

## Article

# Integrated Off-Site Construction Design Process including DfMA Considerations

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**Abstract:** Off-site construction (OSC) offers a promising means to improve the efficiency of construction projects. However, the lack of experience and knowledge regarding its use results in errors in design owing to conflicts and omissions of considerations for OSC projects. To mitigate these problems, the design for manufacturing and assembly (DfMA) is widely used to include the considerations in the OSC design process. Several studies concerning the DfMA application in OSC have been performed, but the comprehensive design process is not suggested for mitigating the aforementioned problems. This study proposes an OSC design process by integrating the fragmented DfMA considerations reported in previous studies. The considerations are identified through a systematic literature review and classified into structural and architectural types. To validate the proposed process, an OSC project design has been undertaken as a case study, wherein a significant portion of the building structure has been modified to comprise precast concrete (PC), instead of its reinforced counterpart, with a demonstrated reduction in the PC element design duration. The proposed process would guide and support the design process for reduction in the duration and errors incurred in the process. Moreover, the process can be considered a design guideline for the execution of future projects.

**Keywords:** offsite construction (OSC); precast concrete (PC); design process; DfMA



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## 1. Introduction

Offsite construction (OSC) methods have many benefits, such as a decrease in construction waste, duration, project cost by standardization, and cost variation, in addition to reduced effect on the construction site, as the building elements are produced in factories [1–4]. Despite its benefits, OSC has yet to become a mainstream technique, even in countries that have successfully implemented it [5–7]. Many studies have been conducted to identify the factors hindering the widespread use of OSC, and the problems related to lack of experience and knowledge of the project stakeholders have been identified as the major barriers and constraints [7–11]. These problems caused errors such as omission and conflict in design and the absence of early interventions for essential decision-making [10]. To mitigate these problems, the need for design guidelines related to the OSC process has been emphasized [5,11–13]. The design for manufacturing and assembly (DfMA) principle is widely considered to include manufacturing and assembly considerations in the OSC design process, and several studies have been conducted to incorporate the same in the downstream design processes. However, the fragmented results of the previous studies do not facilitate the development of a comprehensive design process to mitigate the problems encountered in the OSC industry.

To overcome these limitations, the objective of this study is to establish a design process for OSC projects. The process includes considerations related to the features of the OSC method, which are allocated to the sub-design phase to inform the designers of the essential considerations in the appropriate design phase. This process is expected to reduce the errors and changes in the design phase. To achieve the research objective, the

following sub-objective was established. To facilitate the development of such a process, (1) this paper identifies the problems associated with the OSC industry through a literature review, (2) a systematic literature review (SLR) is conducted to identify and classify the essential considerations concerning the DfMA application in OSC projects, and (3) the considerations are allocated to the design process. The developed process is validated by performing a case study on the design of an OSC project. The scope of the process extended from the pre-design phase to construction documentation; it assumed that the project adopts a delivery method that includes OSC specialists as consultants, and the OSC method was considered in the early project planning phase.

## 2. Literature Review

### 2.1. Background of OSC

In literature, various terminologies are used to refer to OSC according to the material used or structure type, such as modular construction [14], modular integrated construction [15], prefabricated prefinished volumetric construction [16], precast construction [17], modern methods of construction [18], prefab construction [12], and industrialized building systems [19]. Moreover, OSC has been considered a promising approach for reducing the negative effects of construction at a designated site [1,3], mitigation of shortage of skilled labor [20], shortened and flexible project duration [14], reduced construction waste [2], application of environment-friendly methods [21], minimization of project cost and cost variation by elements standardization, and by producing elements in an environmentally controlled factory [4]. The benefits of OSC are attributed to the manufacturing of building elements in an environmentally controlled factory. Owing to its benefits, OSC has been implemented in many countries [2,6,9,10,22–24]. To maximize the benefits highlighted in the various project and represent characteristics of each OSC method, the various OSC methods were classified [25].

Nevertheless, OSC is yet to become a mainstream technique owing to certain constraints that overshadow its benefits during the decision-making process [8]. Therefore, the constraints should be mitigated for the widespread application of OSC projects. Many studies have been conducted to identify these constraints. Pasquire, Gibb [8] argued that the selection of the construction method was based on cost-related factors, and the other factors that were difficult to objectively quantify were rarely included in the decision process. To include these factors, the benefits of OSC were classified and a decision-making tool was developed to evaluate the potential benefits and constraints of OSC in projects, including soft issues such as health and safety. Jaillon and Poon [26] surveyed the potential benefits of the use of OSC by experienced professionals in Hong Kong. The environmental, economic, and social benefits were compared with traditional methods, and the limitations of OSC were identified, such as higher project cost, early decision and collaboration, resistance to changes in the construction industry, and difficulties in implementing design changes. Lu [9] identified the major factors driving the use of OSC in the United States; the inability to incorporate changes onsite and limited design options were emphasized as the most significant barriers. To overcome these barriers, it was recommended to train manufacturers, contractors, and designers to improve their knowledge, and collaborate with owners, designers, and contractors in the early phase to reduce the changes. Blismas and Wakefield [10] identified the drivers and constraints of OSC in Australia through qualitative surveys. Skill and knowledge were selected as the factors driving and hindering OSC. In other words, the labor shortage problem can be mitigated by adopting OSC, but the lack of specialized knowledge pertinent to OSC were identified as the greatest issues that restricted its adoption.

Previous studies to identify and overcome the constraints and barriers of OSC have reduced the gap between research and practice. In developed countries, technologies have been developed to implement OSC effectively [5]. Consequently, the number of effectively implemented OSC projects has increased [1,6,23,27]. However, the effectiveness of OSC is still viewed with uncertainty because many OSC projects have failed to meet expectations. Lee and Kim [7] identified the higher cost of OSC as a significant failure factor and derived

the responsible factors for each phase of the OSC project. A sizable number of factors were concerned with workforce-related problems, such as lack of trained and experienced specialists according to the market size and maturity. Wuni and Shen [5] identified the barriers in OSC adoption through literature reviews and classified them into eight groups, including the knowledge barrier. To overcome the knowledge barrier, the role of education and academic institutions was emphasized for decision making in the early planning phase. To identify and evaluate the failure factors, Wuni and Shen [11] conducted a structured questionnaire survey among experts. Limited technical knowledge, capability, and experience were identified as among the four principal barriers. To summarize, while OSC projects have been implemented for decades, the industry continues to suffer from a lack of knowledge, experience, and availability of skilled engineers. Therefore, the barriers related to knowledge and experience should be overcome for the successful implementation of OSC.

## *2.2. Complexity in Design and Planning Phase of OSC Project*

The decision to adopt the OSC method should be taken in the early project phase, and appropriate decisions should be taken to mitigate the risk of failure factors [10]. This requires early advice on the features of OSC from experienced and skilled specialists; several studies have been conducted to mitigate the lack of specialists and to support the early phase of construction. To determine the appropriate level of modularization in the early phase, Sharafi and Rashidi [28] identified the critical decision-making criteria through a literature review and developed a decision-making support system. Using this system, the building elements for prefabrication were selected and compared with the assessment results of the traditional onsite construction method derived from the system, and the level of modularization was evaluated. However, prefabrication of building elements increases the project complexity because the considerations for OSC such as transportation, connection methods, onsite assembly, and lifting of elements should be included in the planning and design of the project [29]. This increased complexity can be attributed to the possible occurrence of design errors, such as omissions and conflicts, and the unresolved errors are manifested as factors that lead to inefficient project execution. These include out-of-sequence deliveries, fabrication, and onsite errors [30]. Using the traditional design process for OSC projects may lead to design errors because the traditional process does not suggest how the information from the OSC stakeholders should be applied [29]. In OSC projects, changes in the planning and design are more difficult to incorporate than in the traditional construction method, and the cost is higher because the integrated prefabrication process should also be revised [31]. Therefore, to deal with significant failure factors such as poor design, inappropriate supply chain management, and late commitment, it is necessary to ensure early advice and planning to manage the entire project process smoothly [5,11,12].

Building information modeling (BIM) has been used as an effective tool to reduce errors and conflicts in OSC projects. To identify prefabrication errors, BIM was used to compare the as-built elements with the building design. Kim and Wang [32] developed a quality inspection system for precast concrete (PC) elements. The quality of the elements was assessed by comparing the BIM design with the point cloud data of the as-built component collected by laser scanning. The quality inspection data were shared with all project stakeholders through BIM. Arashpour and Heidarpour [33] used a laser scanner to identify discrepancies in the prefabricated elements by comparing them with the BIM model. To minimize geometric variability, an optimization model that included a balanced penalty and incentive scheme was used. These studies focused on the quality inspection of the fabricated elements, but a method that can be used in the design phase is required. Gbadamosi and Mahamadu [34] developed a design assessment system using BIM for OSC by following the lean construction principle. Based on the assessment factors, the design was modified and optimized for the OSC project. Alfieri and Seghezzi [35] developed a BIM-based framework, which included an architectural planning process. The framework lists the BIM tasks for a prefabricated bathroom unit according to architectural planning. Owing to the nature of OSC and its complex processes, the effect of BIM is larger than that

in traditional construction methods. Abanda and Tah [36] investigated and quantitatively assessed the effect and emphasized that the lack of understanding of BIM in OSC projects hindered its use. As reported in previous research, BIM is an effective tool for sharing information between participants and finding errors in design and prefabricated elements. However, previous studies have the limitation that the comprehensive design process or design method for OSC projects was not included in the research scope.

### 2.3. Design for Manufacturing and Assembly (DfMA)

In OSC projects, the building is constructed by assembling discrete prefabricated elements that are integrated through standardized interfaces, rules, and specifications [37,38]. For integration, OSC projects require a high degree of planning, which has been considered a significant challenge [10]. To overcome this challenge, DfMA was considered an appropriate design method in the OSC industry. The goal of DfMA is to provide manufacturing and assembly information during the conceptualization stage of the design [13].

Many studies have been conducted to include manufacturing and assembly information in the design phase. Based on a review of related literature, Gao and Jin [39] defined the following perspectives for the adoption of DfMA in OSC: a systematic process, design evaluation model, and prefabrication technology. To integrate the information for manufacturing and assembly into the design process, a project delivery method that can involve project participants in the early design phase should be selected. Charlson and Dimka [40] identified the risks in OSC projects and suggested a procurement model for volumetric offsite manufacturing. Johnsson and Meiling [41] investigated the defects that occurred in prefabricated timber modules and demonstrated that the defects were associated with an inappropriate building system and structural design. The results of the study indicated that the structural transformation in the assembly process should be included in the structural design. Liew and Chua [42] introduced a lightweight steel–concrete composite modular system. In the design phase of the system, general considerations such as materials, structural type, height, and tolerance of units were considered. Alfieri and Seghezzi [35] included the specific considerations of OSC projects, such as prefabricated building structures and mechanical, electrical, and plumbing (MEP), into the architectural planning process. The lean principle has been adopted to reduce the non-value-adding tasks or processes. By reviewing the process of OSC projects, the constraints and limitations can be addressed in the OSC planning and design phase [34,39]. Gbadamosi and Mahamadu [34] developed a BIM-based design assessment system that integrates lean principles such as the repeatability of prefabrication and simplification of the assembly process in the assessment. To evaluate the design in terms of DfMA, Rausch and Nahangi [43] developed a simulation model based on the tolerance distribution statistical data to predict the misalignment of elements. In the system, the building design was decomposed into a subassembly, and the tolerance of connections between the elements was predicted by the model. By adopting the model in the design phase, the building design can be assessed in terms of quality, tolerance, and efficiency of onsite assembly.

Owing to the complexity of an OSC project, information management is required to facilitate communication between project stakeholders. Persson and Malmgren [44] emphasized on the need for information management in the design phase of OSC projects. Their study demonstrated that the lack of interoperability between various software packages used by manufacturers and constructors resulted in delays caused by searching for, sharing, and recreating information in the design process. The results of the case study demonstrated that knowledge of information management was required to customize the system according to the requirements of manufacturing companies and contractors. BIM has been used as an information-sharing technology in OSC projects. Abanda and Tah [36] investigated the usefulness of information management using BIM. However, the benefits of BIM and OSC were not assessed over the entire lifecycle of OSC projects. Previous studies related to DfMA have focused on specific details or aspects of OSC projects. However, to advise in the early design phase and overcome the lack of knowledge and specialists, a

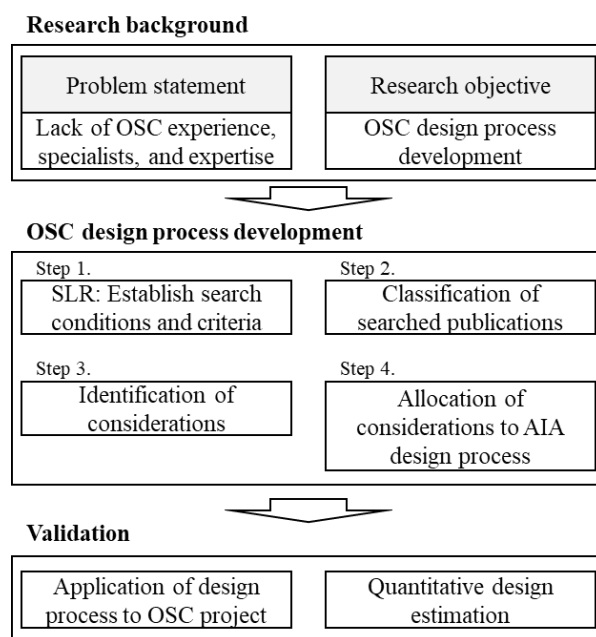
comprehensive design process and guidelines for OSC based on the integrated knowledge from past studies are required.

### 3. Method

To mitigate the lack of experience, knowledge, and specialists in the OSC industry, this research suggests a design process for OSC projects by identifying the considerations that should be integrated into the process. To integrate the fragmented considerations reported in previous studies, a method to search and filter the literature is required. Tranfield and Denyer [45] investigated the review methods that were widely used in evidence-based research, such as those in the field of medical science, and organized the reviewing methods depending on the research topic. In the research, it was emphasized that to address the research question by reviewing relevant literature, the review process should be thorough, unbiased, and rigorous. Systematic literature review (SLR) methods have been widely used for a structured review process, and the trends of studies and directions of future research were identified in various research areas by using this method. Wuni and Shen [5] adopted the SLR method to identify the barriers to the adoption of OSC. To maintain objectivity, the literature collected by using a structured query with a keyword was reviewed. The findings from the reviews were integrated using meta-synthesis. Gao, Jin [39] conducted a literature review related to DfMA by adopting SLR and classified the DfMA into three categories.

Integration of numerous studies is similar to writing a review article in that a broad literature review should be conducted from an unbiased perspective. Therefore, this study adopted the SLR method. As a first step in SLR, relevant studies were searched in Scopus as the search engine because of its wide coverage, accuracy, and ease of retrieval [5,39]. To include publications related to DfMA, keywords such as design for manufacture and assembly, DfMA, design for assembly, design for OSC, design for modular construction, and design for precast concrete were used. Then the keywords were grouped to include studies that focused on considerations after the design phase, such as transportation, element assembly, and lifting. The first group included the subcategories of the OSC method, such as offsite construction, precast concrete, modular construction, and modular integrated construction (MiC). The other group included research topics such as transportation, lifting, and onsite assembly. To search the publications, the keywords in each group were combined, such as transportation in modular construction and onsite assembly of precast concrete.

In the search results, 364 publications related to DfMA and 191 publications related to the considerations in the design phase were identified. The inclusion criteria were as follows: (1) article type of journal, (2) articles written in English, and (3) published articles, i.e., articles that were in press were excluded. Then, the articles were filtered using the following exclusion criteria: (1) general information on DfMA, (2) articles not related to the construction industry, and (3) articles focusing only on the manufacture of specific elements that are not related to the entire building design. Finally, 24 studies were filtered for a literature review to identify the considerations in OSC. Figure 1 shows the steps for developing the OSC design process.



**Figure 1.** Steps for OSC design process development.

#### 4. Considerations in Design Phase for OSC Project

##### 4.1. Considerations in Structural Design

The considerations reported in the publications identified through the search criteria were classified as considerations related to (1) structural design or (2) architectural design. Table 1 shows the studies related to the considerations in structural design. In OSC projects, the size of the prefabricated elements is limited because the size should satisfy the traffic law for transportation and the element should be designed considering the efficiency of lifting and assembly. After transportation, the discrete elements are assembled onsite to construct the building structure; therefore, the structural performance of the assembled elements as the whole building structure should be ensured. To evaluate the performance, many studies have focused on various performance criteria. The origin of anti-seismic research focusing on precast concrete elements can be traced back to the early 1990s [46]. Englekirk [47] investigated the seismic performance of PC buildings and the effect of the connection design between components on the seismic performance. The assembled elements are vulnerable to lateral loads such as seismic loads, and securing the structural performance is a major consideration in OSC projects. Therefore, many studies related to the seismic behavior of an element, performance evaluation of structures obtained by the assembly of the elements, and the connections between the elements have been conducted [46]. Gu and Dong [46] suggested an assembled rebar lap splice and tested the precast and cast in situ shear walls, where the suggested splice was applied by changing the position of the splice and length of the rebar lap in PC shear walls. The test results showed that the seismic performance of the PC shear walls was equivalent to that of cast in situ shear walls. Ding and Ye [48] investigated the seismic performance of a joint between a PC column and girder by using a bolt-connecting system. The experimental results demonstrated that the joint system with bolt connection satisfied the structural requirements and improved the resistance to seismic loading. Feng and Xiong [49] suggested a numerical simulation method for the assessment of the seismic performance of dry connected PC beams and slab assemblies. Wu, Xia [50] investigated the flexural behavior of PC walls and steel shoe composite assemblies with various dry connections. The flexural behavior tests were conducted under five different scenarios, and the results showed that the performance satisfied the requirements regardless of the connection arrangement. In summary, the design of the connection system in prefabricated buildings is a major consideration in structural design because the assembled prefabricated elements are subject to brittle shear

failure during earthquakes and are more sensitive to seismic loading when compared with conventional reinforced concrete (RC) structures.

**Table 1.** Studies related to the considerations in structural design.

Considerations in Structural Design				
Element	Lateral Load	Shear Force	Flexure	Constructability
Joint	[48,49]	[56]	[57]	[42,52,55]
Wall, slab, and column	[46,54]		[50,51]	
Structure	[47,53]			

In addition to lateral loads, connection systems should meet other performance criteria. In the study by Jiang and Zhang [51], the out-of-plane bending performance of a PC hollow core slab with a suggested lateral joint was tested. From the test results, the relationships between the performance and effects of the rib of the slab and the number of joints on the crack of the slab were identified. While assembling the elements onsite, the temporarily connected elements should resist the loads generated during onsite construction. Araújo and Prado [52] focused on the temporary beam-to-column connection during onsite assembly to ensure construction safety. In this study, a beam-to-column connection was suggested, where the U-shaped steel corbel was embedded in the column to support the cantilevered steel tube at the beam extremity. The suggested connection system showed 60% of the theoretical strength of the corbel in the assembly phase, which ensured safety during construction.

In addition to the studies related to the structural performance of element connection systems, studies have been conducted to improve the comprehensive structural performance of whole building structures consisting of prefabricated elements. Dal Lago and Biondini [53] suggested a framework for the structural conception and seismic behavior assessment of PC structures with a cladding panel. The suggested PC structure with a cladding panel showed improved seismic behavior owing to the flexibility of the PC frame and stiffness of the panel. Vertical and horizontal wall connections are considered vital in the PC shear wall structure (PCSW). Horizontal wall connections usually ensure the normal functioning of the PCSW, and the development of a horizontal wall considering constructability and high structural performance is important for the PCSW structures. Wang, Li [54] investigated the seismic performance of precast shear wall structures with suggested horizontal wall connections, and the test results indicated a performance similar to that of the cast in situ concrete shear wall.

In the connection of a 3D volumetric modular unit, the connection system should ensure constructability in addition to satisfying the structural requirements. The lifting and assembly of units at the construction site are considered critical tasks. Therefore, the project efficiency is related to the assembly of large and heavy units. Sharafi and Mortazavi [55] suggested an interlocking system to connect the modular units and tested the structural performance of the proposed system. In addition to satisfactory structural performance, the constructability during onsite assembly was improved by automatically interlocking the units. Liew and Chua [42] suggested a connection system for a high-rise modular building and connected the units via a vertical rod and horizontal tie plate. The system was used to connect the building to an external unit. Lacey and Chen [56] suggested a connection system for modular steel units consisting of structural bolts with interlocking elements. The shear force–slip behavior of the suggested connection was improved when compared with that of the previous interlocking system. In addition to the structural performance, the limitation of small allowable tolerance was mitigated, and the constructability was improved by using bolt connections. Luo and Ding [57] investigated the mechanical performance of beam-to-column connections for steel-framed modular units. The proposed end-plate stiffener connection showed better performance than the other connection types.

In the structural design of an OSC project, discrete elements are assembled to construct a building structure. Owing to the nature of the discrete elements, it is necessary to ensure the following in the structural design phase: (1) the integrity of the elements for the composite behavior to resist various types of loads such as lateral and vertical loads, (2) meeting the structural requirements of the comprehensive building structure after element assembly, and (3) the constructability of the elements during onsite assembly.

#### 4.2. Considerations in Architectural Design

The building design for OSC projects should be separated into elements for transportation and onsite assembly. The constraints related to the nature of the OSC project need to be included in the design. Table 2 lists the studies related to the considerations in architectural design. In modular construction, the building structure consists of 3D-volumetric units and the spaces for the facilities are generated by combining one or more units. However, it has constraints such as heavy weight of the concrete modular units and larger size than the materials used in conventional construction methods. In the study by Liew and Chua [42], the design guidelines for steel–concrete composite high-rise modular buildings were suggested to address these constraints. The steel–concrete composite units have long span, design flexibility owing to the open space framing system, and ease of assembly when compared with concrete units that require in situ grouted joints. Moreover, by using lightweight aggregate concrete, the issues related to heavy weight and fire resistance were mitigated. A high-capacity mobile or tower crane is used to assemble the modular units onsite. Hyun and Park [58] suggested an optimization model for tower crane location by considering the distance between the destination of the units and the locations of the tower crane and trailer at the construction site. The study emphasized that the weight of the units, route of transportation to the tower crane, and trailer parking location should be reviewed in the design phase, and the model can be used to find the optimized tower crane location.

**Table 2.** Studies related to the considerations in architectural design.

Considerations in Architectural Design				
Design Scope				
	Site	Building	Element	Progress Method
Production			[42]	
Transportation			[59–63]	
Onsite assembly	[58]	[64,65]		
Information sharing				[66,67]

Prefabricated elements are usually transported by a trailer. Vibrations during transportation damage the prefabricated elements. The cost of restoring the damage is higher than that of rework in conventional construction methods [29,59]. Therefore, the need for a design procedure to consider non-traditional loads, such as transportation, lifting, and other pre-installation loads, has emerged [60]. In modular construction projects, the effects of vibration are different depending on variables such as speed, road condition, and structural type of the elements and the components of the furnished units. Innella and Bai [59] conducted an experimental study to quantify the acceleration affecting the modular units during transportation. The accelerations of the trailer and units were measured using triaxial accelerometers. Based on the results, the power spectral density, which characterizes the random vibration, was presented according to the speed and road conditions. The mechanical responses of the units during transportation can be calculated using the presented spectra. In a follow-up study, Innella and Bai [60] ascertained that the damage occurrence probability was high in the non-structural elements of modular units such as plaster board and their connections, which are subjected to long cyclic accelerations during transportation. In this study, a framework was developed to evaluate the damage levels of



non-structural elements during transportation according to different parameters such as stress probability, accelerometer position, speed range, and road roughness.

The amount of dynamic loading during transportation depends on parameters such as the amount of load on the trailer, location of the center of mass, trailer suspension type, and level of damping of the vibrating part. Godbole and Lam [61] mentioned that the response behavior of buildings to the loads caused by an earthquake is similar to the behavior of the loads during transportation and investigated the effect of the parameters on the vertical motion of the trailer chassis. The authors suggested the specific vertical acceleration that the mount and its connection to the trailer should withstand and estimated the vertical accelerations that damage the components attached to the unit. In a follow-up study, Godbole and Lam [62] investigated the pounding on trailers caused by the accidental uplifting of a unit during transportation. In this study, a methodology to estimate the impact acceleration resulting from the pounding of a unit on a wooden mount and the response accelerations of the components attached to the unit at the mid-span location were predicted. The prediction results showed that a typical steel unit amplified the component acceleration response up to three times. Previous studies related to unit transportation implied that the design of prefabricated elements such as modular units should consider assembly-related constraints such as weight and size, transportation-related issues such as the deformation of structural components caused by dynamic loads, damage to the non-structural components attached to the unit caused by the transformation, and amplified impact transferred from the structural components. This is in agreement with the study by Bogue [63], who suggested a guideline to reduce damage during transportation and recommended the minimization of the use of fragile parts. These studies indicate the importance of considering assembly and transportation in the design stage of OSC projects.

In OSC projects, the work of enveloping the building structures affects the project performance because the assembled building elements are integrated through the building envelopment. Therefore, novel technologies for envelopment of prefabricated buildings are required. PC panels and cladding have been used to enclose prefabricated and conventional buildings. A prefabricated building envelope is required to be waterproof because the joints of both the prefabricated envelope and building structure, which are connected onsite, are more vulnerable to water problems than cast in situ concrete envelopment. Gorrell [64] investigated the condensation problems that caused damage to the finished materials such as insulation and gypsum boards. In this study, the examples and causes of condensation in PC cladding panels were described and reviewed, which should be included in the design phase to reduce the potential damage from condensation. Orłowski and Shanaka [65] suggested a methodology for designing waterproof seals for prefabricated buildings. They conducted a theoretical review of the generation and transfer of moisture, such as the capillary action of moisture in narrow gaps on the building surface. Then, the considerations for the application of the waterproof seal for prefabricated buildings were identified, such as fast erection time and omission of scaffolding. Based on the theoretical review and considerations, the design details of waterproof seals were suggested and applied to the joints of panelized and modular buildings.

To achieve the goal of design in OSC projects, it is necessary to facilitate collaboration between the project stakeholders. Chen and Lu [66] presented a case study of a curtain wall system designed using a DfMA-oriented approach to meet the requirements of stakeholders such as clients, manufacturers, and contractors, and a multidisciplinary team was organized for the integration of knowledge and experience. The authors recommended that the project delivery method to integrate the team, such as design–build, should be selected, and the stakeholders involved in the design phase need to be identified depending on the project objective. Yuan and Sun [67] argued that although BIM can facilitate information exchange between stakeholders, the existing BIM tools do not fully account for the prefabrication of building elements, such as element production and transportation. In the study, the DfMA approach for prefabricated buildings was integrated with a parametric design method using BIM, and the authors suggested a DfMA-oriented design team, prefabricated element

manufacturing process, and a DfMA-based BIM model development and optimization process. This study described the prefabricated building design process, including the component split from conceptual building design, considering the manufacturability and constructability.

In summary, the design of prefabricated buildings should consider an intermediate process owing to the nature of the OSC project. Many researchers have focused on the transportation aspects of prefabricated units, such as element size limitation set by traffic laws, vibration during transportation, and the use of impact-resistant materials. This means that the space in a building can be separated using the prefabricated elements, and the elements must be able to cope with vibration and deformation during transportation and lifting. Moreover, to consider the assembly at the construction site, the weight of the elements and site layout for facilitating the entry of the trailer should be included in the architectural design. Finally, project delivery methods or information-sharing tools to facilitate OSC project progress are required. Therefore, to support the design process of OSC projects, design guidelines that allocate the considerations for each sub-design phase are required.

### 5. OSC Design Process

The objective of the OSC design process is to support the OSC project stakeholders by sharing the identified considerations for the sub-design process; thus, this process can be used as a design guideline. To develop the process, it is necessary to allocate the considerations to the appropriate design phase to prevent errors such as omissions and conflicts caused by not including the essential considerations. The process is based on the conventional design process of the American Institute of Architects (AIA). AIA provides a checklist consisting of the tasks that should be conducted in each sub-design phase based on the standard form of agreement between the project stakeholders. The scope of the checklist is from the pre-design to construction documentation phase, and the checklist specifies the stakeholders who should be consulted by the designers to conduct the specific tasks in the design phase [68]. For example, in the project programming of the pre-design phase, the architect collaborates with the consultants to determine the preliminary structural, mechanical, and electrical systems. In this phase, the decision making to determine whether the OSC method will be applied can be included by allocating the considerations related to the decision-making process. The suggested process is based on the assumption that the OSC method is considered in the pre-design phase; if it is decided to apply the OSC approach, the project stakeholders will cooperate with the architect to provide consultation for the design, production, transportation, and onsite assembly of the prefabricated elements. The considerations include those reviewed in the previous section and those related to the OSC design and planning mentioned in previous studies. Table 3 presents the OSC design process, including the considerations for the OSC project; the other tasks in the AIA process, which are similarly applicable to the OSC project, are not included in Table 3.

In the pre-design phase, the requirements of the architectural program are reviewed with the owner. Because many studies have argued the importance of the early involvement of the OSC method, the suitability of the OSC method is evaluated in this phase to maximize project efficiency. If the program is suitable for the OSC construction of buildings, such as dormitories and apartments, comprising residential units that can be standardized, the architect supports the decision-making process of the owner based on the identified benefits and constraints [5,8,10,15,16,22,24,31]. After deciding to adopt the OSC method, the architect organizes the design team, including consultants, such as structural, MEP, and special engineers. In the OSC project, the manufacturers and engineers who have experience in or knowledge of OSC are included in the special engineering group to provide advice in the early project phase [69]. At the end of the pre-design phase, the preliminary building systems are determined, and the specific method of OSC (e.g., MiC, PC) is selected based on the consultation and review of previous cases. Before the schematic design phase,

site analysis is conducted and all consulting staff visit the construction site. In this phase, the information for transportation and onsite assembly, such as regulations related to traffic laws, road conditions for transport from potential manufacturing factories, pathways for trailers to approach the site, and potential location of the crane, is collected [29,58].

**Table 3.** OSC design process including considerations for OSC.

Phase	Tasks in AIA Design Process	OSC Design Process		
		ID	Considerations for OSC	Related Studies
Pre-design	Review owner's requirements	1	Evaluate suitability of OSC and support owner's decision-making process	[5,8,10,15,16,22,24,31]
	Organize design and consultant team	2	Include experienced manufacturer and engineer in consultant team	[69]
	Determine preliminary building system	3	Determine the specific OSC method and project delivery method	[66]
Site analysis	All stakeholders visit the construction site	4	Check the site condition for transportation and onsite assembly	[29,58]
Schematic design	Review the laws, codes, and regulations applicable to building	5	Review the laws, codes, and regulations applicable to the selected OSC method	[12]
	Present preliminary design for the owner's approval			
	Select major building systems such as structural and MEP system and determine location and space for the systems			
	Prepare basic schematic design	6	Review the design guideline for OSC	[42]
	Begin research on materials, equipment, fixtures	7	Identify materials that can resist vibration during transportation and assembly	[59,60]
	Determine structural form, design load, materials	8	Consider the load during transportation and assembly	[52,61,62,70]
Design Development	Design typical construction details and layout of building systems	9	Separate building design for element prefabrication in collaboration with designer for split element design	[67]
		10	Consider the constructability for onsite assembly	[42,55]
Construction Documentation	Prepare drawings and specifications for the construction	11	Determine specifications of elements such as size, width, height	
		12	Design the joint for discrete prefabrication of elements considering structural performance requirements and constructability	[46–51,54,56,57,64,65,71]

In the schematic design phase, laws, codes, and regulations applicable to the service of architects and necessary information for the OSC method, such as regulations for transportation and road conditions near the construction site are reviewed. Based on this review, a preliminary design is presented for the owner's approval. After obtaining approval, the tasks in the schematic design are initiated. In this phase, the major building systems to be used in the project, such as structural and MEP systems, are selected through analysis of the comparative systems, and the space and location of the systems are determined based on the requirements. The structural form and design load are determined, and the materials for the interior, exterior, and structure are studied [68]. Therefore, the load caused by transportation, lifting, and assembly should be considered in this phase [61,62,70]. Then a schematic design is prepared, which includes the features of the OSC method, such as repetitive production of elements and allowable span of space [42]. Materials that cannot resist vibrations and shocks during transportation should be excluded from the

design [59,60]. In addition to consulting structural and MEP engineers, the architect draws the architectural design in collaboration with the engineers in the manufacturing unit by considering manufacturability and constructability.

In the design development phase, an approved schematic design is developed. The design documents in this phase include the typical construction details and layouts of the building systems, and they describe the size and features of the architectural, structural, mechanical, electrical, and other elements. The building design is separated into prefabricated elements, which are designed independently to determine their specifications, such as length, width, and height. In the separation process, the building parts to be prefabricated first are identified considering standardization and economic feasibility. For example, certain zones or floors in the architectural program may be excluded from prefabrication. In general, the architectural designs are reviewed for prefabrication of all structural elements. However, if some members are irregular or if the quantity is too small to be prefabricated, it can be evaluated whether the elements are to be constructed using the cast in situ concrete method, whereas non-structural elements, such as the building cladding, can be prefabricated [53]. After identifying the building parts that qualify for prefabrication, the elements of building design, such as beams, slabs, and columns, are split for prefabrication considering their transportation and assembly. Yuan and Sun [67] have recommended that the element-split designers, including the manufacturer and assembly technicians, from the construction company be included during the separation process. These personnel should cooperate with the architectural and structural designers. Additionally, appropriate communication channels must be established between these designers to obtain timely feedback from the stakeholders. The individual elements are assembled onsite; therefore, the constructability of OSC indicates the ease of assembly. In this phase, the details of the connecting system for the elements are prepared.

In the construction document development phase, drawings and specifications are prepared to describe in detail the quality level, performance criteria of materials and systems, and other requirements for the construction. In terms of structural design, the dimensions of the individual elements, such as width, height, and cross-sectional area, are determined. In addition to the size of the elements, the design and performance of the joint connecting the prefabricated elements of the PC structure should also be considered, because the structure is more sensitive to lateral loads, unlike the joint of a traditional reinforced structure. Therefore, in this phase, it should be ensured that the selected joint design can resist lateral loads such as the earthquake loads specified in the structural requirements. At the construction site, the prefabricated elements are assembled according to the joint design. The efficiency of the onsite assembly can be improved by considering the constructability when designing the joint. For example, the PC structural elements are assembled by connecting the rebar of the elements using sleeves or grouting non-shrinkage mortar to the joint, although the connection method differs depending on the joint design. Therefore, it is helpful to improve the constructability to reduce the number of rebars in the elements while preserving the structural performance [71]. After the construction documentation is complete, the manufacturer prepares the drawings for the prefabrication of the elements, and contractors prepare the shop drawings for element assembly based on the construction documentation.

## 6. Case Study

A case study was conducted based on the design of the OSC project to validate the effectiveness of the proposed OSC design process. The Korean government has increased its R&D funds to promote OSC projects. As one of the national R&D projects, the objective of this case study was to construct a complex facility in Seoul by adopting a PC construction method that consists of public housing, welfare facilities for elderly people, and offices for local facility management corporations. Project-relevant data, such as the construction cost, duration, and unpredicted errors, should be collected from the project to improve the efficiency of urban OSC projects. Table 4 presents the information on the project

undertaken in the case study. This project was planned to be built using a traditional construction method and the designs of the design development phase were completed accordingly. However, the construction site was located in an urban area and, thus, the OSC method was considered to suppress the negative impact on the residential area near the site (consideration ID 1 in Table 3). Moreover, to include complex facilities, PC was considered, given that the method makes it relatively easy to construct long span area for commercial facilities compared to the other OSC methods (consideration ID 3). The previous design for the RC method was modified to that for a PC project to achieve the project objectives. Considering the situation in Korea, where the OSC method is not mature, it was decided to apply prefabrication only to the structural elements, and the other building elements, such as MEP and interior and exterior elements, were excluded.

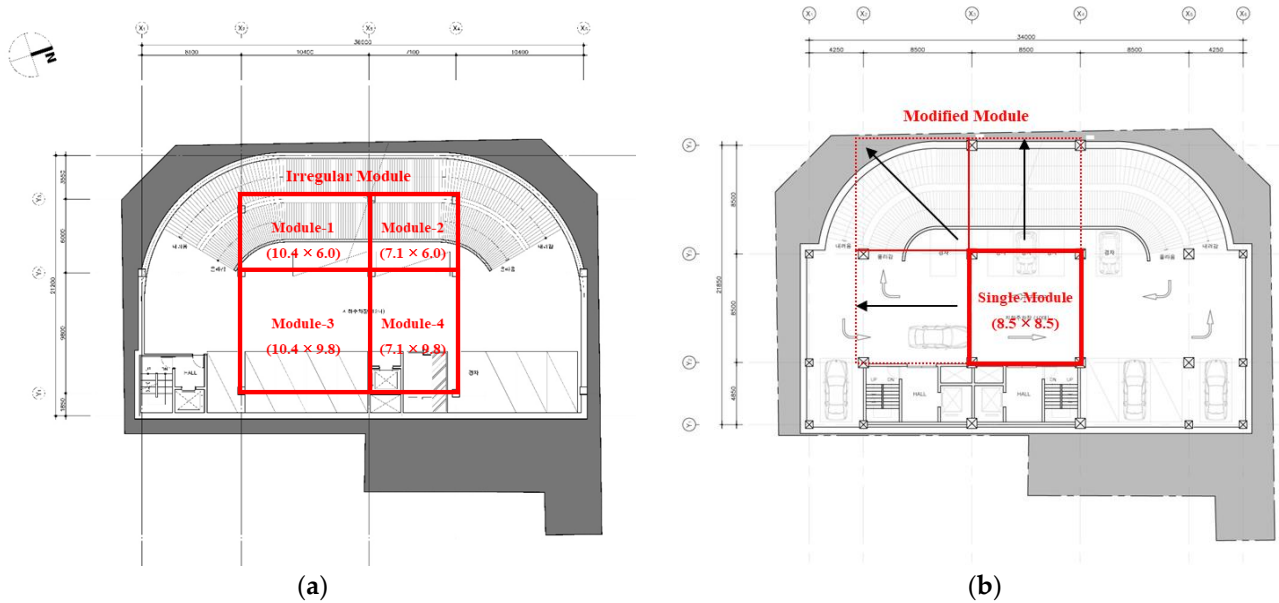
**Table 4.** Case project information.

Project Information	
Location	Yeouidaebang-ro, Yeongdeungpo-gu, Seoul, Korea
Site area	1006.80 m <sup>2</sup>
Floor area	4540.83 m <sup>2</sup>
Floor	10 floors (Basement 3 floors)
Facilities	Public Housing, Welfare facility, Office

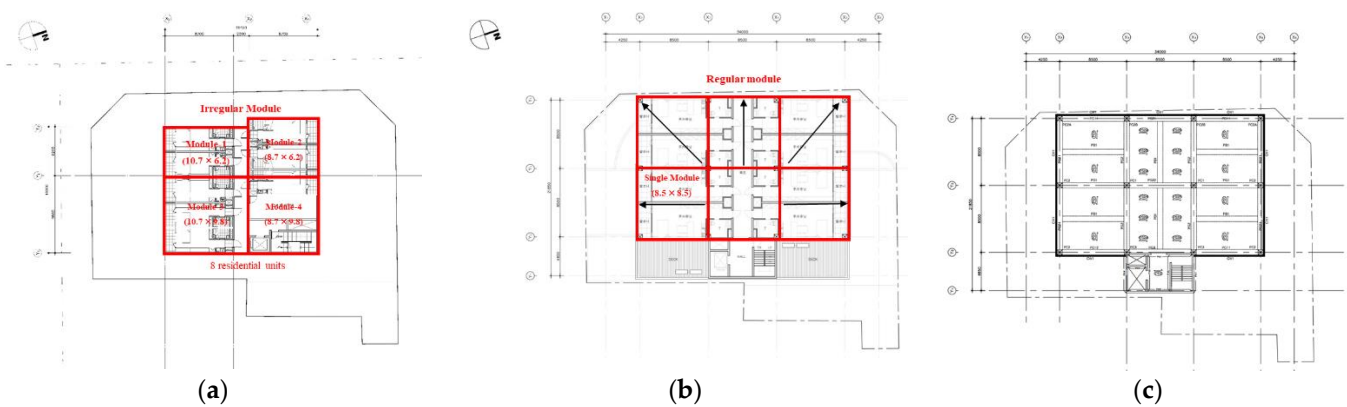
As the first step in the modification, based on the existing design, the scope to which prefabrication would be applied was established by considering the number of elements for repetitive production. The case was planned as a Rahmen structure, and slabs, columns, and girders were included in the scope. Elements that are produced in small quantities, such as the retaining walls of the basement floor, or those that are difficult to produce, such as the ramp of the basement parking lot, were excluded. In terms of standardization, an irregular architectural module was modified to reduce types of the PC elements. Figure 2 shows the architectural drawings of the basement before the modifications and the modified design. To create a regular module, the locations of the columns, cores, and ramps were adjusted. The relocated structural elements were installed at the same position on all floors, so that a regular module could be applied. The modified regular module resulted in the standardization of the elements. Figure 3 shows the floor plan before and after the modification. Figure 3b shows the architectural design of residential units that incorporate the regular design module. By using this module, the irregular shape of floor plan can be modified and the location of structural element from the basement was configured to be the same to improve the manufacturing efficiency. Figure 3c shows an erection drawing representing the standardized PC slab of the repetitive floor plan designed to minimize the element type derivations in the modification process (consideration ID 6 and 9).

When determining the column size, the generation of different column types was predicted owing to differences in the applied column loads and heights of each floor. To mitigate the reduction in manufacturing efficiency owing to the different element types, consultations were conducted with the manufacturer, and it was concluded that the length and width of the column cross sections must remain equal. The PC columns were fabricated using molds set according to the specifications of the columns, and the production cost was directly related to the repetitive use of the set mold. However, the transformation of the mold according to the change in the height of the column does not significantly affect the production efficiency, and the changes in the rebar placement specification of the column are not related to the transformation of the mold. Three types of cross-sectional column designs were created to increase the rate of repetitive use of the molds, and 20 sub-types of columns were prepared by changing the height of the column and rebar placement (consideration ID 6, 10, and 11). Figure 4 shows the examples of the types and sub-types of the columns, and Table 5 presents the specifications of the columns. The column “Sub-Types” in Table 5 indicates the number of types generated from types, and the column “Quantity” indicates the number of columns of each type considered in the

building design. The number of derivations for designing the PC girders was greater than that for the columns. To mitigate the decrease in PC prefabrication efficiency caused by the increased derivations, the cross-sectional designs of the girders were limited to two types, as shown in Table 5.



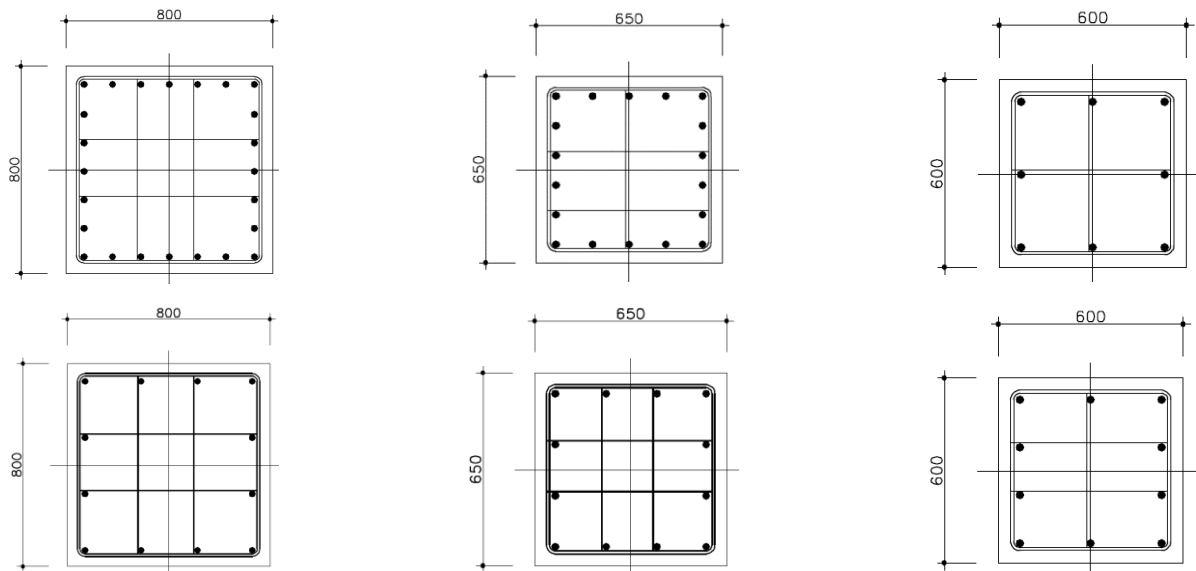
**Figure 2.** Architectural building design modification: (a) architectural design of basement before modification; (b) modified architectural design of basement.



**Figure 3.** Modification for PC slab standardization: (a) floor plan of public housing before modification; (b) floor plan where regular architectural design module is integrated; and (c) standardized PC slab after modification.

In this case study, the PC structural elements were designed and most of the building structures were converted from RC to PC. Table 6 shows the quantities of PC and RC after the conversion. Although the quantity of PC was estimated to be 60%, a significant volume of onsite casting concrete was estimated because, in this case, topping concrete was applied to improve the integrity of the structural elements. Topping concrete was cast on the slab and joints after the installation of the elements. Thus, onsite casting of concrete and rebar placement were required. Improved integrity implies an increase in the structural performance to resist and transmit forces resulting from diaphragm action under lateral loads [72]. The method is also considered to be useful for the tolerance management problems of PC elements because the topping concrete covers all surfaces, including the joint. Moreover, the corrosion occurring in the structure can be alleviated, and problems related to water leakage can be solved (consideration ID 10 and 12). Despite the benefits

of topping concrete, the increased onsite work reduces the efficiency of the OSC project. Therefore, it is necessary to develop a PC method that can mitigate problems such as corrosion, water leakage, and low integrity of structures consisting of all PC elements.



**Figure 4.** Examples of cross-section design of columns.

**Table 5.** Specification of PC columns and girders.

	Types	Size (Width × Length)	Sub-Types	Quantity
Column	Type 1	800 mm × 800 mm	8	44
	Type 2	650 mm × 650 mm	5	76
	Type 3	600 mm × 600 mm	7	38
Girder	Type 1	700 mm × 600 mm	23	262
	Type 2	480 mm × 600 mm	10	34

**Table 6.** Quantity calculations for PC and RC for the building in the case study.

Element	Quantity	Concrete Volume (m <sup>3</sup> )		Quantity of Rebar Installed Onsite (kg)
		Offsite	Onsite	
Column	158	163.97	34.80	
Girder	296	590.59	320.11	40,476.15
Slab	590	508.42	448.07	27,879.93
Joint			21.66	12,866.11
Sum		1262.98 (60.4%)	824.64 (39.6%)	81,222.19

In many OSC projects, the design of prefabricated elements is undertaken during a later phase after construction documentation, which implies a high possibility of design changes. In this case study, the OSC method was applied in the design development phase, and the design modification for the PC structure was conducted based on the suggested OSC design process. In the modification process, the considerations from the design development process such as building design separation for elements produce, design considering on-site productivity, determining element specification considering manufacturing productivity, and the joint between discrete elements were included. By adopting this approach (1) design changes could be reduced, (2) the portion of standardized element can be increased using this module design, and (3) the manufacturing efficiency could be improved by considering DfMA in the early design phase and by communicating with element manufacturer. By applying the suggested design process, a significant portion

of structural elements changed to PC elements. This implies that the efficiency of the design phase in the OSC project will be improved. However, a limitation of this case study is that (1) the design process from the design development phase was applied in this case study because the case study based on the existing design for RC project, (2) only the structural design was considered in the design modification, (3) the considerations that are searched using selected keyword were included, and (4) design processes such as MEP and architectural planning, such as interior and exterior planning, were not validated.

## 7. Discussions

The benefits of OSC have been investigated in many previous studies and projects. However, there are still barriers and limitations to the widespread use of OSC projects. The lack of expertise and knowledge of the project stakeholders were considered major barriers, which resulted in design errors such as omissions and conflicts of information related to the OSC considerations. The errors decreased the project efficiency and caused a negative perception of the OSC method. To mitigate these problems, many studies have emphasized the need for OSC design guidelines. In this research, to meet this need, the design process for the OSC project was suggested, including the considerations for each design phase. To identify the considerations, a comprehensive literature review was conducted, and the considerations were classified into structural and architectural considerations. From the review, it was identified that the structural integrity of discrete prefabricated elements should be ensured because the prefabricated components are susceptible to transfer the lateral load to the other elements. To ensure integrity, the structural considerations were sub-classified according to the element type and external forces on the elements. The other finding was that the elements should be designed considering the efficiency of manufacturing, transportation, and assembly. To improve the efficiency, the architectural considerations were sub-classified according to the scope of design, such as site, building, elements, and the downstream processes of OSC projects such as manufacturing, transportation, and onsite work. Based on the findings, the classified considerations were allocated to the related sub-design phase, which was based on the design process of the AIA.

To validate the suggested process, design modification of the OSC project was conducted as a case study with consultants from OSC engineering and manufacturing companies. In the modification, 60% of the building structure was changed from RC to PC, and 40% of the onsite casting concrete was topping concrete to improve the integrity of the elements. Using the suggested process, the separation of building design for element production was conducted with the consultants by considering DfMA. By involving consultants, the increase in cost and project duration caused by design changes can be reduced. In the case study, the element design was conducted in the schematic design phase. Given that the results of a phase affect the subsequent activities and phases, the involvement of OSC design in the early phase implies that a potential design change was mitigated. The reduction in design changes by adopting the suggested process can be considered a contribution of this research. The second contribution is that it can shorten the project period by shortening the design time for fabrication of the elements. The suggested process can also be used as an OSC project guideline because the project stakeholders lack the necessary expertise to know when and with whom the relevant information should be shared. The limitations of this research are as follows: (1) the design process was developed based on a review of selected publications, and (2) the case study focused on the structural design and excepted other design considerations such as MEP and exterior cladding planning.

## 8. Conclusions

OSC is considered a promising construction method owing to its various benefits, and an increasing number of projects have adopted this method. However, OSC is not a mainstream technique in the industry owing to various limitations and constraints that hinder its widespread use. The lack of expertise and knowledge of project stakeholders were identified as the major limitations. Moreover, these limitations caused errors such as



omissions and conflicts in the design phase, which affected project efficiency and created a negative perception regarding the technique in the construction industry. These problems indicated the need for a design guideline.

To meet this need, this research suggested a design process for an OSC project, which included the considerations related to the features of an OSC project. To identify the considerations, a comprehensive literature review was conducted, and the identified considerations were classified into considerations for structural and architectural design. To develop the design process, the considerations were allocated to the related sub-design process based on the recommendations of the AIA. To validate the suggested process, design modification was conducted as a case study and, as a result of the modification, 60% of the structural elements were converted from RC to PC. Moreover, in the modification, the considerations to be applied at each phase were intended to be reflected in the design process of the case study as follows: (1) the structural elements were standardized by the application of module design (design phase), (2) the design method that included detailed elements without a decrease in manufacturing productivity was suggested (manufacturing phase), and (3) the topping concrete method to increase the integrity between discrete structural element was suggested (on-site assembly phase).

Through this process, the duration for building and element design could be shortened, and the errors in the design phase could be reduced by considering the features of the OSC project and consulting with an OSC engineering company. However, this study has the following limitations: (1) the design process is based on a review of selected publications, (2) the case study focused on the structural and architectural design, (3) other design considerations such as MEP and exterior cladding planning were excluded, (4) some considerations in the process were not included in the case study because it was based on the results of design development phase for RC, and (5) the effectiveness of the suggested process was not quantitatively estimated. In future work, to overcome the limitations, an additional validation will be conducted based on the quantitative project data.

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