.9	100,624,351	−24.6
Transportation	Modules transportation	N/A	55,401,359	N/A	117,797,610	N/A
Installation	Modules installation	N/A	12,249,167	N/A	12,264,400	N/A
Total project cost ($USD)		2,886,043,321	2,716,335,695	−5.9	2,913,687,149	1.0

According to industry practitioners, uncertainties and risks from application of the modular methods (e.g., complex transportation and installation techniques, the lack of experiences) increased costs and resulted in a significant difference in USD 348,685,219 in engineer estimate. Therefore, it could not be concluded that the result of the estimated value from framework is fully positive, it shows that it could be verified through this case study.

4. Discussion

Several researchers have emphasized that modularization can reduce total project cost and thus have generated considerable interest in that approach as an alternative to stick-built (Barbosa et al., 2017; Choi et al., 2019b; CII, 2002). This study identifies the positive and negative items affecting modularization project cost and evaluates probability and impact of items via expert survey and interview. The estimation of stick-built and modularization methods can be compared using the developed framework. Modularization may not always be cost-effective compared to stick-built, and sometimes caused a cost increase in the case study. However, the results cannot be generalized to the point that the factors do not always occur with the same probability and impact; that could be a result of changing project characteristics and users.

The study results show that the cost of scenario 1 is lower and scenario 2 is higher than the stick-built estimate. Therefore, total project cost can vary depending on the conditions of the fabrication shops and the dependent logistics. In scenario 1, the total project cost is reduced due to the low all-in rate in fabrication shops and short transportation distance for one of them. In scenario 2, though project cost is higher than stick-built, the project can achieve the performance improvement such as short duration and high quality of modules due to high productivity and highly skilled workers. These results support that considering the performance trade-offs such as cost, schedule, and quality is necessary for a successful project when the practitioners are attempting to select the fabrication shops.

To evaluate the influence of the factors on total project cost, a sensitivity analysis was completed by examining the result of the estimation from the framework. The sensitivity analysis allows this study to be more interpretable and provides several scenarios (El Asmar et al., 2009). The analysis results are shown in Figures 2a and 2b. The Tornado diagrams show the cost variation ratio of each project phase, which indicates the influence of factors compared to stick-built. The cost of the construction phases of both scenarios 1 and 2 is subject to the largest variation. Thus, contractors should attempt to manage closely the work items of this phase since it has the highest percentage of costs with the largest variation. The fabrication phase ranks second on the list in scenario 2 because the cost of fabrication in scenario 2 is larger than that in scenario 1. This implies that practitioners should be concerned for the fabrication phase when increasing the modularization

a)

Inputs Ranked By Effect on Output Mean

Construction phase	−4.0569	0.064953
Management phase	−3.1110	−1.0117
Design phase	−2.7110	−0.91556
Fabrication phase	−2.3483	−1.1227
Procurement phase	−2.1747	−1.6440
Transportation phase	−2.0952	−1.6409
Installation phase	−2.0102	−1.6683

Baseline = −1.8876

b)

Inputs Ranked By Effect on Output Mean

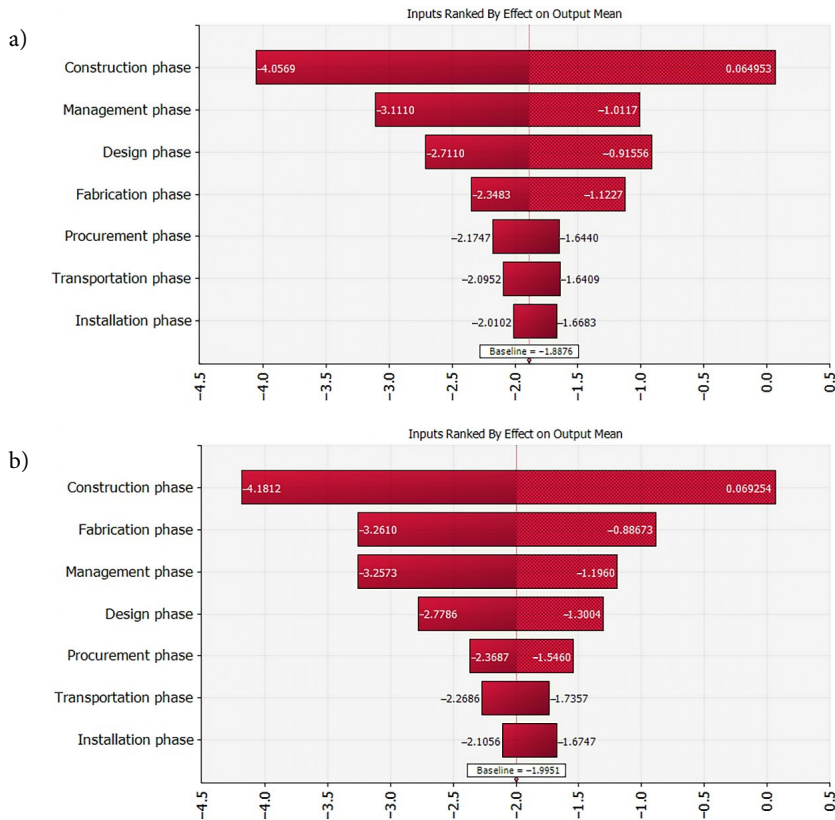|		
Construction phase	−4.1812	0.069254
Fabrication phase	−3.2610	−0.88673
Management phase	−3.2573	−1.1960
Design phase	−2.7786	−1.3004
Procurement phase	−2.3687	−1.5460
Transportation phase	−2.2686	−1.7357
Installation phase	−2.1056	−1.6747

Baseline = −1.9951

Figure 2. Tornado diagram of the cost variation ratio of scenario 1 (a) and 2 (b)

ratio and its cost on their projects. On the contrary, the procurement, transportation, and installation phases do not show a significant cost variation ratio and the ranking remains unchanged. Therefore, these three phases are low priorities for contractors because they are contracted with a specialized company. When contractors make plans for the management scope, the sensitivity analysis results can assist in controlling the project budget.

Conclusions

This paper develops a framework for estimating industrial modular project cost, which allows for appropriate comparisons between stick-built and modularization approaches. The framework supported inexperienced contractors in estimating total project cost, even though they lacked previous experience and design data, by adjusting from the stick-built cost. This research also conducted a case study to demonstrate the applicability of the framework. The framework was verified through comparison with basic engineer's estimates with a difference of −1.8%. Even against detailed engineer's estimates, there was a difference of −12.8%, which was within the expected level of accuracy for this early stage of the project. However, the framework described in this study presents different estimates depending on user input values (Table 5) and there are limitations to generalization from the study: more real data is needed for modeling.

The major contributions of this study can be stated as follows. First, the study attempted to quantify the factors

influencing the differences in cost between modularization and stick-built methods based on practitioners' interviews for the petrochemical project. The probability and impact of each factor were presented to reflect their positive and negative impact. Second, this study compared total project cost and cost changes moving to modularization using the framework developed. The cost estimation framework can support decision making regarding the construction method selection despite a lack of information. It is still difficult to be generalized, but the framework is believed to be the first attempt to use mathematical calculations to incorporate the cost differences in modular construction based on the different selected fabrication shops. Therefore, this study practically contributes to the body of knowledge of conceptual cost estimation for industrial modular projects.

Despite these contributions, this study has several limitations. First, the developed framework was dependent on input by industry practitioners' judgment. Thus, the framework results cannot be completely generalized due to inherent difficulties, such as individual bias. Second, the number of sample projects used to quantify the probability and impact of the influencing factors is small. In addition, these values do not capture the location characteristics of the construction site and fabrication shops. Future studies will concentrate on complementing the requirements of more cases for a generalized framework with large amounts of data. Continuous improvement of the framework is required through the evaluation of various industrial project types. Finally, this study did not

consider how to control the estimated cost, nor how to maximize the modularization. To overcome these limitations, the author's future research will focus on developing a robust cost estimation model applicable to various types of industrial modular projects. It also would be meaningful to analyze the optimal modularization ratio in the specific case where the modularized work items are not properly addressed. Follow-up studies can overcome these limitations and contribute more information for both researchers and practitioners.

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Author contributions

Y.C, C.Y.P and S.H.H conceived and designed the Framework. Y.C collected data, developed the framework, interviewed experts, and wrote the manuscript. C.L and C.Y.P analyzed results and validations and revised the manuscript. S.Y and S.H.H developed the overall idea and revised the manuscript. All authors have read and agreed to the published final manuscript.

Disclosure statement

The authors declare that no conflict of interest exists.

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APPENDIX

Survey for Performance assessment of industrial modular projects

1. Project Information

Project title; Project (Product) type; Host country; Contractor name; Contract price; Contract period; Location of the construction site (country and city); Location of fabrication shops (country and city)

2. Respondent Information

Respondent name; Affiliation; Assigned task at the project; Work experience in the total construction industry; Work experience in the industrial construction industry

3. Criteria and objective of adopting modularization method

Question	Evaluation				
What were the objectives for adopting modularization for your project?	Owner's requirement	Environment damage minimization	Cost reduction	Duration Reduction	Improvement in quality
What were the criteria for adopting the modularization for your project?	Construction process plan	Impossible stick-built construction parts	Repeatability of work	Pursuit of better construction process	Existence of special equipment

4. Quantifying the impact of influence factors on cost in the project

#	Question	Evaluation								
N-1	What was the influenced work items?	The influenced work item		(				)		
	How much was the checked negative factor in the work item compared to stick-built?	factor impact (+)	N/A	1% – 3%	4% – 6%	7% – 9%	10% – 13%	14% – 16%	17% – 19%	More than 20%
P-1	What was the influenced work items?	The influenced work item		(				)		
	How much was the checked positive factor in the work item compared to stick-built?	factor impact (–)	N/A	1% – 3%	4% – 6%	7% – 9%	10% – 13%	14% – 16%	17% – 19%	More than 20%