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DfMA Integrated Assessment Model for Selecting Optimal Design Alternatives in OSC Projects

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Abstract: To select the optimal design alternative in off-site construction (OSC) projects, the building industry has turned to design for manufacturing and assembly (DfMA). However, most DfMA developments in the OSC field until now have been on improving the production process in OSC projects and guideline strategies on how to apply them. The application of DfMA guidelines only provides background knowledge to designers on how to design. However, it cannot inspect whether the DfMA concept is fully reflected in a design draft to examine the suitability to the OSC production environment, and it cannot determine the optimal alternative from among multiple design alternatives. Thus, this study developed an integrated assessment model of OSC-DfMA consisting of the OSC-DfMA production suitability assessment model and the OSC-DfMA production efficiency assessment model to support decision-making for selecting the optimal design alternative of an OSC project. In this study, the scope of the main research was limited to precast concrete (PC)-based OSC projects. Firstly, we developed an OSC-DfMA production suitability assessment model to review whether design drafts are suitable in the OSC production environment by applying checklist and matrix techniques. Secondly, we developed an OSC-DfMA production efficiency assessment model to select an optimal alternative in terms of production efficiency among multiple design drafts. Thirdly, we conducted a case study to validate the usefulness of the OSC-DfMA assessment model developed in this study. Finally, we discuss the possibility of using AI technology to consider the facility capacity and resource constraints during the production of OSC building components. The study results are of practical value in providing the basis for expanding the applicability of DfMA by proposing a DfMA assessment model suitable for OSC contexts.

Keywords: off-site construction (OSC); design for manufacture and assembly (DfMA); precast concrete (PC); DfMA assessment

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1. Introduction

Traditionally, building production has been on-site and labor intensive, with the majority of raw and manufactured materials being transported to the building site and constructed by workers using equipment. The productivity of this traditional construction production method is declining due to deterioration in the industrial environment, such as the skilled labor shortage and declining skill levels, safety issues for field workers, and rising construction costs. According to the McKinsey Global Institute (2017) [1], the global economy's productivity has grown over the past two decades at an average annual rate of 2.7%, with manufacturing growing at 3.6%, whereas the construction industry has grown at just 1%. Due to low productivity and profitability, a shift in construction production methods is required—from traditional site-built construction (SC) to off-site construction (OSC), which is the focus of the construction industry.

Unlike the existing SC method, the OSC method can improve production efficiency through standardization; modularization; and repeated production in the design and engineering, manufacturing, and construction phases. It has the advantage of securing production quality and safety by reducing outdoor work, so much attention has been directed toward OSC as a solution to the limitations of traditional production methods. Therefore, the adoption of OSC is increasing, particularly in advanced construction companies, such as those in the USA and European nations. Other nations are also making efforts to proactively adopt OSC due to aging among construction workers and a rapid increase in the number of foreign workers.

However, despite the need to introduce and utilize OSC and its advantages, it has not yet fully penetrated the construction market due to factors that hinder its adoption. Scholars studying this problem have found several reasons for this, including the production environment and technical constraints as well as a lack of experience and expertise among project participants [2–7]. This leads to design errors and poor completion quality [3,8], which have been identified as major hindrances. Unlike traditional production methods, the OSC method has many constraints that correspond to production environments and technologies, such as factory facilities, transportation and lifting equipment, and assembly construction methods. Thus, developing design drafts that reflect these constraints and selecting optimal alternatives in terms of production efficiency is important. If the constraints are not properly considered in the design process or optimal alternatives are not selected in terms of production efficiency, fatal impacts due to delayed production caused by redesign and rework, occupational safety, and production quality degradation, among others, may result.

To remediate these problems, developing optimal design drafts by considering the suitability of the production process (manufacturing, transportation, on-site assembly, and maintenance) and selecting optimal design alternatives that have high production efficiency are critical. To achieve optimal design drafts in OSC projects, the building industry has turned to design for manufacturing and assembly (DfMA). DfMA is a concept developed to minimize design changes in the manufacturing industry. This design approach prevents potential errors in the production and assembly phases by inspecting various circumstances related to the production phase in advance of the design phase by applying the concurrent engineering concept. Many companies in the manufacturing sector have seen productivity gains and quality improvements, among others, by applying DfMA.

Similarly, the need to consider construction and maintenance processes in the design phase by applying the DfMA concept has been recognized in the building industry, and the effect of applying DfMA has been predicted to be greater in the case of OSC production methods that aim for modularization and standardized production than in conventional production methods. Accordingly, Singapore, the UK, and the USA, who are more advanced in OSC, have leveraged the DfMA concept to propose DfMA guidelines and strategies that are suitable to the characteristics of OSC industries, and research on how to incorporate DfMA in the building industry is underway. However, most DfMA developments in the OSC field until now have been explanations on how to conduct production in OSC projects and strategy guidelines on applying DfMA. However, the limitation of applying DfMA as a guideline is that it simply provides designers with background knowledge on how to design, but it does not clearly identify and itemize what must be considered in the design, which can be confusing for project participants. In addition, project participants cannot review whether the design fully reflects the DfMA concept and is suitable for the OSC production environment nor identify the optimal alternative among multiple design alternatives.

Thus, this study develops an OSC-DfMA integrated assessment model consisting of an OSC-DfMA production suitability assessment model and an OSC-DfMA production efficiency assessment model to support decision-making for selecting the optimal design of an OSC using the derived DfMA evaluation items. Then, we conducted a case study to validate the usefulness of the integrated OSC-DfMA assessment model developed in this study. In addition, we explored the applicability of AI technology so as to see if it can further consider the capacity of production facilities based on resource constraints during OSC building component production in a factory.

This study limits the scope of OSC projects to PC-based OSC projects. OSC projects can be classified according to the size and shape of the basic units that make up the building, materials used, and prefabrication degree. Furthermore, this study is limited to the modular method of PC members in line/plane shape (wall, slab, column, girder, and beam) to develop an OSC-DfMA assessment model that is suitable for the PC-based OSC industry. Another limitation of this study is that implementing the discussed AI-enabled model for production capacity checking is left for follow-up research.

This study is structured as follows. In Section 2, we explain the verification method and target project used in this study. In Section 3, we first review existing OSC studies related to success and the associated obstacles to understand why deriving an optimal design is essential for OSC. We analyze the development and application status of DfMA as a concept that can support OSC and present the novelty of our study by reviewing similar studies. Second, we develop detailed models of the OSC-DfMA assessment model, which include the OSC-DfMA productive suitability evaluation model and the OSC-DfMA productive efficiency evaluation model and present the OSC-DfMA integrated evaluation model. Third, we apply the developed OSC-DfMA integrated evaluation model to a PC-based OSC project case and verify the usefulness of the evaluation model through expert interviews. In Section 4, we discuss a conceptual model for production capacity checking that combines the integrated assessment model of OSC-DfMA, BIM, and AI. We then discuss the applicability of the proposed conceptual model based on the literature and previous studies. In Section 5, we summarize our findings and discuss the academic and practical implications of our research. Additionally, we present the limitations of this study and discuss future research.

2. Materials and Methods

- Target Project

The target case used in this study is a Rahmen structure apartment built with PC, which consists of one basement and seven floors above ground located in Chungcheong-do. The overview of the target project is summarized in Table 1.

Table 1. Target project overview for the case study.

Category	Contents
Project type	Apartment Buildings Adopting PC Composite Rahmen Structure
Construction period	December 2019~July 2022
Household size	36 m^2
Number of floors	7 stories (B1~7F) (floor height: 4.9 m underground; 25.5 m above ground)
Number of households	36
Material of structural members	• Concrete: PC slab, girder, beam, wall 27 MPa/column 40 MPa/cast-in-place concrete 24 MPa • Reinforcing bar: D13 and under SD 500, D16 and over SD600
Structural members	• Half PC Slab - Household, Stairwell, and Bathroom: 1800 mm (PC t = 70 mm) - Hallway: 250 mm (PC t = 70 mm) • Girder: Depths 540, 600, 700, and 800 mm • Beam: Depth 600 mm • Solid Wall - Core wall: t = 200 mm - Side wall: t = 150 mm
Application of precast concrete	• Main structure, core (wall, stairs) • Side wall (exterior wall) • Entrance wall • Non-extended balcony wall (exterior wall) • Expandable balcony (wall + window)

- Method for the Integrated Assessment Model of OSC-DfMA

To verify the usability of the integrated assessment model of OSC-DfMA proposed in this study, experts were instructed to perform an OSC-DfMA production suitability and efficiency assessment based on the design and plan, confirming that such an evaluation is feasible. Additionally, to verify the usefulness of the proposed model in this study, expert interviews were conducted face-to-face from 9 to 13 May 2022 with three experts (in PC structural design, PC manufacturing and construction, and PC architectural design) with more than 15 years of experience (Table 2).

Table 2. Summary description of experts.

Experts	Specialized Field	Experience
Expert A	PC Structural Design	19 years
Expert B	PC Manufacturing and Construction	35 years
Expert C	PC Architectural Design	16 years

3. Results

3.1. Literature Review

3.1.1. Necessity of Design Optimization to Activate OSC

OSC as a solution to the productivity problem in the current site-built construction has garnered considerable attention. OSC has been defined variably by many institutions and scholars, but it is generally defined as a method of construction production that departs from traditional site-built production, in which building elements are planned, produced, and assembled at a location such as a factory rather than at the building site and then transported to the site for installation and construction [9–11]. The term encompasses similar concepts, such as prefabricated construction, industrialized construction, modular construction, panelized construction, off-site prefabrication, off-site manufacturing, and modern methods of construction that involve producing and assembling construction materials in a factory.

As defined above, the OSC production method differs from conventional on-site production methods and has several expected benefits. First, unlike the on-site production method, the OSC production method can reduce costs and save time through standardization, modularization, and repeated production in the design and engineering, manufacturing, and construction phases [11,12]. In addition, unlike conventional production methods, OSC can improve working conditions because most of the production activities are performed in a controlled environment, such as a factory, which can improve construction quality and safety, reduce rework, reduce waste, and secure sustainability and reliability [13–15]. Moreover, with the adoption of the OSC method increasing, skilled laborers in construction will change from simple labor to complex operation, which is expected to lead to an improvement in work productivity and an increase in the influx of new skilled laborers.

Therefore, studies on various technologies and management measures that can be applied to planning, designing, off-site manufacturing, transportation, and on-site assembly phases have been conducted to improve the adoption and utility of OSC. Among OSC design phase-related studies, we conducted an in-depth review of studies related to optimal designs [16–20]. It revealed that many studies suggest that the design phase of OSCs should consider the suitability for OSC production environments by incorporating considerations related to production environments, such as transportation and lifting conditions, and considerations related to production safety and quality, such as safety and energy efficiency, into the design. Furthermore, many studies suggest that considerations directly related to production efficiency, such as module size, the number of joint points, and equipment use, should be incorporated into the design to identify the optimal alternative. Thus, in this study, the optimal OSC design is defined as a design that reflects considerations related to the entire production process (off-site manufacturing, transportation, on-site assembly, and maintenance) of OSC in a given production environment (off-site and on-site facilities), thus enabling suitable production in terms of production availability, production safety, production quality, and high production efficiency.

3.1.2. DfMA Applicability for OSC

DfMA was developed to minimize design changes in the manufacturing industry. It is a design approach for preventing potential errors in the production and assembly phases by inspecting various circumstances related to the product production phase in advance during the design phase by applying the concurrent engineering concept. In manufacturing, DfMA principles such as minimizing the number of typical parts, simplifying handling, and standardizing are employed in the design process in a variety of ways. If these DfMA principles in manufacturing are applied to OSC, they can be translated and leveraged to consider production conditions and work hazards, minimize the breakage of parts, ensure the quality of connections, minimize the number of parts, standardize parts, consider the reusability of parts, minimize additional work, and simplify assembly and handling methods.

It is understood that DfMA in manufacturing can be developed in the form of guidelines and provided to designers to reflect DfMA throughout the design process to communicate the content that should be reflected in the design. Alternatively, it can be developed in the form of a checklist to evaluate whether DfMA items should be reflected in the design. Moreover, DfMA is used when the proposed design is applied to the production process, and a method that can predict and evaluate the work efficiency of the proposed design is also now under development. Therefore, DfMA can be used to determine whether an OSC project is optimally designed, and for DfMA-based optimal design assessment, assessment items should be developed based on DfMA principles.

In the construction industry, we also found that OSC-leading countries, such as Singapore, the UK, and Hong Kong, are proposing design standards and guidelines that apply DfMA concepts at the government level, and several other researchers are conducting research on incorporating DfMA into the construction industry. Singapore is one of the leading countries seeking to improve the productivity of the construction industry in a public-led manner, and the Building and Construction Authority (BCA) in Singapore selected DfMA as one of three key areas for construction industry innovation in the Construction Industry Transformation Map (2017) [21]. In addition, active efforts are being made to revitalize OSC projects by making it mandatory to use public order projects in the DfMA method, presenting guidelines for project performance technologies, and supporting R&D. On the other hand, the Royal Institute of British Architects (RIBA) in the UK has suggested that the application of DfMA to the construction industry yields effects such as 20–60% air reduction, 20–40% construction cost reduction, 70% or more reduction in field labor, quality improvement, enhanced safety, and reduced construction waste [22,23]. Additionally, the Construction Industry Council (CIC) in Hong Kong has provided guidelines for reviewing the legal requirements of Hong Kong's Modular Integrated Construction (MiC) project, aimed at facilitating its implementation [24].

Most existing DfMAs in the construction industry are in the form of guidelines that describe how the production process of OSC projects should be conducted. However, this approach to DfMA has limitations in that it only provides designers with background knowledge on how to design. In addition, the DfMA contents that must be considered in the design are not itemized, and many project participants, including the project owner, cannot review the designer's proposed design to ensure that it is consistent with the DfMA concept.

In academia, research on the application of DfMA to the construction industry began in the late 1990s and early 2000s, and many DfMA-related studies have been conducted since the late 2010s, during which OSC began to gain attention. On the one hand, studies on the analysis of cases applying DfMA and verification of the application effects of DfMA [25,26] have been conducted. These studies aimed to analyze the application effects of DfMA through case studies. On the other hand, the present study is novel in that it develops a DfMA assessment model for design optimization and conducts case studies to verify the usefulness of the assessment model. Additionally, several studies [8,27–32] have proposed the application of DfMA to OSC projects. These studies aimed to propose development directions for applying DfMA principles used in the manufacturing sector to the construction sector, but the present study is novel in that it derived specific DfMA assessment items and used these to develop a DfMA assessment model. Finally, studies to propose assessment methods using DfMA have been conducted to select optimal alternatives for OSC projects [19,33]. These studies contribute to identifying the evaluation factors of DfMA as it relates to production efficiency, including the number of components and assembly time, and using these to propose an alternative design assessment method. However, for an optimal design that minimizes design changes by minimizing design errors in OSC, although it is important to know which design alternatives are better in terms of production efficiency, whether the design alternative is suitable for the OSC production environment should be determined first in the process of generating design alternatives. Accordingly, in this study, DfMA assessment items are derived by dividing items according to production suitability (production availability, production safety, and production quality) and production efficiency. Then, the production suitability assessment method that can be utilized for generating design alternatives and the production efficiency assessment method that can be utilized for selecting design alternatives are presented to confirm the novelty of this study.

3.2. Integrated Assessment Model of OSC-DfMA

3.2.1. Overview of the Proposed Model

In this study, we aim to propose an OSC-DfMA integrated assessment model to support decision-making on the selection of an optimal OSC design to prevent redesign by overcoming the limitation of the DfMA application method in the existing OSC field. Therefore, we propose an OSC-DfMA integrated assessment model by deriving specific process-based OSC-DfMA assessment items that reflect the requirements of OSC optimal design and DfMA principles projected onto the production process of OSC and presenting an assessment method that reflects these.

The OSC-DfMA integrated assessment model is composed of two detailed models: the OSC-DfMA production suitability assessment model and the OSC-DfMA production efficiency assessment model, as shown in Figure 1. First, the OSC-DfMA production suitability assessment model is an assessment model that evaluates the DfMA conformity of a design by evaluating whether and what items related to production availability, production safety, and production quality are reflected among the OSC-DfMA assessment items. The OSC-DfMA production suitability assessment model supports designers in self-reviewing their own designs by utilizing the DfMA checklist for DfMA conformity after design completion and contributes to improving the reliability of the design by creating a detailed assessment of each item as a DfMA review report and submitting it to the assessor. Additionally, the OSC-DfMA production efficiency assessment model evaluates the degree of DfMA reflection in a design using items related to production efficiency among OSC-DfMA assessment items. The OSC-DfMA production efficiency assessment is used to derive the optimal design plan by comparing alternatives based on OSC-DfMA production efficiency assessment items when multiple design plans exist through the combination and division of modules.

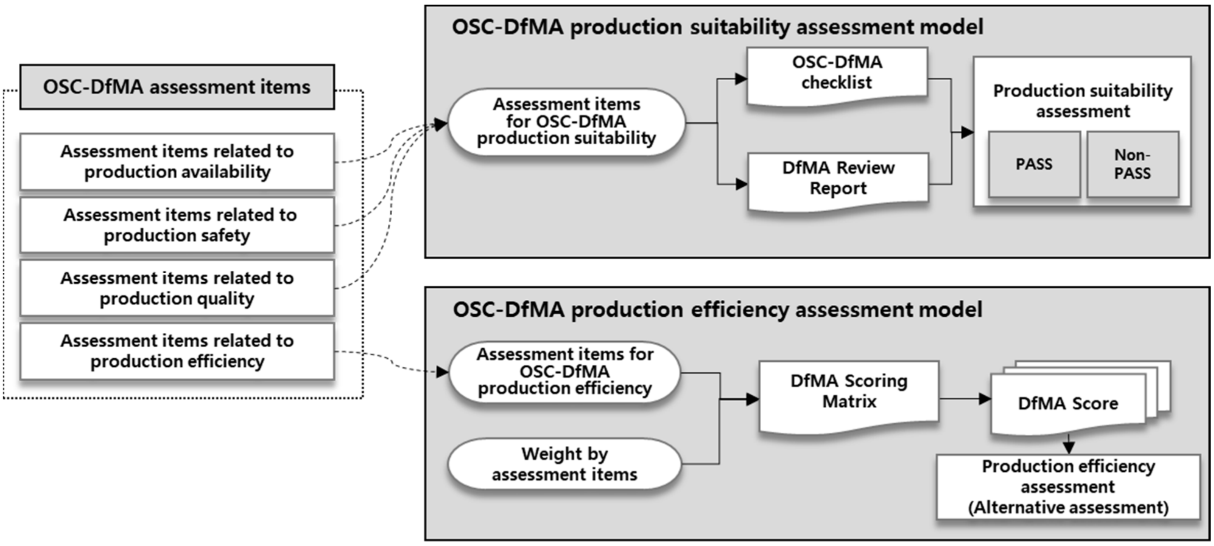


Figure 1. Concept of the OSC-DfMA integrated assessment model.

OSC-DfMA assessment items are those that make up the OSC-DfMA production suitability assessment model and OSC-DfMA production efficiency assessment model, which represents the items that should be considered for the optimal design of OSC projects (see Figure 2).

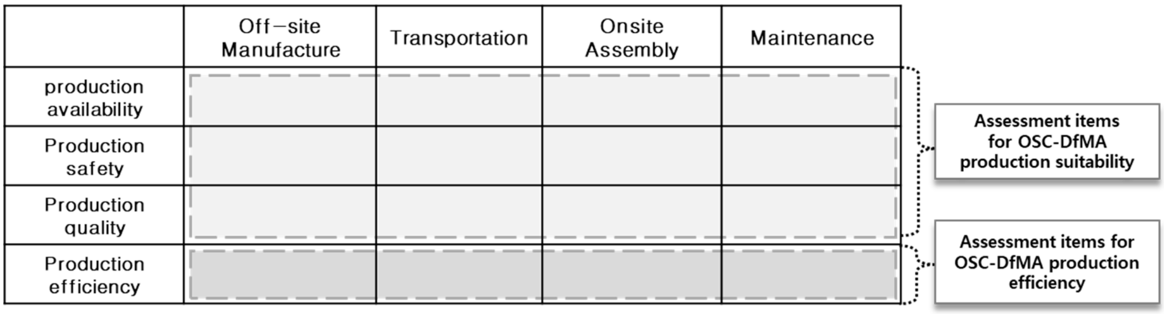


Figure 2. Composition of the OSC-DfMA assessment items.

3.2.2. Assessment Items of OSC-DfMA

In the authors' previous study [34], OSC-DfMA evaluation items were derived by combining a systematic literature review, structured interviews, and content validity analysis methods. Among the total assessment items, the OSC-DfMA production efficiency assessment model was developed based on the relative comparison of each assessment item between design alternatives, so it is composed of items that can be assessed relative to each assessment item as follows: manufacturability (MF), deliverability (DL), assemblability (AS), and maintainability (MT). The OCS-DfMA production suitability and efficiency assessment items used in this study are presented in Tables 3 and 4.

Table 3. Assessment items for OSC-DfMA production suitability [34].

No.	Assessment Items
A1	Have you reviewed the size/weight/shape/configuration of the module in consideration of the manufacturing facilities (such as lifting equipment) at the factory?
A2	Was the tolerance for factory production presented?
A3	Have you reviewed possible safety issues in the production process of the factory?
A4	Have you reviewed the location of the lifting point and the balance of the module during lifting?
A5	Have you reviewed the curing measures for the PC module?
A6	Have you reviewed the structural performance (including stress and deformation) of the lifting point designated for each module?
A7	Have you provided the loading conditions (type, position, and spacing of the pedestal)?
A8	Have you reviewed the structural performance of the fixing device (anchor bolt) installed at the lifting point?
A9	Have you reviewed the possibility of module deformation, cracks, and partial breakage during the factory manufacturing process?
A10	Have you reviewed the performance (position and route) of the piping connection for water supply, drainage, and sanitation facilities?
A11	Have you designed considering the application of an appropriate ventilation system?
A12	Have you reviewed the performance of plumbing connections for electrical and telecommunication facilities?
B1	Have you reviewed the size/weight/configuration of the module in consideration of transportation equipment?
B2	Have you reviewed the size/weight/configuration of the module in consideration of road conditions inside and outside the site?
B3	Have you chosen the size/weight/configuration of the module in consideration of the Road Traffic Act?
B4	Have you reviewed possible safety issues during the transport process and presented a transport method that can ensure stable transport?
B5	Have you reviewed the possibility of module deformation, cracks, and partial breakage during the transport process?
C1	Have you considered the size/weight/configuration of the module in consideration of the lifting equipment on the site?
C2	Have you reviewed the size/weight/configuration of the module in consideration of the field layout of the lifting equipment?
C3	Have you properly planned the temporary work of the junction joining method between modules?
C4	Have you simulated the configuration of all junctions between modules in advance?
C5	Have you considered the construction error of the junction?
C6	Have you reviewed the workers' accessibility to the junction point?
C7	Have you presented an open-storage method, by reviewing possible safety issues during open-storage work?
C8	Have you established a lifting plan, by reviewing possible safety issues during lifting?
C9	Have you established a joining plan, by examining possible safety issues during the joining process?
C10	Have you reviewed the possibility of deformation, cracks, and partial breakage of the module during on-site work (including open storage, lifting, and joining)?
C11	Have you selected the joining method in consideration of the junction spacing and the level of stress?
C12	Have you reviewed the structural performance of the module junction?
C13	Have you reviewed the use performance (including watertightness, fire resistance, durability, insulation, and sound insulation) of the module junction?
C14	Have you reviewed the ease of vertical/horizontal adjustment of the joining method between modules? (Is it easy to adjust?)
C15	Have you applied a joining material (such as grouting material or hardware) that can ensure good performance against chemical and physical influences?
D1	Have you reviewed the location of periodic maintenance activities (including electricity, firefighting, gas, water supply, and rescue) conducted during the building-use phase to minimize user inconvenience?
D2	Have you checked and repaired defects (including cracks and leaks) of the junction during the building-use phase?
D3	Have you considered increasing the durability of modules and junctions?

A: off-site manufacturing phase, B: transportation phase, C: on-site assembly phase, D: maintenance phase.

Table 4. Assessment items for OSC-DfMA production efficiency [34].

No.	Assessment Items
MF1	The number of mold types
MF2	Reusability of the mold
MF3	The number of module types
MF4	The total number of modules
MF5	Module size and weight
MF6	The difficulty of manufacturing the module
DL1	Number of module types
DL2	Total number of modules
DL3	Module size and weight
DL4	The number of types of transportation equipment
DL5	Whether special transportation equipment is needed
AS1	The number of module types
AS2	The total number of modules
AS3	Module size and weight
AS4	The number of junction points
AS5	Number of joint method types
AS6	Joint difficulty
AS7	Protection management of the joints and whether additional finishing work is needed
MT1	Accessibility to the joint
MT2	The difficulty of joint maintenance
MT3	Ease of remodeling

MF: manufacturability, DL: deliverability, AS: assemblability, MT: maintainability.

3.2.3. Assessment Method of OSC-DfMA

The OSC-DfMA integrated assessment model, which is the main contribution of this study, is largely divided into two models: OSC-DfMA production suitability and production efficiency assessment models. Because each of the detailed assessment models has different assessment items and purposes, the assessment method applied needs to be applied separately according to the characteristics of the assessment model. Thus, in this study, we selected an assessment method by considering the characteristics of each detailed assessment model.

(1) OSC-DfMA production suitability assessment

The OSC-DfMA production suitability assessment model refers to an assessment model for evaluating whether an OSC design plan is a suitable design for an OSC production environment by determining whether and what items related to production availability, production safety, and production quality are reflected among the OSC-DfMA assessment items. The OSC-DfMA production suitability assessment model aims to ensure the quality of the design plan by allowing the designer to self-evaluate the production suitability of the design plans and report the review results for each assessment item. Thus, in this study, a checklist method, which is effective for reviewing important contents without omission, is applied as the assessment method of the OSC-DfMA production suitability assessment model. The DfMA checklist is assessed via the pass/nonpass method for each item, and all items should be passed in principle. The OSC-DfMA production suitability checklist is developed in such a way that designers can report the results of assessing the DfMA conformity of their design plans for each item through the OSC-DfMA production suitability checklist to validate the rationales for evaluating the checklist.

(2) OSC-DfMA production efficiency assessment

The OSC-DfMA production efficiency assessment model refers to an assessment model for selecting the optimal design plan by ranking design alternatives using the items related to production efficiency among the OSC-DfMA assessment items. The OSC-DfMA production efficiency assessment model is intended for use in selecting the optimal alternative by comparing design alternatives by assessing items. Thus, the matrix assessment method, which is effective for selecting optimal alternatives, was used in this study. The matrix assessment method generally involves five steps (assessment item development, weight assignment, scoring for each alternative, calculation of weight score, and discussion of results). In this study, the analytic hierarchy process (AHP) was used to quantify weights for the matrix assessment. AHP is useful for efficient weighting in the case of multiple and complex evaluation criteria. In addition, because the OSC-DfMA production efficiency assessment model presented in this study involves ranking alternatives, the forced ranking method was applied as a scoring method for each alternative. The forced ranking method involves ranking alternatives against each other and assigning a score according to the rank rather than assigning a score based on standardized criteria. If the actual performance data of the OSC project are fully available, the assessment criteria for each item can be set up by analyzing and standardizing the performance data for each item, but if the performance data are not available, it is inevitable to assess alternatives relatively, so this study established the assessment criteria for each item via the forced ranking method. The range of the assignable assessment scores varies according to the number of alternatives, and the lowest score starts from 1. If there are n design alternatives, n points are assigned to the alternative that best reflects the assessment items, and then $n - 1$, $n - 2$, . . ., and 1 point are assigned to the subsequent rankings. Here, if duplicate rankings (ties) occur during the ranking process for a specific item, points should be awarded in the following manner. Initially, if there are duplicate rankings for all alternatives, the score for that item should be assigned 1 point per alternative to minimize the impact of that item on the overall score. In another case, if only some of the alternatives have duplicate rankings, the duplicate-ranked alternatives should be scored by giving them the same top ranking, and subsequent rankings should not be affected by the duplicate ranking. For example, if there are three alternatives (Alternatives A, B, and C) and Alternative A and Alternative B have a duplicate ranking of the first rank, then Alternative A and Alternative B should be assigned first rank and Alternative C should be assigned third rank, giving Alternative A and Alternative B three points each and Alternative C one point.

The assessment results for each item are entered in the "Score" column of the DfMA scoring matrix. Once the weight for each assessment item is reflected in the score for each assessed item, a weighted score can be calculated for each item, and the calculated results are entered in the "Weighted Score (W.S.)" column in the DfMA scoring matrix. In this way, the calculated score and weighted score are summed for each detailed assessment item, and each manufacturability, deliverability, assemblability, and maintainability score can be calculated. In addition, the sum of the manufacturability, deliverability, assemblability, and maintainability scores for each alternative will be the "DfMA Score", and the optimal alternative is selected by comparing the DfMA scores.

3.2.4. Utilization of the OSC-DfMA Assessment Model

The OSC-DfMA assessment model can be used for (1) alternative assessment during the design process, (2) self-assessment of the production suitability of the design plan after design completion, (3) qualitative assessment of the DfMA reflection results of the design plan, and (4) alternative assessment for the selection of a designer, as shown in Figure 3, and can be used in the following order.

Alternative assessment during the design process: If multiple design plans are present in the design process through the combination and division of modules, scores are assigned in the DfMA scoring matrix by comparing alternatives via the DfMA production efficiency assessment items, and the scores for each item are summed to calculate the DfMA score for each alternative. After comparing the DfMA score for each calculated alternative, the one with the highest score is selected as the optimal design plan.

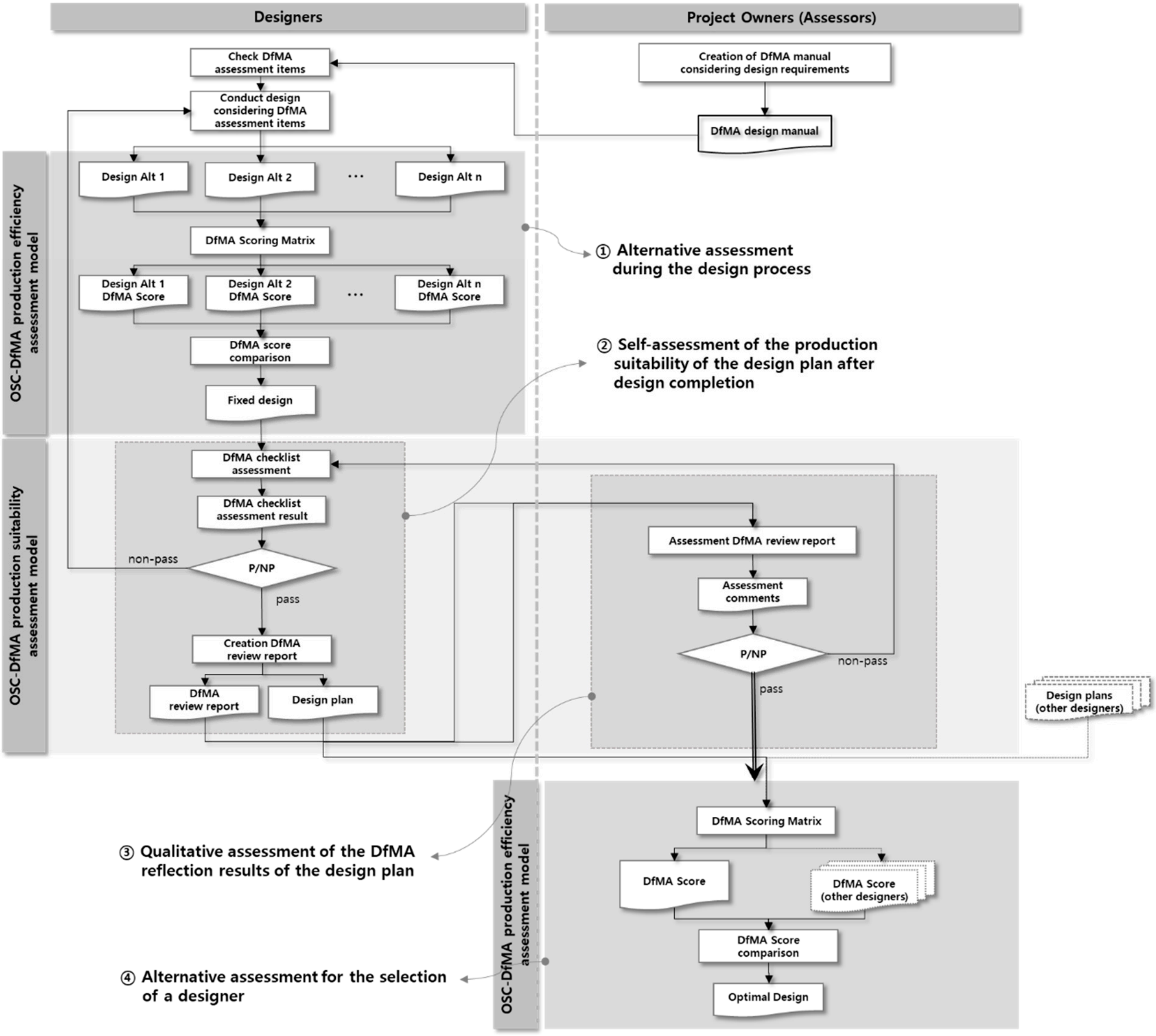


Figure 3. Utilization of the OSC-DfMA integrated assessment model.

Self-assessment of the production suitability of the design plan after design completion: To self-assess the DfMA conformity of their design plans, designers should assess whether their design plans meet each assessment item in the DfMA checklist consisting of DfMA production suitability assessment items in a pass or non-pass manner. Because the DfMA production suitability assessment items are composed of items that must be reflected in all design plans, the DfMA checklist items should all be checked as pass. If any of the items are checked as non-pass, the designer must redesign them to properly incorporate them into the design plan. The designer also prepares a DfMA review report for each item after completing the DfMA checklist assessment and submits it to the project owner (assessor) along with the design plan. The submitted DfMA review report can be used as a basis for a qualitative assessment by the project owner (assessor). In principle, the designer should be responsible for reviewing the DfMA checklist and preparing the DfMA review report. However, depending on the nature of the DfMA review items, the designer may request cooperation from the module manufacturer/consulting firm, structural design firm, and contractor in reviewing the DfMA checklist and preparing the review report, and the PC manufacturer/consulting firm, structural design firm, and contractor requested to cooperate shall actively cooperate in reviewing the DfMA checklist and preparing the review report.

Qualitative assessment of the DfMA reflection results of the design plan: The project owner (assessor) may reassess the results of the designer's DfMA checklist assessment by evaluating the DfMA review report submitted by the designer with the design plan after the design is completed. The assessment can be conducted in a pass or non-pass manner to determine whether each assessment item conforms to the checklist, and all assessment items must be checked as pass. If an item is evaluated as non-pass, the project owner (assessor) may request the designer to re-reflect the item.

Alternative assessment for the selection of a designer: The DfMA production efficiency assessment model can be used in when the project owner is selecting a designer. Note that when alternatives are assessed using the DfMA production efficiency assessment model, the design plans subject to alternative assessments should have completed the "(3) Qualitative assessment of the DfMA reflection results of the design plan". The project owner (assessor) assigns a score by comparing alternatives for each assessment item of the DfMA production efficiency in the DfMA scoring matrix and calculates the DfMA score for each design plan by summing the item scores. After comparing the DfMA score for each calculated alternative, the one with the highest score is selected as the optimal design plan.

3.3. Case Study for Validation

3.3.1. Validation of OSC-DfMA Production Suitability Assessment Model

To verify the usefulness of the OSC-DfMA production suitability assessment model proposed in this study, the OSC-DfMA production suitability review report was first created based on the design plans and plan drafts. Because the target case only utilized PC members as a frame, the feasibility of preparing an OSC-DfMA production suitability review report for 32 of the OSC-DfMA production suitability assessment items, except for three items (A10–A12) related to mechanical, electrical, and plumbing connection performance out of a total of 35 items, was confirmed using information related to the design, off-site manufacturing, and construction plans of the target case.

After explaining the purpose of production suitability assessment to OSC experts in Korea, we asked them to identify assessment items suitable for design conformity assessment based on their experiential knowledge and then qualitatively and quantitatively compared the identified assessment items with the assessment items of the assessment model proposed in this study. In addition, we presented the OSC-DfMA production suitability review report prepared earlier to the experts to assess its usefulness on a seven-point scale. The review opinions of the experts are as follows:

Expert A identified 12 assessment items (4 in the off-site manufacturing phase, 4 in the transportation phase, and 4 in the on-site assembly phase), which corresponded to 10 of a total of 35 items in the production suitability assessment model (refer to Table 4). This verifies that the OSC-DfMA production suitability assessment model proposed in this study is a useful judgment tool in the systematic suitability review by experts. In addition, Expert A rated the usefulness of the OSC-DfMA production suitability assessment model as six points (out of seven full points).

Expert B identified 31 assessment items (10 in the off-site manufacturing phase, 7 in the transportation phase, and 9 in the on-site assembly phase), which corresponded to 19 items of a total of 35 items in the production suitability assessment model (refer to Table 4). This verifies that the proposed OSC-DfMA production suitability assessment model is useful for experts in the systematic suitability review process. In addition, Expert B rated the usefulness of the OSC-DfMA production suitability assessment model as seven points (out of seven full points).

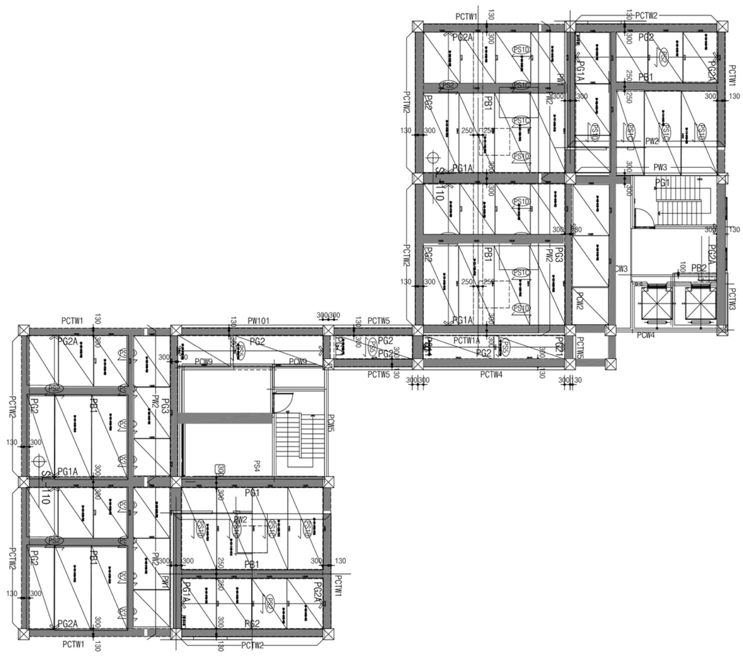
Expert C identified ten assessment items (three in the off-site manufacturing phase, five in the transportation phase, and two in the on-site assembly phase), which corresponded to 11 of a total of 35 items in the production suitability assessment model (refer to Table 5). This verifies that the OSC-DfMA production suitability assessment model proposed in this study was useful to the experts for the systematic suitability review process. Expert C also rated the usefulness of the OSC-DfMA production suitability assessment model as seven points (out of seven full points).

Table 5. Production suitability assessment items of the OSC project identified by the experts.

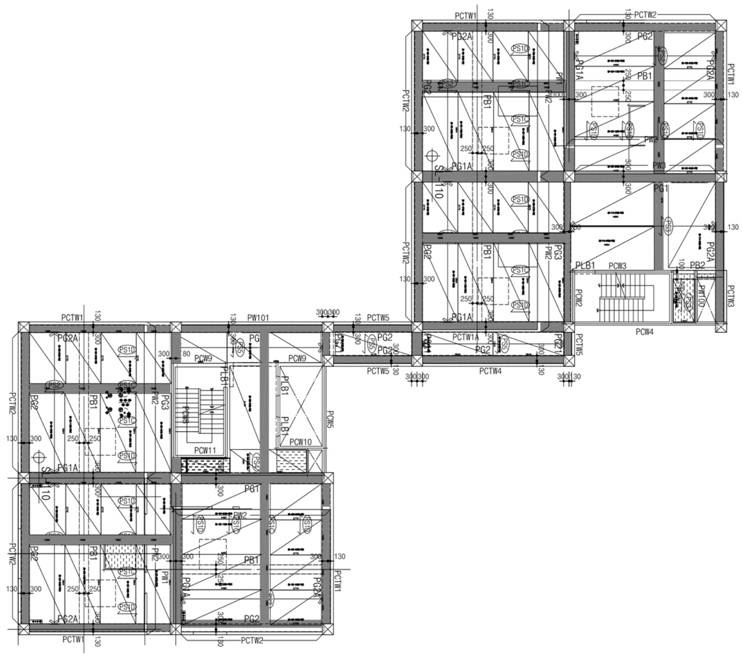
Division			Expert A	Expert B	Expert C
Off-site manufacture	Production availability	A1	O	O	O
		A2	O		
	Production safety	A3		O	O
		A4			
	Production quality	A5		O	
		A6		O	
		A7			
		A8			
		A9	O	O	O
		A10			
		A11			
		A12			
Transportation	Production availability	B1		O	O
		B2	O	O	O
		B3	O	O	O
	Production safety	B4	O	O	O
	Production quality	B5	O	O	O
On-site assembly	Production availability	C1	O		
		C2		O	
		C3			
		C4			
		C5	O		
		C6		O	
	Production safety	C7			
		C8		O	
		C9		O	O
	Production quality	C10		O	O
		C11	O		
		C12			
		C13			
		C14	O	O	
		C15			
Maintenance	Production availability	D1			
	Production quality	D2		O	
		D3		O	

3.3.2. Validation of the OSC-DfMA Production Efficiency Assessment Model

The alternatives were assessed based on the proposed assessment model to verify the usefulness of the OSC-DfMA production efficiency assessment model proposed in this study. The assessment results of the design alternatives (refer to Figure 4) of the target case verified that the model can be used to assess design alternatives.

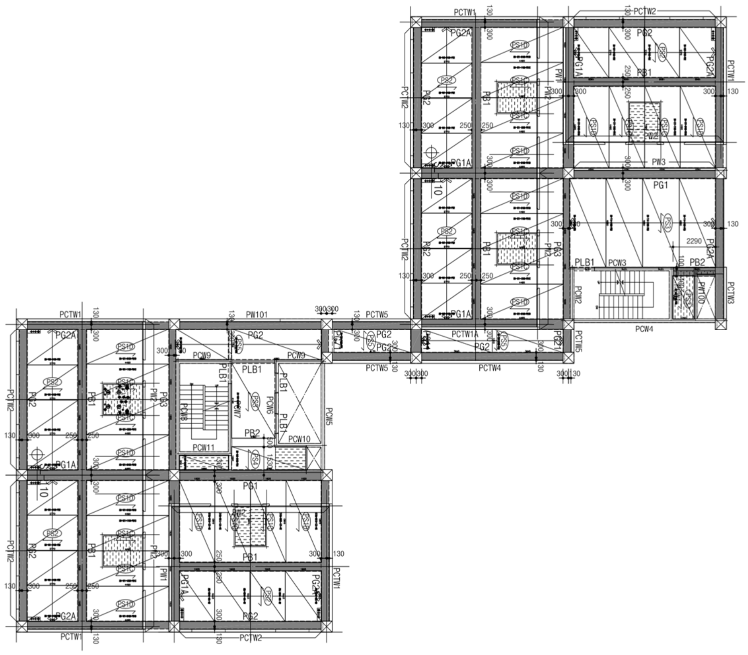


Design Alt 1.



Design Alt 2.

Figure 4. *Cont*.



Design Alt 3.

Figure 4. Design alternatives for case studies.

First, relative importance was derived in this study for each assessment item via the AHP method. The survey to determine importance was conducted for two weeks from 11 and 12 February 2022 by 13 experts from OSC project ordering organizations, architects, structural designers, PC manufacturers, contractors, and academics with experience in OSC and similar projects (including OSC-related research). Of the 13 individual responses from the collected samples, only 9 responses with a consistency ratio of 0.2 or less were included in the weighting calculation. The demographic characteristics of the respondents in the nine valid samples are presented in Table 6.

Table 6. Respondent characteristics considered to calculate the weight of each assessment item.

Division		All Respondents		Valid Samples (Consistency Ratio of 0.2 or Less)	
		Frequency	%	Frequency	%
Organizational type	Ordering organization	2	15.38%	1	11.11%
	Architectural design	2	15.38%	2	22.22%
	Structural design	2	15.38%	1	11.11%
	PC manufacturing	2	15.38%	1	11.11%
	Construction	2	15.38%	1	11.11%
	Academic	3	23.08%	3	33.33%
Experience	Construction work	Approx. 20 years		Approx. 15.8 years	
	OSC	Approx. 4.8 years (3.2 projects)		Approx. 5.4 years (3 projects)	
Total		13	100%	9	100%

Table 7 presents a weight for each assessment item derived through the AHP method. The assessment metrics and weights of the assessment items proposed in this study should not be considered absolutely correct because assessment metrics and items that are considered important may vary depending on project goals and experts' biases. However, because our results were obtained from the comprehensive opinions of experts who have conducted OSC projects in Korea, they can be generally applied to OSC projects in Korea.

Table 7. Weight calculation result for each assessment item.

Assessment Index		Assessment Factors	Weight
Manufacturability (MF)	MF1	The number of mold types	0.023
	MF2	Reusability of the mold	0.041
	MF3	The number of module types	0.040
	MF4	The total number of modules	0.023
	MF5	Module size and weight	0.024
	MF6	The difficulty of manufacturing the module	0.036
		Sub-Total	0.188
Deliverability (DL)	DL1	Number of module types	0.023
	DL2	Total number of modules	0.011
	DL3	Module size and weight	0.054
	DL4	The number of types of transportation equipment	0.028
	DL5	Whether special transportation equipment is needed	0.044
		Sub-Total	0.161
Assemblability (AS)	AS1	The number of module types	0.037
	AS2	The total number of modules	0.033
	AS3	Module size and weight	0.089
	AS4	The number of junction points	0.084
	AS5	Number of joint method types	0.069
	AS6	Joint difficulty	0.157
	AS7	Protection management of the joints and whether additional finishing work is needed	0.064
		Sub-Total	0.534
Maintainability (MT)	MT1	Accessibility to the joint	0.069
	MT2	The difficulty of joint maintenance	0.033
	MT3	Ease of remodeling	0.016
		Sub-Total	0.016
Total			1.000

Second, we ranked the alternatives for each assessment item (refer to Table 8). The design alternatives of the case used in this study were those that emerged during the case study, so the off-site manufacturing and transportation environment of the PC components and the joining construction methods applied were the same. Thus, the scores for these items were the same. Furthermore, for items related to assessment metric MT (manufacturability), a case study was conducted for PC members only, and frames consisting of PC members were covered with finishing materials after construction. Thus, we assumed that all alternatives were equal. However, in this case, each alternative differed in the type and number of PC members applied, the size and weight of the modules, and the number of junction points. Accordingly, the related items for each alternative were ranked.

Third, the scores for each assessment item of the three design alternatives were assigned to the Score column using the forced ranking method. Afterward, a weight for each assessment item was reflected in the score for each assessment item to calculate the weight-reflected score for each item, which was then entered into the weighted score column. Finally, the DfMA score was calculated by summing the score and weighted score for each assessment item. In the calculation results, Alternative A scored 27 and 1.332 points before and after reflecting the weight, and Alternative B scored 31 and 1.383 points before and after reflecting the weight, respectively. Moreover, Alternative C scored 37 and 1.546 points before and after reflecting the weight, respectively, making it the highest weighted score (refer to Table 9).

Table 8. Assessment results for each alternative.

AssessmentIndex		Assessment Factors	Design Alternatives			Note
			Alt. 1	Alt. 2	Alt. 3	
MF	MF1	The number of mold types	1	1	3	Proportional to the number of modules
	MF2	Reusability of the mold	1	1	1	Equality assumption
	MF3	The number of module types	90	90	88	Average number per area
	MF4	The total number of modules	193	183	183	Average number per area
	MF5	Module size and weight	1973.372	2017.528	2021.216	Average volume
	MF6	The difficulty of manufacturing the module	1	1	1	Equivalent assumptions because the configuration and size of the modules do not vary significantly by alternative
DL	DL1	Number of module types	90	90	88	Average number per area
	DL2	Total number of modules	193	183	183	Average number per area
	DL3	Module size and weight	1973.372	2017.528	2021.216	Average volume
	DL4	The number of types of transportation equipment	1	1	1	Equivalent assumptions because the configuration and size of the modules do not vary significantly by alternative
	DL5	Whether special transportation equipment is needed	1	1	1	No design alternative with modules of size and shape that are difficult to use for general transportation equipment
AS	AS1	The number of module types	90	90	88	Average number per area
	AS2	The total number of modules	193	183	183	Average number per area
	AS3	Module size and weight	1973.372	2017.528	2021.216	Average volume
	AS4	The number of junction points	1	2	3	Average number of junction points
	AS5	Number of joint method types	1	1	1	Average number per area
	AS6	Joint difficulty	1	1	1	equality assumption
	AS7	Protection management of the joints and whether additional finishing work is needed	1	1	1	equality assumption
MT	MT1	Accessibility to the joint	1	1	1	Assume that it is equivalent because it only targets PC members
	MT2	The difficulty of joint maintenance	1	1	1	
	MT3	Ease of remodeling	1	1	1	Equivalent because the number of non-load-bearing walls and the joint method are the same

To validate the production efficiency assessment model, experts were asked to select the optimal design for the three design alternatives presented above and compare these results with those obtained through the assessment model presented in this study. Furthermore, the experts were asked to evaluate the usefulness of the design alternatives on a seven-point scale. The review opinions of the experts are as follows:

As presented in Table 10, Expert A identified 4 DfMA assessment items related to production efficiency before checking the OSC-DfMA production efficiency assessment model of this study, which corresponds to 4 out of a total of 21 items of the OSC-DfMA production efficiency assessment model presented in this study. Although the assessment factors could be identified, the optimal design could not be derived without an assessment model, and Alternative C was selected as the optimal alternative by utilizing the presented OSC-DfMA assessment model. Thus, the OSC-DfMA production efficiency assessment model presented in this study is useful for assessing design alternatives for OSC projects. In addition, the usefulness of the OSC-DfMA production efficiency assessment model was rated as seven points (out of seven full points).

Table 9. Results of applying the DfMA scoring matrix.

Assessment Index		**Assessment Factors**	**Weight**	**Design Alternatives**					
				Alt. 1		**Alt. 2**		**Alt. 3**	
				Score	**W.S.**	**Score**	**W.S.**	**Score**	**W.S.**
MF	MF1	The number of mold types	0.023	1	0.023	1	0.023	3	0.069
	MF2	Reusability of the mold	0.041	1	0.041	1	0.041	1	0.041
	MF3	The number of module types	0.040	1	0.04	1	0.04	3	0.12
	MF4	The total number of modules	0.023	1	0.023	3	0.069	3	0.069
	MF5	Module size and weight	0.024	3	0.072	2	0.048	1	0.024
	MF6	The difficulty of manufacturing the module	0.036	1	0.036	1	0.036	1	0.036
		Manufacturability Score	0.188	8	0.235	9	0.257	12	0.359
DL	DL1	Number of module types	0.023	1	0.023	1	0.023	3	0.069
	DL2	Total number of modules	0.011	1	0.011	3	0.033	3	0.033
	DL3	Module size and weight	0.054	3	0.162	2	0.108	1	0.054
	DL4	The number of types of transportation equipment	0.028	1	0.028	1	0.028	1	0.028
	DL5	Whether special transportation equipment is needed	0.044	1	0.044	1	0.044	1	0.044
		Deliverability Score	0.161	7	0.268	8	0.236	9	0.228
AS	AS1	The number of module types	0.037	1	0.037	1	0.037	3	0.111
	AS2	The total number of modules	0.033	1	0.033	3	0.099	3	0.099
	AS3	Module size and weight	0.089	3	0.267	2	0.178	1	0.089
	AS4	The number of junction points	0.084	1	0.084	2	0.168	3	0.252
	AS5	Number of joint method types	0.069	1	0.069	1	0.069	1	0.069
	AS6	Joint difficulty	0.157	1	0.157	1	0.157	1	0.157
	AS7	Protection management of the joints and whether additional finishing work is needed	0.064	1	0.064	1	0.064	1	0.064
		Assemblability Score	0.534	9	0.711	11	0.772	13	0.841
MT	MT1	Accessibility to the joint	0.069	1	0.069	1	0.069	1	0.069
	MT2	The difficulty of joint maintenance	0.033	1	0.033	1	0.033	1	0.033
	MT3	Ease of remodeling	0.016	1	0.016	1	0.016	1	0.016
		Maintainability Score	0.016	3	0.118	3	0.118	3	0.118
		DfMA Score (total)		27	1.332	31	1.383	37	1.546
		Priority for selection		3		2		1	

Expert B identified 4 out of a total of 21 items in the OSC-DfMA production efficiency assessment model proposed in this study (refer to Table 10). Design Plan C was selected as the optimal alternative based on these four items. The OSC-DfMA production efficiency assessment model also derived Design Plan C as the optimal alternative. Thus, the OSC-DfMA production efficiency assessment model presented in this study is useful for assessing design alternatives for OSC projects. In addition, the usefulness of the OSC-DfMA production suitability assessment model was rated as seven points (out of seven full points).

Expert C identified 4 of a total of 21 items in the proposed OSC-DfMA production efficiency assessment model, as presented in Table 10. As with Expert A, the optimal design could not be derived without an assessment model, and Alternative C was selected as the optimal alternative by utilizing the proposed OSC-DfMA assessment model. Thus, the proposed OSC-DfMA production efficiency assessment model was deemed useful for assessing design alternatives for OSC projects. In addition, the usefulness of the OSC-DfMA production efficiency assessment model was rated as seven points (out of seven full points).

Table 10. Production efficiency assessment items of the OSC project identified by experts.

	Assessment Factors	Expert A	Expert B	Expert C
MF1	The number of mold types		O	O
MF2	Reusability of the mold		O	O
MF3	The number of module types		O	O
MF4	The total number of modules	O		
MF5	Module size and weight	O		
MF6	The difficulty of manufacturing the module		O	
DL1	Number of module types			O
DL2	Total number of modules			
DL3	Module size and weight		O	
DL4	The number of types of transportation equipment	O		
DL5	Whether special transportation equipment is needed			
AS1	The number of module types			O
AS2	The total number of modules	O		
AS3	Module size and weight		O	
AS4	The number of junction points			
AS5	Number of joint method types			
AS6	Joint difficulty		O	
AS7	Protection management of the joints and whether additional finishing work is needed			
MT1	Accessibility to the joint			
MT2	The difficulty of joint maintenance			
MT3	Ease of remodeling			

4. Expansion of the OSC-DfMA Assessment Model with AI and BIM

In a broad sense, the proposed OSC-DfMA assessment model is a kind of design optimization process focused on the production efficiency of building components and relies on design information. The main points of design optimization in the models are viewed from the efficiencies of manufacturing, delivering, assembling, and maintaining building components. This approach is very useful and provides significant information for decision-making during the design phase. However, when it comes to production planning, for the proposed OSC-DfMA assessment model to be more practical, it is important to consider both production efficiency and capacity. This is because production capacity affects the production schedule, which in turn affects the entire project schedule and cost. Furthermore, we need to consider how the entire assessment process can be automated, given the large amount of data handled through the production efficiency and capacity assessment process. In this regard, we propose a conceptual model for OSC-DfMA optimization and automation, which incorporates the proposed OSC-DfMA assessment model, a deep learning model for optimizing the manufacturing–delivering–assembling schedule based on production efficiency and capacity, and a BIM-based data management automation model as follows (refer to Figure 5).

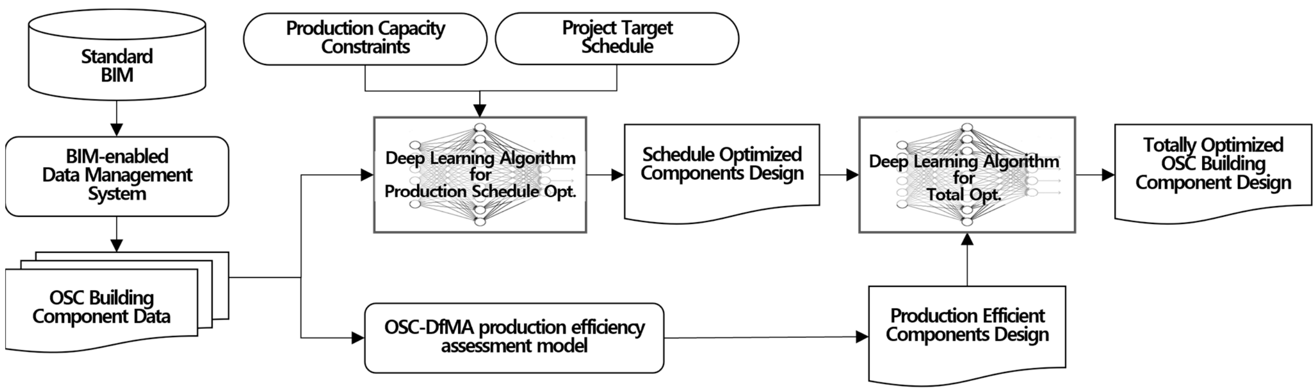


Figure 5. A conceptual model for OSC-DfMA optimization and automation.

According to the literature [35–40], AI technologies such as machine learning, deep learning, and other similar technologies can be successfully used in optimization problems. Moreover, previous studies [41–44] confirm that BIM-enabled applications help automate the DfMA process. Thus, the implementability and applicability of the above-proposed model are supported by the evidence provided in previous studies, and the details are summarized in Table 11.

Table 11. Evidence of the implementability and applicability of the proposed model found in previous studies.

Subject Area	Ref.	Key Contents
Deep Learning for Schedule Optimization under Resource Constraints	[35]	A deep learning model, which learns scheduling knowledge from existing records automatically, is applied to validate the logic in input schedules
	[36]	A hybrid model, which utilizes reinforcement learning, agent-based simulation, and graph embedding methods, is developed for schedule optimization
	[37]	An autonomous resource allocation model using deep reinforcement learning agents, which aims to simulate portfolio–project information, is presented
Deep Learning for Total Optimization (Multi-Objective Optimization)	[38]	A new multi-objective optimization approach, which uses a hybrid Hooke and Jeeves and genetic algorithm to search for an optimal design, is developed
	[39]	A deep learning model is established for reliable estimation of TBM's trajectory deviations, which is a kind of multi-objective optimization problem
	[40]	A machine learning model is developed to predict bridge conditions, which adopts multi-attribute utility theory to capture the decision-maker's preferences
BIM-enabled data management (3D Models combined with DfMA studies)	[41]	A computerized model is suggested and tested if the information in a BIM model meets DfMA requirements
	[42]	DfMA-oriented parametric BIM is proposed to integrate domain knowledge from the DfMA process into the BIM model
	[43]	A BIM-based design algorithm is implemented to reduce potential reworks in manufacturing, assembly, and construction
	[44]	A deep learning-based 3D object recognition modal using geometric data to enable the reuse and enrichment of BIM models is proposed

5. Conclusions

To overcome the productivity problem in existing on-site production systems, intense efforts have been directed at shifting the construction production paradigm toward OSC in the building sector. Unlike existing on-site production methods, the OSC method is an attractive solution for improving productivity in the construction industry because it can reduce costs; save time; and improve quality through standardization, modularization, and repeated production in the design and engineering, manufacturing, and construction stages. For such OSCs to be efficiently introduced and utilized in the construction industry, an optimal design plan that reflects the entire production process of OSCs (off-site manufacturing, transportation, on-site assembly, and maintenance) at the design stage should be selected.

Accordingly, the construction industry has emphasized efficiently applying DfMA to optimally design OSC projects. Thus, OSC-advanced nations such as Singapore, the UK, and the USA have established DfMA concept-applied design criteria and guidelines and researched methods of incorporating DfMA into the building industry. However, DfMA, as it has been developed and used to date, is limited because it only provides designers with background knowledge on how to design without clearly identifying the design criteria that must be considered when designing, which can be confusing to designers. In addition, many project participants, including the project owner, cannot review whether the designer's proposed designs conform to the DfMA concept.

Therefore, the present study developed an OSC-DfMA integrated assessment model that can assess the suitability of OSC production in terms of production availability, production safety, and production quality and select the optimal design alternative in terms of production efficiency. It also verified the usefulness of the OSC-DfMA integrated assessment model through a case study. The main study results are as follows:

In this study, an OSC-DfMA production suitability assessment model that can assess the suitability of OSC production from the aspect of production availability, safety, and quality was developed. The OSC-DfMA production suitability assessment model is an evaluation model for assessing whether the assessment items related to production availability, work safety, and production quality are reflected and the evaluation of the reflected content. This model allows design participants to self-review DfMA conformity in their design using the checklist method, report the review contents and results, and submit them to the project owner or assessor to evaluate the level of DfMA reflection, thereby improving the reliability of the design.

In this study, an OSC-DfMA assessment model that can select optimal design alternatives from the production efficiency perspective was developed. The OSC-DfMA production efficiency assessment aims to support the selection of optimal alternatives by conducting a relative assessment in terms of production efficiency when multiple design plans exist in the process of designing through the combination and division of modules by the designers participating in the OSC project. Furthermore, it can be used to support decision-making when the project owner or assessor selects designers.

In this study, the results of using the OSC-DfMA assessment model are presented, and its usefulness was verified through a case study. The verification results revealed that the OSC-DfMA production suitability assessment model and OSC-DfMA production efficiency assessment model are practicable and useful for selecting the optimal design plan for OSC projects.

The academic and practical contributions of this study are as follows:

Providing the research foundation in relation to DfMA in the construction industry: Most of the existing research on DfMA in construction has focused on providing conceptual design principles or suggesting future directions for DfMA applications and related technologies for OSC. However, this study is novel in that it clearly identifies detailed items to be considered for optimizing the design of PC-based OSC projects and provides a method for evaluating whether these items are properly reflected in the design, thereby enhancing the applicability of DfMA in OSC projects and laying the foundation for related research.

Expanding DfMA applicability through the OSC-DfMA assessment model: DfMA guidelines and criteria, implemented in countries such as Singapore and the USA were developed to focus on how OSC projects applying DfMA are conducted. The existing literature does not clearly identify the factors that must be considered in the design process, and it only provides the necessary background for the design process. In addition, no method for checking whether the DfMA concept is properly reflected in the design, which can confuse users and make establishing the reliability of the design difficult. To overcome these limitations, the present study clearly identifies detailed items that should be considered in selecting the optimal design plan for PC-based OSC projects, considering DfMA principles, and presents a method to assess whether these items are properly reflected in the design plan, thereby increasing the applicability of DfMA. The present study is also novel in its foundational contribution to expanding the applicability of DfMA by categorizing evaluation items according to the purpose of assessment (production efficiency, production availability, production safety, and production quality) and presenting different assessment methods and assessment times considering the characteristics of each assessment item.

Diversity in the use of the OSC-DfMA integrated assessment model: The OSC-DfMA integrated assessment model proposed in this study can be used in various ways for the optimal design of OSC projects. First, the OSC-DfMA assessment items proposed in this study can be used as design guidelines for design participants during the design process. Second, the OSC-DfMA production suitability assessment model proposed in this study can be used by design participants to review the conformity of the DfMA in the design process, and it can be used by the project owner to review the conformity of the DfMA in the design proposed by the designer. Third, the OSC-DfMA production efficiency assessment model proposed in this study can be used to select the optimal alternative when multiple design proposals are generated during the design process. It can also be used in selecting the optimal design among the design proposals presented by each designer when the project owner selects a designer through a design competition. This study is novel because it contributes to realizing optimal design through various applications of the OSC-DfMA integrated assessment model and establishing confidence in the design.

Besides the proposed OSC-DfMA integrated assessment model, the authors explored the possibility of using AI to automate the DfMA optimization process. Although the AI-based solution was not implemented in this study, the technical models were logically demonstrated, and their applicability was discussed and validated based on previous research results.

Future research directions for improving the usability of the OSC-DfMA integrated assessment model are as follows:

A need to develop assessment items for various OSC types other than PC: OSC production methods are classified depending on the degree of industrialization and types of materials used, among others. Although the present study focuses on PC-based OSC types, it will be necessary to develop DfMA metrics that are applicable to different types of OSC depending on the evolution of OSC.

A need to develop assessment items and assessment methods that apply the DfX concept: Currently, DfMA is expanding into various areas such as DfS (design for service), which considers A/S, and DfE (design for environment), which considers environmental impact, and recently, it has expanded to DfX (design for excellence), which means a design considering all areas [45]. In this study, the OSC-DfMA assessment model was proposed that only considers production possibility, production safety, production quality, and production efficiency, but in future studies, it is necessary to develop additional DfX-related assessment items and assessment methods, such as those addressing sustainability and service, which were not considered in this study.

A need to establish absolute assessment criteria: The OSC-DfMA integrated assessment model in this study was developed by identifying DfMA assessment items and applying assessment methods suitable to the characteristics of each assessment item. However, this model is limited in that it does not provide standardized assessment criteria for each assessment item due to the lack of performance data on OSC construction projects and limited data collection. If performance data of OSC construction projects are accumulated in the future, standardized assessment criteria for each assessment item will be achievable. Once standardized assessment criteria are established, the OSC-DfMA production efficiency evaluation model can be used to evaluate alternatives as well as to measure the degree of optimization in a single design.

Improving the efficiency of assessment through linkage with building information modeling (BIM) and computerized tool development: The OSC-DfMA integrated assessment model proposed in this study can be used more efficiently through linkage with BIM and computerized tool development. Some of the DfMA metrics presented in this study require excessive time and effort to manually extract data from two-dimensional drawings. If the required information for DfMA assessment is entered and managed in the International Foundation Class, the international standard data format for BIM, as a module level to make up a building, the extraction of information required for DfMA assessment from BIM can be automated. In turn, if a computerized system that can synthesize the information extracted in this way to automate DfMA assessments can be developed, DfMA assessments will be more efficient.

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