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RESEARCH

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Process for Integrating Constructability into the Design Phase in High-Rise Concrete Buildings: Focused on Temporary Work

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Abstract

With the increase in high-rise building construction, failure to consider constructability in the design phase can result in huge wastes in the construction phase, as well as losing opportunities for design improvement. However, existing approaches for reflecting constructability rely heavily on reviews, resulting in an inefficient decision-making process. Thus, by considering appropriate timing and detail levels when applying construction knowledge, this study proposes a process for integrating constructability activities related to temporary work into the design phase in high-rise concrete buildings. Through an investigation of information-dependency relationships, 22 constructability activities were linked with 33 design activities. Further, these activities' implementation processes were constructed based on optimized information flows from a partitioned dependency structure matrix. The results of this study can help a project team address constructability issues at the appropriate time during the design process and will contribute to improving the efficiency of the overall project operation in high-rise building construction.

Keywords: constructability, design phase, high-rise concrete buildings, information flow, dependency structure matrix

1 Introduction

As building construction projects have become more complex and larger in magnitude, enhancing the interface between the design and construction has become more important for their successful completion (Kwon and Kim 2003). Most decisions in the pre-construction phase affect the construction performance (Pulaski and Horman 2005), and those impacts increase with the projects' size. However, the traditional procurement approach tends to separate the design from the construction, which hinders contractors from providing designers with suggestions and feedback, based on their construction expertise during the design phase (Lam et al. 2006). In addition, many designers have indicated that failure to consider constructability is a major problem in the design process (Bae et al. 2006). This leads to increased waste, e.g., design changes and reworking in the construction stage, as well as losing opportunities for design enhancement (Motsa et al. 2008).

Thus, continuous efforts have been made to minimize the fragmentation between participants and to make better use of construction knowledge in the design process. The Construction Industry Institute published guidelines for implementing constructability programs (CII 1993), and Singapore introduced the Buildable Design Appraisal System for making more buildable and labor-efficient designs (Poh and Chen 2010). Several programs, e.g., design reviews, constructability reviews, and value engineering, have been introduced to enhance the design quality and project performance (Pulaski and Horman 2005; Park et al. 2009; Li et al. 2018).

Although these methods have led to improvements in project performance, they are relatively unsophisticated and inefficient and rely heavily on reviews. In addition, existing approaches tend not to consider the appropriate timing when applying knowledge or the level of

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detail for efficient decision-making in the design process (O'Connor and Miller 1995). This can result in productivity loss by frequent reworking at the design stage, as well as adversarial relationships among the participants. Thus, to utilize constructability knowledge effectively, the right information at the proper time should be provided to the design team. The information should also have appropriate levels of detail to enable its successful integration with specific design activities.

This study proposes a process model for integrating constructability activities (CA) into the design phase in high-rise concrete building construction. In this study, the CA focuses on the temporary work including facilities, equipment, and construction methods. This is because there have been lack of efforts and attempts to enhance the constructability of temporary work from the design phase, even though this can greatly affect the construction efficiency of permanent structures as well as cost and time during the construction phase. The model organizes activities for constructability improvements based on appropriate timing and detail levels. The proposed model considers the information-exchange efficiency and minimizes overlapping activities in the design process.

2 Literature Review and Methodology Overview

2.1 Constructability

The concept of constructability, which initially focused on productivity, was first studied in the United Kingdom in the 1970s. It has been developed into an integrated concept for each production phase, including planning, design, and construction, to improve the cost effectiveness and quality of the construction industry (Griffith and Sidwell 1995; Oh et al. 2002). The definition of constructability varies slightly from country to country, but the common concept is to foster efficient decision-making by fully reflecting construction knowledge and experience from the early stages of the project. As observed in Table 1, existing studies have focused on investigating constructability factors and proposing efficient methods for constructability improvement. However, the approaches do not consider the timing or level of detail in applying the CA for an effective decision-making process in the design phase.

Table 1 Literature review of constructability.

Author (year)	Content
Yoon and Kim (2014)	Analyzed factors affecting constructability and verified their impact on productivity
Othman (2011)	Proposed an innovative framework to facilitate the integration of construction knowledge and builder experience at the design phase
Park et al. (2010)	Proposed a design management process between design activities and constructability knowledge
Lam et al. (2006)	Analyzed factors influencing constructability in the design phase through questionnaires
Pulaski and Horman (2005)	Proposed a conceptual model for organizing constructability knowledge for design
Fisher et al. (2000)	Proposed a constructability review process for the efficient use of analytical tools to improve constructability
Fischer and Tatum (1997)	Classified the knowledge into construction methods and structural elements to ensure appropriate and specific constructability input

2.2 Constructability Activities for Temporary Work

Lee et al. (2017a) investigated the CA related to temporary work for constructability improvement at the design phase in high-rise building construction. Based on questionnaires and statistical analyses, they derived 22 activities classified into five categories: (1) structural methods and surveying, (2) vertical transportation of resources, (3) space zoning, (4) water supply, and (5) temporary facilities and services (Table 2). However, it is difficult to apply the activities in the design phase because no information is available on when the activity should be applied or who should be involved in carrying it out.

Thus, Lee et al. (2017b) investigated the above matters through interviews with experts to effectively reflect the CA in the design process. Based on the similarity of execution subjects, applicable design stage, and characteristics of each activity, they presented 13 regrouped activities, shown in Table 2. In addition, 22 subdivided activities were provided, considering the work scope at each design stage. It allows appropriate levels of the CA to be applied at each design stage, which include schematic design, design development, and construction documentation.

For example, a regrouped activity "Construction methods for structures" includes three constructability activities: "Zoning for concrete placement," "Rebar placing and splicing method," and "Formwork operation method." Following the subdivided activities, alternative construction methods are compared in the design-development stage, and the final method selection and construction planning are carried out in the construction documentation stage. In this study, we try to link those subdivided CA with specific design activities at each design stage.

2.3 Dependency Structure Matrix

In modeling the design process, there have been several ways such as critical path method and integration definition functional modeling. However, those methods

Table 2 Constructability activities for temporary work and regrouping for integration with design activities. Modified from Lee et al. (2017a; b).

Category	Constructability activities	Regrouped activities	(Design stage) Subdivided activities
Structural methods and surveying	Access roads and pits for permanent measurement	Surveying	(SD) Comparison of alternatives
	Measurement method and sensor installation		(DD) Selection of surveying method and locations
	Zoning for concrete placement (i.e., construction joints)	Construction methods for structures	(DD) Comparison of alternatives
	Rebar placing and splicing		(CD) Method selection and construction planning
	Formwork operation method		
	Evacuation routes and spaces	Evacuation	(DD) Review of evacuation floors and routes
			(CD) Selection of evacuation plan
	Core construction method	Core construction	(SD) Comparison of alternatives
			(DD) Method selection
	Circulation for vertical lifting of resources by construction phase	Vertical transportation	(CD) Plan for resource transportation route
	Facade protection during structural framework	Facade protection	(CD) Facade protection plan
Vertical transportation of resources	Switching to permanent elevator and platform design	Lifting equipment and concrete pumping	(DD) Comparison of alternatives
	Centralization of temporary systems for vertical transportation (temporary bridge, ramp, etc.)		
	Location of lifting equipment considering finishing work		(CD) Selection of equipment and methods
	Concrete pumping method		
	Other equipment for on-site material handling (gantry cranes, monorails, forklifts, trucks, etc.)	On-site material handling	(CD) Plan for material-handling machinery
Space zoning	Design of the temporary access control system and CCTV layout	Security and ventilation	(CD) Space zoning for security and ventilation systems
	Ventilation and dust reduction in working zones during internal finishing		
	Separation between built and working zones	Separation between zones	(SD) Discussion about separation plan
			(DD) Alternatives review
			(CD) Selection of optimal plan
Water supply	Switching between temporary and main water tank according to water consumption	Water supply	(DD) Comparison of alternatives
	Switching between temporary and main septic tank according to sewage capacity		(CD) Selection of water supply plan
Temporary facilities and services	Standardization and fire protection of the temporary facility	Temporary facilities	(CD) Review of standardization and fire protection
	Lighting to prevent collision (T/Cs, airplanes, etc.)	Electricity and lighting	(DD) Comparison of alternatives
	Temporary electric power supply and distribution, and electric room		(CD) Selection of electric power supply and lighting plan

SD schematic design, *DD* design development, *CD* construction documentation.

have limitations on representing the precedence relationships between activities clearly or the repetitive activities. On the other hand, the Dependency Structure Matrix (DSM), proposed by Steward (1965), has been widely used as an effective tool for identifying information exchanges between activities and handling the iterative process (Steward 1965; 1981). Thus, this study uses the DSM methodology to create an efficient process for integrating the CA with design activities. It uses a square N × N matrix to represent the information-flow dependencies and sequences among N activities.

In the matrix, the information dependencies between activities are generally represented with an X mark in the off-diagonal cells according to the type of relationship between activities, as shown in Fig. 1 (Park et al. 2012; Ahn et al. 2013). For example, if activity B requires information from activity A to start and progress, the X mark lies at the intersection of column A and row B. In other words, the activities along the columns become "gives information to" and the activities along the rows become "needs information from." When the marks are below the diagonal, it is called "feedforward". It is called "feedback" when the marks are above the diagonal.

To appropriately sequence the activities, the rows and columns in the matrix should be reordered. Partitioning the DSM means reordering the activities by moving the feedback marks below the diagonal and as close as possible to the diagonal. This minimizes the need for activities that use information assumptions and avoids the possibility of reworking because a mark's distance from the diagonal roughly indicates the scope of the feedback (Browning 2001; DSM 2018). This study optimizes the information flows between the CA and design activities using a partitioning algorithm.

3 Process for Integrating Constructability with Design Activities Based on the DSM

3.1 Construction Design Activities

It is necessary to investigate the existing design process to reflect the constructability activities in the design phase. The construction design process can be generally divided into three stages: (1) schematic design (SD), (2) design development (DD), and (3) construction documentation (CD). In this study, the design activities classified into design disciplines (architectural, structural, mechanical and electrical (M&E), and fire/disaster prevention) at each design stage are derived from literature reviews (Kim 2005; Shon 2013; Kwon et al. 2016) and interviews with design experts (Table 3). In this study, design activities only include the activities affecting decision-making in the design process.

At the schematic-design stage, architectural design concepts should be established to clarify the client's requirements, and the basic system architecture of the building structure, M&E facilities, etc. should be reviewed. Starting from sketches and study models, the architect prepares a schematic building design and preliminary cost estimates. In the structural design, structural materials and systems are reviewed and compared. M&E systems are also reviewed based on rough load calculations.

The design-development stage involves finalizing the design and specifying major components, e.g., materials, preliminary structure, and general details. The M&E and fire-protection systems are also selected based on preliminary capacity calculations. During this stage, efficient coordination and information exchanges among participants become more important because numerous decisions should be made.

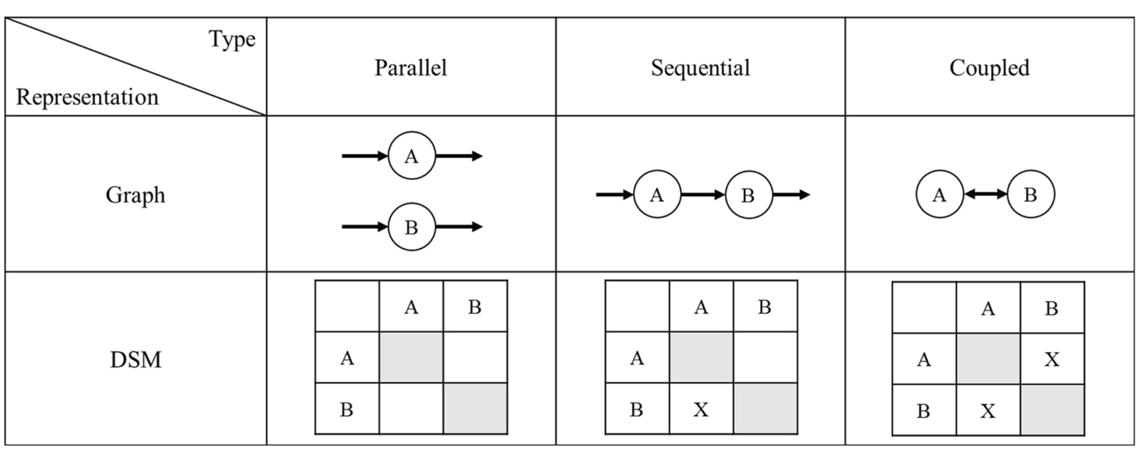

Fig. 1 Types of relationship between activities and their representations in the DSM.

Table 3 Design activities at each design stage.

Design stage	Design discipline			
	Architectural (A)	Structural (S)	M&E (M)	Fire/disaster prevention (F)
SD	Concept design Sketches/study models Preliminary building design Preliminary system design Preliminary cost estimate	Review of structural materials Comparison of structural systems	Preliminary load calculation Review of M&E systems	Preliminary load calculation Review of evacuation routes and fire-protection systems
DD	Detail planning and initial design development Facility space check System design determination Design development drawings	Selection of structural materials Structural analysis and selection of preliminary structure	Preliminary capacity calculation and systems selection	Evacuation simulation and systems selection
CD	Plan for detail drawings Partial detail drawings Review of standardizations Final drawings Final specifications Final cost estimate Documentation	Structural calculation sheet Structural drawings	Load/capacity calculation sheet for mechanical system Load/capacity calculation sheet for electrical system Partial detail drawings	Capacity calculation sheet Partial detail drawings

The construction-documentation stage completes the design to the optimal levels for bidding and construction. Detail drawings of all design disciplines are created. Construction documents include a complete set of architectural drawings, combined with structural and M&E drawings, specifications, and a final cost estimate.

3.2 Constructability Integration into the Design Phase

3.2.1 Dependency Relationship Analysis and DSM Application

To create the CA integration process, the information-dependency relationships between activities are firstly analyzed. In this study, the activities include both the 33 design activities in Table 3 and the 22 constructability activities (i.e., subdivided activities in Table 2). In this study, the constructability activities are to improve the efficiency of temporary work and equipment operation and to find optimal solutions by considering along with ease of construction for permanent structures. By applying these activities in the design process and reflecting into the drawings and specifications, inefficient project operations such as design changes and reworks are minimized at the construction phase. The dependency relationships also include information flows between design activities, between constructability activities, and between design and constructability activities. Thus, in this study, information dependencies among the activities are derived through iterative interviews and feedback from experts with over 20 years' experience in both the design and construction fields. Table 4 shows the survey results of the precedence relationships among all 55 activities, along with the information dependencies.

Once the activity DSM is formed, based on the activity list and precedence relationship in Table 4, the matrix is partitioned to reduce feedback, as shown in Fig. 2. In the partitioned DSM, shaded elements are the constructability activities, and different marks represent information flows between design activities (X mark), between constructability activities (● mark), and between design and constructability activities (◎ mark). Here, eight blocks (A–H) with interdependent relationships between activities have been identified; they have a relatively short cycle including two to three activities.

Most information exchanges between design and constructability activities occur during the design development stage (C–E, G blocks), which implies that the design team should actively cooperate with the construction experts at this stage to produce a better output. In contrast, no feedback loops appeared between the design and constructability activities in the construction-documentation stage, although 11 constructability activities exist; i.e., information flows sequentially between the design and construction teams. Blocks F and H show the interdependence between the constructability activities, which only requires simultaneous review and decision-making within the construction team.

During the schematic-design stage, a design activity "Review of structural materials (4)" has an interdependent relationship with a constructability activity "Discussions about separation plan (35)". In high-rise building construction, the separation between the built and working zones can be discussed to enhance the business value, and requires the participation of the owner and construction experts for proper

Table 4 Analysis of precedence relationships among the activities.

Category	Discipline	Activity name	ID	Predecessors
Design activity	A	Concept design	1	–
	A	Sketches/study models	2	1
	A	Preliminary building design	3	1,2
	S	Review of structural materials	4	3,34
	M	Preliminary load calculation for M&E system	5	3
	F	Preliminary load calculation for fire-protection system	6	3
	S	Comparison of structural systems	7	3,4,10,35,36
	M	Review of M&E systems	8	3,5
	F	Review of evacuation routes and fire-protection systems	9	3,6
	A	Preliminary architectural system design	10	3,7,8,9
	A	Preliminary cost estimate	11	7,8,9,10,34
	A	Detail planning and initial design development	12	10,11
	S	Selection of structural materials	13	4,12
	A	Facility space check	14	7,8,9,12,36,37
	A	System design determination	15	10,12,13,14,41
	S	Structural analysis and selection of preliminary structure	16	7,13,15,17,18,37,38,39,40
	M	Preliminary capacity calculation and M&E systems selection	17	5,8,14,15,42,43
	F	Evacuation simulation and fire-protection systems selection	18	6,9,14,15,44
	A	Design development drawings	19	3,12,15,16,41
	A	Plan for detail drawings	20	19
	F	Capacity calculation sheet for fire-protection system	21	18,20,51,53
	M	Load/capacity calculation sheet for mechanical system	22	8,17,20,45,50
	M	Load/capacity calculation sheet for electrical system	23	8,17,20,46,50
	S	Structural calculation sheet	24	16,20,47
	A	Partial detail drawings	25	19,20,47,48
	S	Structural drawings	26	16,19,24,25,47,52
	M	Partial detail drawings for M&E system	27	17,19,22,23,45,46,50
	F	Partial detail drawings for fire-protection system	28	18,19,20,21,51
	A	Review of standardizations	29	25,26,27,28,53
	A	Final drawings	30	26,27,28
	A	Final specifications	31	29,30,55
	A	Final cost estimate	32	29,30,54,55
	A	Documentation	33	30,32
Constructability activity	A	Discussions about separation plan	34	3,4
	S	Comparison of alternatives for core construction	35	3,4
	S	Comparison of surveying plans	36	3,4,35
	S	Selection of core construction method	37	12,13,35
	S	Comparison of alternatives for structural framework	38	12,13,37,39
	A	Comparison of lifting equipment and pumping plans	39	12,13,14,37,38
	S	Selection of surveying method and locations	40	16,36,37,38
	A	Alternatives review of separation plan	41	12,15,34
	M	Comparison of alternatives for water supply	42	17
	M	Comparison of alternatives for electricity and lighting	43	17
	F	Review of evacuation floors and routes	44	18
	M	Selection of water supply plan	45	17,19,42
	M	Selection of electric power supply and lighting plan	46	17,19,43
	S	Construction method selection for structural framework	47	19,38,48,49
	A	Selection of lifting equipment and pumping plan	48	20,39,47,49
	A	Plan for vertical resource-transportation route	49	19,47,48

Table 4 (continued)

Category	Discipline	Activity name	ID	Predecessors
	M/F	Space zoning for security and ventilation systems	50	17,19
	F	Selection of evacuation plan	51	18,19,44
	S	Facade protection plan	52	25,47
	F	Standardization and fire protection for temporary facilities	53	54
	A	Selection of optimal separation plan	54	19,41
	A	Plan for material-handling machinery	55	30,47,49,52

decision-making. Only after the preliminary building design is completed, the necessity review and discussion about the separation can be carried out. The structural materials should be reviewed at the same time because they can directly influence the necessity and economic feasibility.

In the design-development stage, a design activity "Preliminary capacity calculation and selection of M&E systems (17)" has a feedback loop with two constructability activities, "Comparison of alternatives for water supply (42), and electricity and lighting (43)". The plans for M&E systems should be established with consideration for temporary water and electric power supplies during construction stage and switching plan to permanent systems. These constructability activities should also be conducted based on the capacity calculation and economic feasibility review, according to each alternative. For similar reasons, "Systems selection for fire/disaster prevention (18)" should be implemented with "Alternatives review of evacuation floors and routes (44)" by considering disaster occurrence and effective evacuation during construction stage. In addition, "Appropriate surveying methods and locations (40)" should be investigated to effectively monitor the column shortening and structural health while "Determining the preliminary structural systems (16)".

3.2.2 Constructability Integration Process Based on Optimized Information Flows

Based on the information flows of the partitioned DSM in Fig. 2, a work process integrating the CA on temporary work with existing design activities is proposed, as shown in Fig. 3. The proposed work process clearly specifies the timing for applying the CA with appropriate levels of detail, considering the efficiency of the information exchange. Thus, it allows proper construction knowledge to be effectively utilized in the decision-making process during the design phase. It can also minimize productivity losses at the design stage through optimizing information transfers and exchanges among the activities.

The proposed process model represents the relationship between the activities and related expertise for performing each activity. The project manager can recognize how each person collaborates with whom, based on the information dependency. The activities involved in the blocks (in Fig. 2) require close cooperation and the continuous exchange of information and ideas between the related design and construction teams, while one-way collaboration is enough for the other activities. Thus, the proposed model can facilitate efficient collaboration and communication among the working groups. Consequently, it enables a project team to address constructability issues at the appropriate time during the design process and contributes to enhancing the efficiency of the overall project operation in high-rise building construction.

4 Summary and Limitations

With the increasing number of high-rise building construction projects, utilizing construction knowledge and expertise during the design phase has a significant effect on the successful project completion. It enables the minimization of inefficiencies, e.g., design changes and reworking, and allows constructability improvements in the construction phase. Thus, this study proposed a process integrating constructability activities related to temporary work into the design phase for high-rise concrete buildings. The proposed model organized constructability activities based on appropriate timing considering the information flows of the existing design activities. As a result, the interdependence relationships between design and constructability activities were mostly occurred in the design development stage, implying that the design team during this stage needs active cooperation and

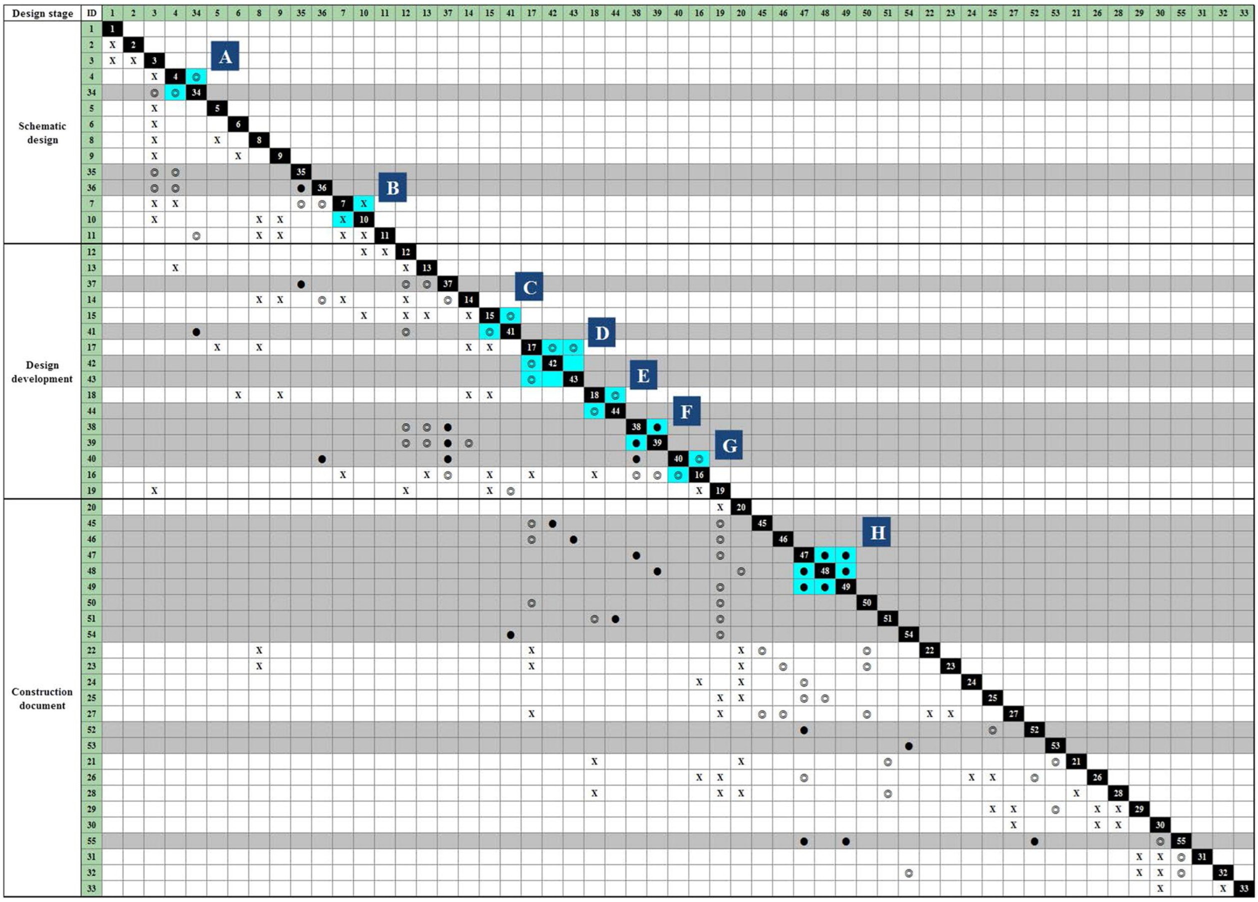

Fig. 2 Partitioned dependency structure matrix.

information exchange with construction experts to make better design outputs. On the other hand, the construction documentation stage only required sequential information transfer between the design and constructability activities because major decisions should be made in preceding stages. The proposed process, as a useful mechanism to organize constructability issues, can help to utilize construction knowledge most effectively during the design decision-making. Consequently, it could contribute to improve the constructability by minimizing design changes and reworking at the construction stage, as well as enhancing the design quality.

The limitations of this study are as follows. First, this study focused on constructing an efficient process for utilizing the CI in each design stage. However, the quantitative effectiveness of applying the proposed process was not fully investigated, even though the process was made through iterative review from both design and construction experts. Thus, it is necessary to verify how useful the proposed activities and processes are in terms of reducing the reworking, time, cost, etc. Second, the proposed model specified the timing and related participants for each activity and interrelationships among activities. Although it is helpful to recognize the decision-making

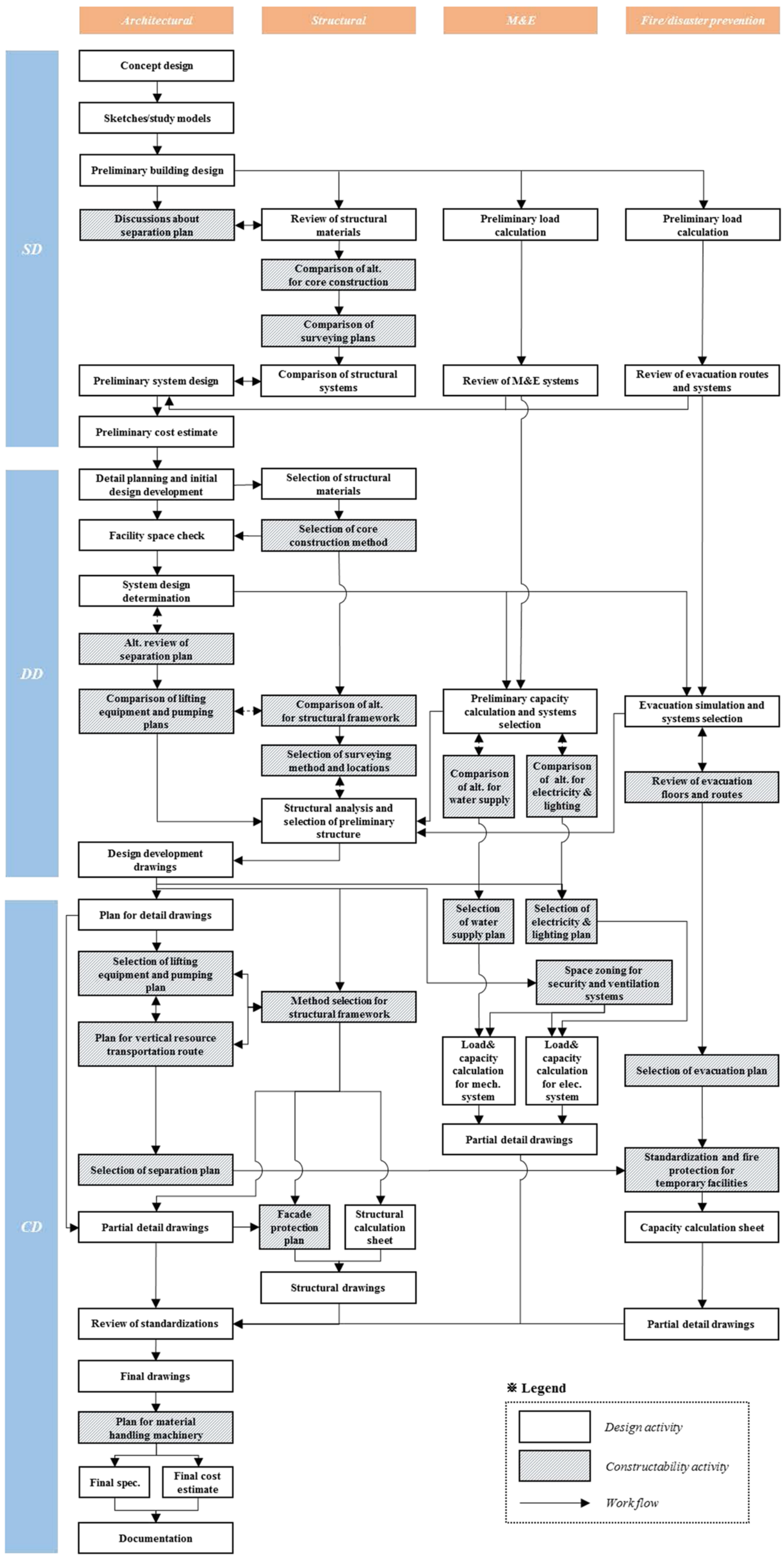

Fig. 3 Work process integrating constructability into the design phase.

points and necessary participants, the simple introduction of different participants at each decision-making point is not enough to take full advantage of the proposed process. Further research is required to determine how best to organize the project participants and use information at each design point to optimize the decision-making process.

Authors' contributions
In this paper, JWL and TK developed the research ideas and completed the writing. KC and TH helped in collecting and analyzing data and organizing the overall research flow. JH also helped in collecting data and enhancing overall quality of the content. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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