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A Process for Integrating Constructability Information into the Design Phase in High-rise Building Construction

The Graduate School of Chosun University

Department of Architectural Engineering

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고층건축공사 설계단계에서의 시공성 정보 통합 프로세스

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ABSTRACT

A Process for Integrating Constructability Information into the Design Phase in High-rise Building Construction

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최근 건축공사 프로젝트가 고층화, 대형화 및 복잡화됨에 따라 설계업무와 시공업무 간의 협업이 중요시 되고 있다. 프로젝트 설계단계에서의 의사결정은 시공성과에 직접적인 영향을 미치나, 전통적인 설계-시공분리 발주방식에서는 설계업무와 시공업무를 분리함으로써 시공성 및 설계자와 시공자간의 의사소통을 저해하며, 이는 곧 설계변경 및 재작업 등의 낭비요인을 발생시켜 생산성을 저해시키는 결과를 야기한다. 이에 시공성을 향상시킬 수 있는 다양한 방안이 제시되어왔지만 설계과정에서 시공성 지식의 구체적인 활용시점 및 수준에 대한 고려가 부족함에 따라, 효율적인 시공성 지식의 도입과 활용에 한계가 존재하였다. 이러한 비효율성을 최소화하기 위해서는, 의사결정과정의 기본 단위가 되는 설계 업무 수준에 부합하는 적정 수준의 시공성 정보가 설계과정 내에서 적정 시점에 제공되어야 한다.

이에 본 연구에서는 고층 건축공사 프로젝트의 시공성 향상을 위하여 설계단계에서의 시공성 정보 통합 프로세스를 제시하고자 한다. 이를 위해 먼저 설계단계에서의 시공성 정보 적용 효과, 장애 및 필요 업무 조사를 수행함으로써 본 연구 수행의 필요성을 확인하였다. 시공성 정보 통합 프로세스 구축을 위한 선행 단계로써, 문헌고찰, 전문가 자문 및 설문, 요인분석을 토대로 21개의 중요 엔지니어링 업무를 도출하였으며, 각 업무별 수행시기 및 참여주체 조사를 토대로 설계 업무와의 호환성, 업무수행 효율성을 고려하여 업무 그룹화 및 세분화

를 실시하였다. 이러한 과정을 통해 도출된 시공성 정보를 반영한 엔지니어링 업무와 기존 설계 업무를 토대로 의존관계구조행렬 방법론을 활용하여 정보흐름 기반의 시공성 정보 통합 프로세스를 제시하였다.

본 연구결과를 활용하여 설계단계의 적정한 시점에 필요한 시공성 지식을 반영함으로써 프로젝트 참여자간의 의사소통 향상 및 정보교환의 효율성을 증진시킬 뿐 아니라, 시공성 향상, 중복작업 최소화를 통한 설계품질 향상 등의 효과를 얻을 수 있을 것으로 기대된다. 또한 프로젝트 관리자가 효율적으로 업무들을 관리할 수 있게 해줌으로써 전반적인 건설프로젝트의 생산성 향상에 기여할 수 있을 것으로 사료되며, 본 연구의 결과는 향후 국내 고층건축공사 설계단계에서의 체계적인 시공성 정보 통합 프로세스 도입을 위한 기초자료로 활용될 수 있을 것이다.

1. Introduction

1.1. Research Background and Purpose

As building construction projects have become more complex and larger in magnitude, enhancing the interface between design and construction has become more important for their successful completion (Kwon and Kim, 2003). Most decisions from the preconstruction phase affect construction performance (Pulaski and Horman, 2005), and those impacts increase as projects grow bigger. However, the traditional design-bid-build procurement approach tends to separate design from construction, and this hinders contractors from providing designers with suggestions and feedback based on constructability expertise during the design phase (Lam et al., 2006). In addition, most designers have indicated that lack of consideration of constructability is a major problem in the design process (Bae et al., 2006). This leads to increased waste such as design changes and rework at the construction stage as well as losing opportunities for enhancement of designs (Motsa et al., 2008).

Thus, there have been continuous efforts to minimize the fragmentation between project participants and to make better use of construction knowledge in the design process. The Construction Industry Institute (CII) published guidelines for implementing constructability programs (CII, 1987), and Singapore introduced the Buildable Design Appraisal System for making more buildable and labor-efficient designs (Poh and Chen, 2010). Several programs such as design reviews, constructability reviews, and value engineering have been introduced to enhance design quality and project performance, and some tools such as checklists have been used to improve processes (Pulaski and Horman, 2005; Park et al., 2009). Although those methods have led to improvements in project performance, they are relatively unsophisticated, inefficient, and rely heavily on reviews. In addition, the existing approaches tend not to consider appropriate timing in applying knowledge or the level of detail for efficient decision-making in the design process (O'Connor and Miller, 1995). This can result in productivity loss by frequent rework at the design stage as well as adversarial relationships among participants. Thus, to utilize constructability knowledge effectively, the right information at the proper time should be provided to the design team, and the information should also have appropriate levels of detail to enable successful integration with specific design activities.

The purpose of this study is to propose a process model for integrating constructability information (CI) into the design phase in high-rise building construction projects. This model organizes engineering tasks for constructability improvements based on appropriate timing and levels of detail. To achieve this purpose, relevant literature is first reviewed, and then a preliminary survey to identify the effects and obstacles of introducing this approach in the domestic industry is implemented. Next, engineering tasks applicable to the design phase are derived. Finally, to implement those tasks efficiently, an information flow-based process model, which integrates engineering tasks with design activities, is proposed. The proposed model considers the efficiency of information exchange and the minimization of overlapping tasks in the design process. Consequently, it enables a project team to address constructability issues at the appropriate time during the design process and will contribute to enhancing the efficiency of overall project operation in high-rise building construction.

1.2. Research Scope and Procedures

In this study, the scope of CI required in the design phase is limited to tasks related to facilities, equipment, and construction methods for the temporary works of building construction projects. These components can have a considerable effect on improving constructability and project performance, especially for high-rise building construction. For example, Peurifoy and Oberlender (2011) showed that focusing on improving the constructability of formwork in the design phase may lead to reduction of construction costs for the structural framework by 25% as well as shortening the construction duration. Despite its importance, most engineering efforts on temporary works are currently implemented in the construction planning phase by specialty contractors and vendors. Thus, construction contractors are losing the opportunity to improve constructability of the design and to minimize inefficient work during the construction phase.

Considering its scope, the engineering process for constructability improvement in this study is defined as a process to improve the efficiency of temporary works and equipment operation and to find optimal solutions. By applying this process to the design phase, inefficient project operations such as design changes and rework are minimized and constructability of operations for permanent structures is improved. Therefore, safety facilities (such as safety platforms, temporary fences, and temporary working platforms), and temporary facilities for earthworks and scaffolds were excluded from the scope of this study because they are considered to have low applicability to engineering in the design phase. In addition, construction projects for buildings with more than 40 stories are targeted when introducing the proposed model, considering its necessity and effects, and interviews with experts.

To develop this CI integration process, four steps were followed, as shown in Figure 1.1. In the first step, the concepts and effects of constructability were investigated through literature reviews. In the second step, using a questionnaire, the effects of applying CI in the design phase were investigated. In addition, variations in applicability and responsibilities according to the project delivery method were investigated. Obstacles and necessary activities for implementing engineering tasks reflecting CI were also investigated, which will contribute to the introduction of efficient CI integration processes in Korea. In the third step, based on interviews with experts and a literature review, preliminary engineering tasks for constructability improvement were identified, and the final tasks were derived through importance analysis and factor analysis. In the fourth step, based on the identified tasks, appropriate execution points in time and participants for engineering tasks were analyzed through interviews with experts, and similar tasks were grouped together. Then, using a dependency structure matrix (DSM), a CI integration process was proposed that can integrate the information flow between the engineering activities reflecting CI and the design activities.

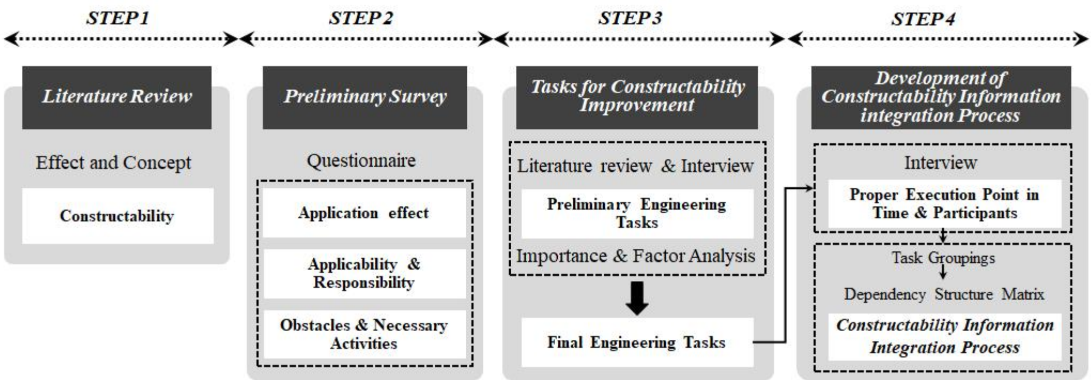


Fig. 1.1. Research framework

2. Literature Review

The concept of constructability, which was initially focused on productivity, was first studied in the United Kingdom (UK) in the 1970s, and it has been developed into an integrated concept of 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). Table 2.1 shows the definition of constructability in several countries. First, the concept of constructability defined by the Construction Industry Research and Information Association (CIRIA) in the UK is ‘To facilitate construction by carrying out the building design considering quality, cost and safety required in completed building’. Second, the CII in the United States defined constructability as ‘Making the best use of construction knowledge and experience in planning, design, procurement and field operations for successful projects’. Finally, the Construction Industry Institute Australia Inc. (CIIA) defined it as ‘Utilizing construction knowledge to achieve the project goals and building performance in the whole process’. There is little difference in the definitions; the common concept of constructability is to foster efficient decision-making by fully reflecting construction knowledge and experience from the early stage of the project.

Since the concept of constructability was presented, numerous foreign and domestic studies on constructability have been conducted. They can be categorized as: i) concepts and application effects of constructability, ii) methods for applying constructability effectively, and iii) design processes for enhancing constructability.

Table 2.1. Definition of constructability by country

Country (Institute)	Definition
United Kingdom (CIRIA)	The extent to which the design of the building facilitates ease of construction, subject to the overall requirements for the completed building
United States (CII)	The effective and timely integration of construction knowledge into the conceptual planning, design, construction, and field operations of a project to achieve the overall project objectives in the best possible time and accuracy at the most cost-effective levels
Australia (CIIA)	The integration of construction knowledge in the project delivery process and balancing the various project and environmental constraints to achieve the project goals and building performance at the optimal level

Table 2.2 shows some investigations of the concept and application effect of constructability. Hyun (1998) and Oh et al. (2002) emphasized that constructability is applicable during the life cycle of the project and the maximum effect can be obtained when applying constructability in the early stages of a project. Pulaski and Horman (2005) and Othman (2011) emphasized that construction knowledge and experience should be exploited in the design phase, so most existing studies emphasized the application of constructability in the design phase. Francis et al. (1999) mentioned that the application of constructability in the design phase can provide effects such as reducing construction time and cost, and improving safety and communication. Fischer and Tatum (1997) mentioned that the role of the designer is most important for applying constructability in the design phase, and that designers who have not received clear construction knowledge can cause multiple construction problems. In addition, Shon (2012) mentioned that designing without consideration of constructability causes unnecessary work such as design changes and rework, which may cause problems such as construction duration delay and cost increase. Apart from these studies, many existing studies have described the effects that can be obtained by application of constructability, and the problems that may arise when designers do not consider constructability.

Table 2.2. Studies investigating the concepts and effects of constructability

Authors (Year)	Research title
Shon (2012)	Importance of Review Process for the Constructability Implementation of the Reinforced Concrete Building Structural Design
Othman (2011)	Improving Building Performance through Integrating Constructability in the Design Process
Pulaski and Horman (2005)	Organizing Constructability Knowledge for Design
Oh et al. (2002)	A Study on the Application of Constructability in Construction Project Process
Francis et al. (1999)	Constructability Strategy for Improved Project Performance
Hyun (1998)	Application of the Constructability Program at the Early Phase of the Project
Fischer and Tatum (1997)	Characteristics of Design-Relevant Constructability Knowledge

As mentioned above, many domestic and foreign researchers have recognized the necessity of applying constructability and have conducted research on its effective application, shown in Table 2.3. Fischer and Tatum (1997) proposed a method for efficient utilization of constructability by collecting and structuring the construction knowledge used in the design phase. Fisher et al. (2000) investigated 52 constructability analysis tools based on previous studies and proposed a constructability review process for efficient use of these analysis tools. This approach encourages systematic and practical constructability review. Pulaski and Horman (2005) proposed a conceptual product/process matrix model (CPPMM) that can be used for each stage of a project using an integrated building process model and product model architecture. The project team was able to identify construction problems in the design phase and to respond to problems effectively using CPPMM. Lam et al. (2006) investigated the factors affecting constructability through questionnaires, and Lam et al. (2007) analyzed the priorities of constructability factors in the design phase using the analytic hierarchy process, so that the designer could apply constructability efficiently in the design phase. Park et al. (2009) developed a checklist to improve the constructability of steel structure construction, so that designers can easily identify factors of constructability and solve problems caused by insufficient application of constructability. Lee et al. (2010) and Kim et al. (2014) proposed a BIM(Building Information Modeling)-based design process to enable systematic and effective constructability reviews. Yoon and Kim (2014) mentioned that there had been few empirical studies on the effects of the constructability improvement in Korea, and analyzed the correlation between constructability and productivity using field data. However, even though studies for improving constructability have progressed, existing approaches lack consideration of appropriate timing in applying constructability knowledge or level of detail for effective decision-making process in the design phase. Park et al. (2010) proposed a design process management model using a DSM to enable designers to use the proper constructability knowledge at the proper point in time and to make effective decisions in the design process. However, this study applied the model on only a small part of design process and focused more on proposing the methodology. Therefore, for efficient utilization of CI in the design phase, an integrated process considering interrelationships between CI and design activities must be developed.

Table 2.3. Studies of methods for effectively applying constructability

Authors (Year)	Research title
Yoon and Kim (2014)	Analysis of Constructability Factors Affecting the Productivity of Tall Building Construction: with Focused on the Area of Steel Work
Kim et al. (2014)	A Proposal of BIM Work Process to Support Construct-ability Analysis from Practitioners Viewpoint
Lee et al. (2010)	A Case Study of BIM-based Framework on Constructability Tasks
Park et al. (2010)	Development of Design Process Management Model Using Dependency Structure Matrix for Constructability
Park et al. (2009)	Development of Checklist for Improving Constructability in Steel Structure Construction
Lam et al. (2007)	Constructability Rankings of Construction Systems Based on the Analytical Hierarchy Process
Lam et al. (2006)	Contributions of Designers to Improving Buildability and Constructability
Fisher et al. (2000)	Integrating Constructability Tools into Constructability Review Process

Existing studies on design process model were additionally reviewed for efficient application of CI in the design phase (Table 2.4). Shin et al. (2006) emphasized the importance of information exchange and communication among participants in construction projects, and required that the design process should allow all participants to exchange information in the design stage. Bae et al. (2006) mentioned the problems of the existing design process and presented a design process information flow for efficient communication among the participants. Bae et al. (2007) proposed a standard process model to set the foundation for design management systems by supplementing the previous research, and Shin et al. (2008) proposed a standard design process by collecting detailed data from design processes. In addition, Song et al. (2009) proposed a business process model for the DB method in view of its increasing use, thus laying a foundation for efficient design management and improvement of constructability. The following processes are expected to contribute to constructability improvement by minimizing unnecessary work such as design rework by improving communication among project participants. Based on the results of those studies, design activities and processes for introducing CI will be examined in more detail in section 5.

Table 2.4. Studies on design process model

Authors (Year)	Research title
Song et al. (2009)	Business Process Model for Progress Phase of Design-Build Project
Bae et al. (2007)	Development of Architectural Design Process Model for Information Flow
Shin et al. (2008)	Information-centered Design Work Process for Effective Design Management
Bae et al. (2006)	A Suggestion for Design Process Improvement to Develop a Design Management Model
Shin et al. (2006)	Introducing Information-oriented Work Process Modeling Method for Effective Design Management in Design Collaboration

3. Preliminary Survey[1)]

3.1. Survey Overview

Although there have been considerable efforts on constructability improvement in high-rise building construction, few studies have been conducted to introduce a process for integrating CI into the design phase in Korea. Therefore, in this section, the effects of applying CI in the design phase, and the current obstacles and the necessary activities required in the future were investigated using questionnaires. In addition, the applicability of CI and responsibilities according to each project delivery method were investigated. The survey was conducted using a five-point scale and it was conducted with the assistance of 18 practitioners in construction, design, construction management (CM), and engineering companies to obtain opinions on various subjects. Most (about 93%) of the respondents had more than 10 years of work experience, and all respondents agreed that it is necessary to introduce CI in the design phase, thereby ensuring the reliability of the results.

3.2. Survey Results

3.2.1. Effect of applying CI in the design phase

Following the survey, the effects of applying CI in the design phase were investigated as follows: i) duration reduction; ii) construction cost reduction; iii) improved design quality; iv) improved communication between designer and constructor; v) reduction of design changes and rework; and vi) constructability improvement. Among the effects, construction cost reduction (4.2 points) and constructability improvement (4.2 points) were considered most important, followed by construction duration reduction (3.9 points) and reduction of design changes and rework (3.6 points). Improved communication between designer and constructor (3.3 points) and improved design quality (3.1 points) showed relatively low scores. However, the survey results show that introducing CI in the design stage can have

1) Taken from the results of Lee et al. (2017a)

strongly positive effects on successful project operation, as all scores were greater than 3 points. Figure 3.1 shows the survey results.

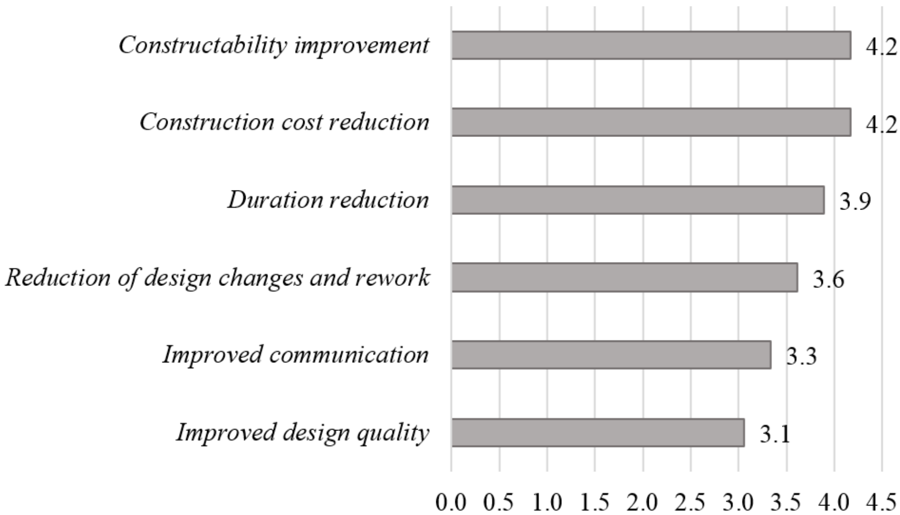


Fig. 3.1. Importance of effectiveness of applying CI

3.2.2. Applicability of CI by project delivery method

As construction projects have become larger and more complicated, various project delivery methods have been implemented. They can be largely divided into design–bid–build (DBB), design–build (DB), and CM methods. To apply CI in the design phase, it is necessary to analyze the applicability within each project delivery method.

As shown in Figure 3.2, 56% of the respondents answered that ‘CI can be applied in the design phase to the DBB method’ and 28% answered that ‘It cannot be applied to the DBB method’. For the DB method, 100% of the respondents answered that ‘It can be applied’. In the CM method, 67% of respondents answered that ‘It can be applied’ and 22% answered that ‘It cannot be applied’. These results indicate that CI can be applied most efficiently to the DB and CM methods. For the DBB method, the applicability of CI in the design phase appears to be relatively low because of inadequate laws and institutional strategies, as well as insufficient communication between designers and constructors. Thus, engineering tasks reflecting CI are more likely to be performed within the DB and CM methods than in the DBB method, because efficient communication and exchange of information between participants is possible.

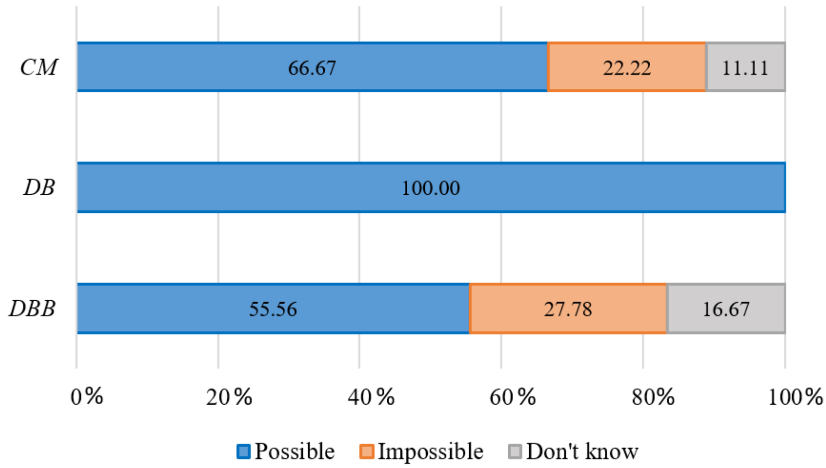


Fig. 3.2. Applicability of CI by project delivery method

The existing research literature and the consultation results confirmed that engineering responsibilities vary according to the project delivery method. It is necessary to clarify the responsibility for problems that may arise when performing engineering tasks reflecting CI. From the survey, the DBB and DB methods showed the highest responsibility ratios for the general contractor (Figure 3.3); the architect also showed high responsibility because engineering work was required to improve constructability in the design phase. In the CM method, the construction manager showed the highest ratio, and the architect was found to have a low ratio of responsibility. The possibility that the owner could become a responsible entity also appeared.

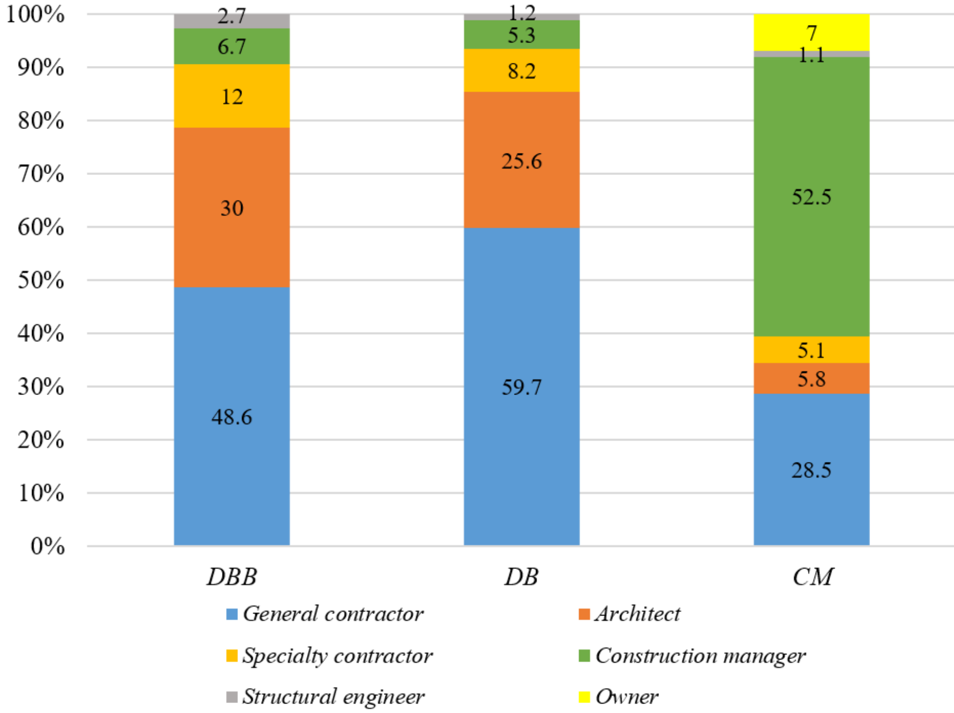


Fig. 3.3. Responsibility ratio of subjects by delivery method

3.2.3. Obstacles and necessary activities for applying CI

At present, there are many restrictions regarding the execution of engineering processes reflecting CI in the design phase in Korea. For effective introduction of the process, it is necessary to analyze current obstacles and necessary activities in future studies.

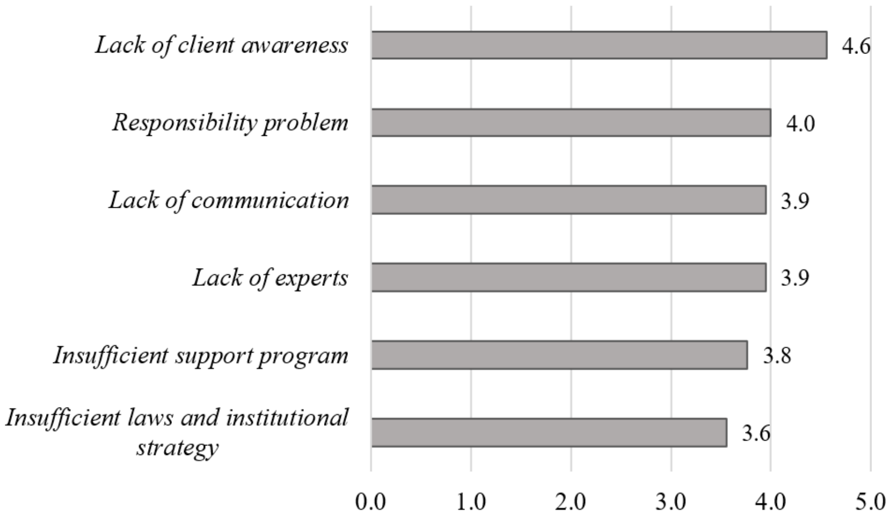


Fig. 3.4. Analysis of obstacle factors

According to Figure 3.4, the lack of client awareness (4.6 points) was the largest obstacle, followed by the problem of responsibility (4.0 points), a lack of experts (3.9 points), and a lack of communication and information exchange (3.9 points). This can be interpreted as the result of a lack of proper conceptualization because of a lack of both professional research in this area and training of engineering experts. To solve these problems, the necessary activities were investigated (Figure 3.5). All respondents answered that ‘Training of experts and professional organization activities (3.9 points)’ is needed. Activities to verify the effectiveness of their work and establish monitoring systems also showed a high importance of 3.8 points. It is also necessary to revise current legal and institutional strategies.

The survey results show that applying CI in the design phase has a strong impact on construction cost reduction and constructability improvement. In contrast to the existing

DBB method, the DB and CM procurement methods are expected to have a significant impact on the application of CI. Consequently, as project deliveries based on integration of design and construction are gradually increasing, the necessity and effect of engineering efforts reflecting CI from the early stages of the project will be further increased. In the next section, specific engineering tasks applicable to the design phase will be derived.

Fig. 3.5. Analysis of necessary activities

4. Tasks for Constructability Improvement[2)]

4.1. Preliminary Tasks

This section presents the preliminary engineering tasks to improve the constructability of high-rise buildings. Based on existing research on temporary works and on constructability, engineering tasks were categorized into ‘Temporary facility (A)’, ‘Lifting equipment (B)’, ‘Structural method (C)’, ‘Surveying and space zoning (D)’, and ‘Mechanical and electrical services (E)’. These can be further classified as ‘Surveying method’, ‘Space zoning’, ‘Ventilation’, ‘Water supply’, ‘Disaster prevention’, ‘Communication/Access control system’ and ‘Electric power supply’ (Figure 4.1).

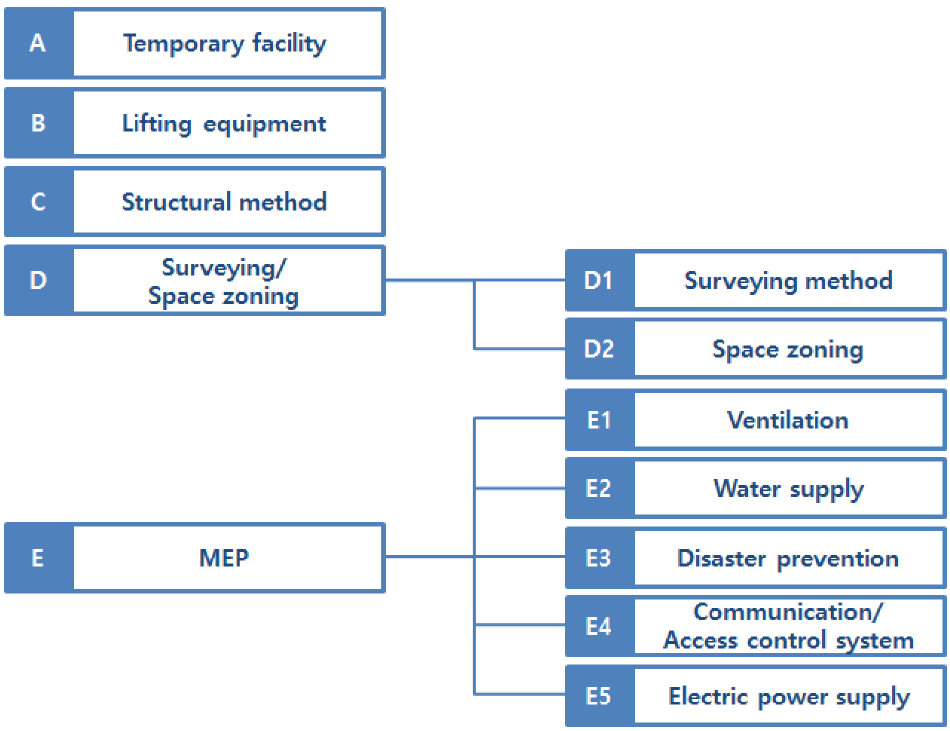


Fig. 4.1. Engineering task classification

2) Taken from the results of Lee et al. (2017b)

The review of existing studies related to high-rise building construction and the group interview (Jan-Jun 2017) with three experts (each with over 20 years of experience) in high-rise building construction were conducted using the detailed classification. As a result, 27 feasible engineering tasks that can contribute to improvements in constructability were identified.

First, investigating existing research literature on temporary facilities showed that the planning of temporary facilities in high-rise building construction can improve the constructability and reduce the time and costs, and the standardization of temporary facilities such as storage and open-air storage yards can contribute to improving work efficiency through securing the work space (Lee et al., 2003; Ahn et al., 1999).

Second, the existing research on structural construction method showed that improvements in constructability according to a formwork operation plan in the early planning stage (Kim, 2013), efficiency improvement of reinforcement work and reduction of construction duration according to the reinforcing assembly method (Jung et al., 2010), securing of concrete quality, time and cost reduction according to a concrete works plan in the design stage (Kim, 2010), and improvement of constructability through the selection of a core wall method at the early stage of the project (Ahn, 2004) should be investigated.

Third, the existing research literature on lifting equipment showed that a lifting equipment plan should be thoroughly analyzed and reviewed in the design phase because productivity and efficiency depend greatly on the selection of the lifting equipment, maximum lifting loads and location (Park et al., 2011). Lifting plans considering time taken for elevator and lifting equipment installation and dismantling is also necessary for efficient transportation of materials and workers (Ahn et al., 2001).

Fourth, the literature on measurement and space zoning plans showed that preparing temporary evacuation routes and creating evacuation space plans in preparation for disasters that may occur during construction (Lim et al., 2007; Choi and Kang, 2003), and measurement techniques for improving constructability and quality of the building structure are required. Efficient circulation plans for workers and material transportation can also increase work efficiency and yield positive effects in time and cost.

Finally, existing literature on mechanical and electrical services has been largely classified as air conditioning, water supply, and fire/disaster prevention. For air conditioning, Lee

(2013) mentioned that an efficient heating and cooling equipment plan in the design phase is required according to the various heating and cooling systems used in a high-rise building. Cho et al. (2008) presented a method to reduce energy loss through the selection of the air-conditioning method in the design phase. For water supply, Cho (2005) mentioned that a thorough water supply plan is required to prevent supply pressure problems and water-hammer problems caused by the height of a high-rise building. For fire protection and disaster prevention, Chun (2009) mentioned that an installation plan for temporary disaster facilities for fire prevention is required during the construction period. Table 4.1 shows the preliminary engineering task derived through this process.

Table 4.1. Preliminary tasks derived from literature review and group interview

Category	Code	Preliminary engineering tasks for temporary work	LR *	GI **
Temporary facility	A1.1	Standardization and fire code requirements of temporary facilities	√	
	A2.1	Location of temporary disaster control room and switching to the permanent one		√
Lifting equipment	B1.1	Location of lifting equipment in consideration of finishing work	√	
	B1.2	Other machinery for on-site materials handling (gantry cranes, monorails, fork lifts, trucks, etc.)	√	
	B1.3	Lifting plans for tower cranes, hoists, and elevators	√	
	B1.4	Centralization of material transportation systems		√
Structural method	C1.1	Construction method for core structure and formwork operations	√	
	C1.2	Concrete pumping methods	√	
	C1.3	Rebar placing and splicing methods	√	
	C1.4	Zoning for concrete placement (i.e., construction joints)	√	
	C1.5	Facade protection during structural work		√
	C1.6	Adjustment and reinforcement of structural members for the installation of lifting equipment		√
Surveying and space zoning	D1.1	Method of surveying and sensor embedment	√	
	D1.2	Access roads and pits for permanent measurement		√
	D2.1	Vertical transportation plan by construction stage		√
	D2.2	Space zoning between built and working zones		√
	D2.3	Evacuation routes and spaces	√	
Mechanical and electrical services	E1.1	Heating and cooling systems for efficient construction operation	√	
	E1.2	Ventilation and dust reduction in working zones during internal finishing work	√	
	E2.1	Switching between temporary and main water tank according to water supply capacity	√	
	E2.2	Switching between temporary and main septic tank according to sewage capacity		√
	E3.1	Sizes and locations of temporary fire protection facilities	√	
	E4.1	Emergency communication systems		√
	E4.2	Temporary access control system and CCTV layout		√
	E5.1	Electric power supply and distribution system, and electric room		√
	E5.2	Temporary distribution panel layout and switching to main panel		√
	E5.3	Lighting for collision prevention (tower cranes, airplanes, etc.)		√

Note: *LR = Literature review, **GI = Group interview

4.2. Task Importance

4.2.1. Survey overview

The survey was conducted to refine 27 preliminary tasks for practitioners in construction, design, and CM companies. The questionnaire consisted of two parts: respondent information (including position and experience in high-rise building construction projects) and necessity and importance of each task survey (five-point scale). It was distributed via e-mail and online. In total, 74 questionnaires were collected during the survey period of about one month (July-August 2017). Among them, respondents with no construction experience of buildings with 40 stories or more and less than 10 years of working experience were considered not reliable. Five questionnaires were therefore rejected and 69 were used for the analysis. Most respondents had more than 10 years of work experience (about 94%) and high-rise building construction work experience (about 58%).

4.2.2. Reliability analysis

Reliability analysis is concerned with producing consistent results when measuring one object multiple times with similar measurement tools or repeatedly with one measurement tool. More consistent results are considered more reliable. Methods for assessing the reliability of the scale include internal consistency, test-retest reliability, and alternative-form reliability. The most commonly used method is internal consistency. The most commonly used method of reliability assessment of the scale by internal consistency is Cronbach's coefficient alpha (Cronbach's α). The calculation method is (Song, 2013):

$$\alpha = \left(\frac{k}{k-1}\right)\left(1-\frac{\sum_{i=1}^{k}\sigma_i^2}{\sigma_t^2}\right) \text{or } \frac{k\bar{r}}{1+\bar{r}(k-1)} \quad (1)$$

where k is the number of components, σ_t^2 is the variance of the observed total test scores and σ_i^2 the variance of component i, and $\bar{r}$ is the average correlation coefficient between components. Reliability tests were conducted to measure the consistency of the surveys collected from survey respondents. Cronbach's α was used for the reliability analysis, and the reliability criterion was determined to be 0.7 or more. The analysis showed that the necessity (0.908) and the importance (0.913) were higher than the standard value. Therefore, the reliability of the questionnaire of 27 factors is high (Table 4.2).

Table 4.2. Reliability analysis

Item	Cronbach's α
Necessity	0.908
Importance	0.913

4.2.3. Ranking analysis

Based on the survey results, Equation 2 below was used to analyze the ranking of necessity and importance of each engineering task. i is the score given by the survey respondents from 1 to 5, and is the weight for each score: '1' is 'very low' for importance and necessity, while '5' is 'very high'. The weights apply each weight to each item of the response, is the frequency of the score of each item, is the number of respondents, and a is the highest score of the response (5 points) (Chen et al., 2010).

$$\text{Severity Index(SI)} = \left(\sum_{i=1}^{5} w_i \cdot \frac{f_i}{n} \cdot 100\right) / (a \cdot 100) \quad (2)$$

The results of the SI calculations are shown in Table 4.3. If the SI of each need and importance is $0.8 < SI \leq 1$, then it is called 'highly important work,' and if the score is $0.6 < SI \leq 0.8$, it is called a 'highly critical task.' If it is $0.4 < SI \leq 0.6$, it is called a 'high–medium critical task,' if $0.2 < SI \leq 0.4$, it is called a 'middle–low critical task,' and if $0 < SI \leq 0.2$, it is called a 'low critical task'. The analysis showed that 27 preliminary tasks showed the necessity and importance of the work above the 'high–medium' level, and tasks with high necessity and importance (SI value exceeding 0.8) were identified as the structural method and layout plans (C1.1, C1.2, C1.4), lifting equipment locations and operation plans (B1.1, B1.3), vertical transportation and evacuation plans (D2.1, D2.3), and electric power capacity and location plans (E5.1).

Table 4.3. Results for necessity and importance of tasks

Code	Necessity			Importance		
	SI	Rank	Grade	SI	Rank	Grade
A1.1	0.739	19	H–M**	0.730	19	H–M
A2.1	0.606	27	H–M	0.620	27	H–M
B1.1	0.849	2	H*	0.852	1	H
B1.2	0.745	15	H–M	0.733	18	H–M
B1.3	0.843	3	H	0.846	3	H
B1.4	0.751	14	H–M	0.757	13	H–M
C1.1	0.852	1	H	0.846	2	H
C1.2	0.835	5	H	0.841	4	H
C1.3	0.791	9	H–M	0.812	7	H
C1.4	0.823	6	H	0.800	8	H
C1.5	0.745	15	H–M	0.751	16	H–M
C1.6	0.774	10	H–M	0.780	11	H–M
D1.1	0.739	18	H–M	0.754	14	H–M
D1.2	0.733	20	H–M	0.725	20	H–M
D2.1	0.841	4	H	0.826	5	H
D2.2	0.762	12	H–M	0.783	10	H–M
D2.3	0.814	7	H	0.800	8	H
E1.1	0.719	22	H–M	0.716	23	H–M
E1.2	0.728	21	H–M	0.725	20	H–M
E2.1	0.713	24	H–M	0.713	24	H–M
E2.2	0.629	26	H–M	0.643	25	H–M
E3.1	0.751	13	H–M	0.774	12	H–M
E4.1	0.719	22	H–M	0.716	22	H–M
E4.2	0.638	25	H–M	0.635	26	H–M
E5.1	0.812	8	H	0.817	6	H
E5.2	0.771	11	H–M	0.754	14	H–M
E5.3	0.742	17	H–M	0.742	17	H–M

Note: *H = High, **H–M = High–Medium

In Figure 4.2, the values of importance and necessity of each task are shown as X–Y axes. The trend of necessity and importance value of each task is generally proportional, and there is not much difference in distribution except for a few tasks. The tasks that are more necessary and important compared with other tasks (quadrant 1) include the structural work (five tasks), space zoning (three tasks) and the lifting equipment plan (two tasks). On the other hand, most of the tasks with relatively low importance and necessity (quadrant 4) included tasks related to plans for mechanical and electrical services (seven tasks).

Among the engineering tasks, it seemed appropriate to exclude the ‘Sizes and locations of temporary fire protection facilities (E3.1)’ considering the necessity and importance of the tasks absolutely and relatively, and the possibility of overlap with other tasks. Thus, 26 construction engineering tasks excluding E3.1 were first refined.

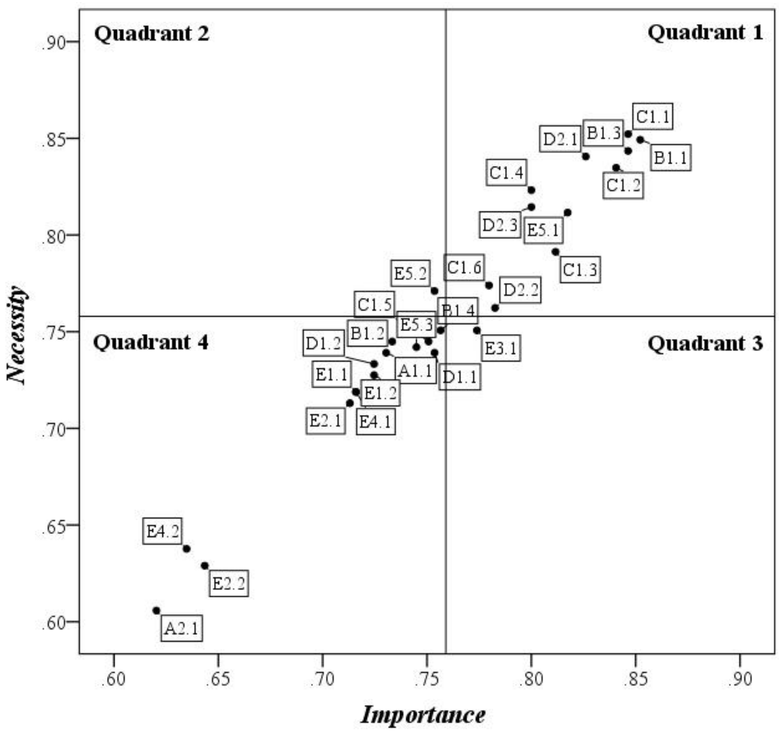
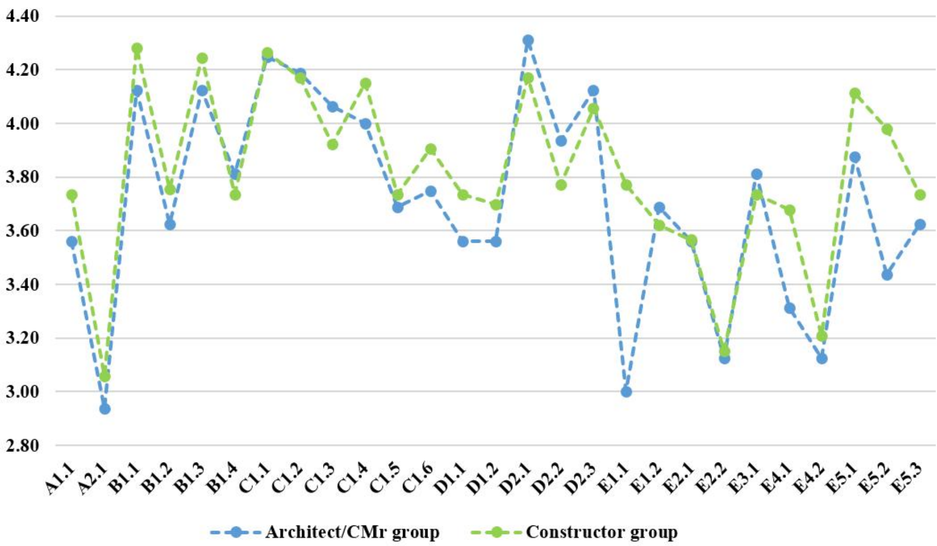


Fig. 4.2. Importance-necessity analysis

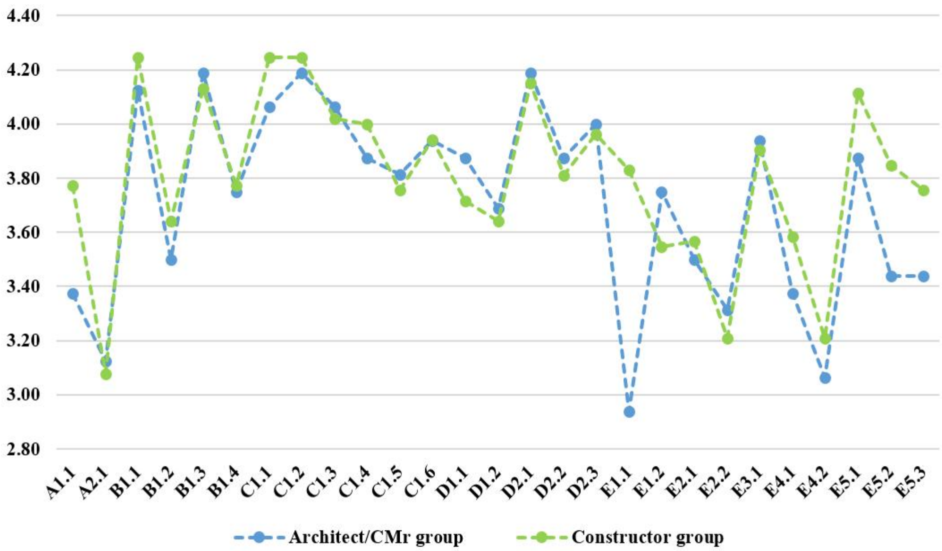
4.2.4. Analysis of differences in recognition

For efficient performance of engineering tasks reflecting CI in the design phase, it is necessary to investigate the recognition of differences between groups because smooth communication is required among participants. In this section, differences in recognition of tasks between the architect, the construction manager (CMr), and the constructor group are analyzed.

Based on the personal data in questionnaires, the architect and CMr group (16 people) from the constructor group (53 people) was separated and the averages of the necessity and importance of tasks for each group (Figure 4.3) were derived. Both necessity and importance showed similar trends and there was little difference between groups in most tasks. However, three tasks (E1.1, E4.1, E5.2) in terms of necessity and four tasks (E1.1, E5.2, E5.3, A1.1) in terms of importance showed larger differences than other tasks. The constructor group perceived the necessity and importance of these tasks to be relatively higher than the architect and CMr group did. On the other hand, for task D1.1, the constructor group perceived the necessity of the task to be relatively higher than the architect and CMr group did, while the architect and CMr group perceived the importance of the task to be relatively higher than the constructor group did.



(A) Necessity



(B) Importance

Fig. 4.3. Comparison of average values on each task by groups

A *t*-test analysis was conducted for a more accurate assessment of recognition differences between the groups. This is the analytical method used to examine the average difference between two sample groups (Kim, 2017). It was applied to confirm whether there is a statistically significant difference between the two groups in terms of the average of necessity and importance of each task. The analysis showed that there is no statistically significant difference in the necessity and importance of tasks except for task E1.1 ('Heating and cooling systems for efficient construction operation'); the *t*-test results for task E1.1 are shown in Table 4.4. The *t*-test results indicate that the constructor group considers the necessity and importance of this task to be higher than the architect and CMr group do. This is because the constructor group, whose members perform construction in person clearly understand that the efficient planning of the heating and cooling equipment can improve the efficiency of construction through efficient management of resources at the finishing stage.

Table 4.4. *t*-Test results on E1.1

Category	Code	Group	Average (SD)	t-value	*p*
Necessity	E1.1	Architect/CMr	3.00 (1.37)	2.493	0.015*
		Constructor	3.77 (0.99)		
Importance	E1.1	Architect/CMr	2.94 (1.18)	3.053	0.003**
		Constructor	3.83 (0.98)		

Note: *p < 0.05, **p < 0.01, SD = Standard deviation

4.3. Task Determination by Factor Analysis

Factor analysis is a statistical technique that analyzes the correlations between multiple variables and describes the variables through common underlying dimensions (Lee and Lim, 2005). In this section, factor analysis is applied to refine the 26 engineering tasks described previously and to reclassify criteria based on the literature review and group interviews (Table 4.1), and analyzed using the program SPSS 23.0 based on the importance data.

First, exploratory factor analysis was carried out to verify the validity, and Kaiser-Meyer-Olkin (KMO) and Bartlett's tests and communality were confirmed for interpretation of results. The KMO and Bartlett's tests confirm the fit of the model produced by the factor analysis; the KMO value is close to 1 while the Bartlett's significance probability is less than 0.05, which means that the model is appropriate. The KMO value obtained is 0.793 and Bartlett's significance probability (P) is 0.000, showing that the use of factor analysis of derived tasks is appropriate.

Principal component analysis using the Varimax method was used as the factor extraction model for the feasibility analysis. In the initial rotated component matrix, the 26 tasks were grouped into seven factors. The explanatory power of all factors was 70.68%, which is high. To refine the tasks through the factor analysis, the factor loadings and reliability analysis of the tasks were repeated. The first factor analysis found ungrouped tasks (E3.1 and E4.1) that were relatively low in reliability, and both tasks were thus eliminated. The second factor analysis was performed again and task E5.2 was removed because the 'Cronbach's α if item deleted' value increased through the reliability analysis. Task E5.2 is considered to have been removed because it is simultaneously executable with the task 'Electric power supply and distribution system, and electric room (E5.1).' From the third factor analysis, the reliability of task E1.1 was analyzed to be very low, so it was also removed. For task C1.6, factor loadings were redundantly over 0.4, which was relatively high, so it was also removed. In the first factor analysis, there were 26 tasks and seven factors, while 21 tasks and five factors remained after the elimination of inappropriate tasks.

KMO and Bartlett's test of the final items after factor analysis are shown in Table 4.5.

The KMO value is 0.829, which is higher than the initial value, and the Bartlett's significance probability remains at p = 0.000, so the suitability of the model remains very high.

Table 4.5. KMO and Bartlett's test

KMO measure of sampling adequacy		.829
Bartlett's Test of Sphericity	Approx. chi-square	698.193
	df	210
	Sig.	.000

Note: df = degree of freedom, Sig. = Significance probability

Table 4.6 shows the communalities. The communality can be explained by the extracted factors, and it is better to exclude the variables with low communality (Song, 2010; Kim et al., 2015). Although task C1.1 has a relatively low communality of less than 0.5, when the factor analysis was performed for the initial 26 tasks, the communality value (0.55) was relatively low compared with other tasks. Therefore, task C1.1 was not removed. The ranking analysis showed that it was better not to remove task C1.1 because it has high necessity and importance.

Table 4.6. Communalities

Code	Variable name	Initial	Extraction
A1.1	Standardization and fire code requirements of temporary facilities	1.000	.793
B1.1	Location of temporary disaster control room and switching to the permanent one	1.000	.694
B1.2	Other machinery for on-site materials handling (gantry cranes, monorails, fork lifts, trucks, etc.)	1.000	.545
B1.3	Lifting plans for tower cranes, hoists, and elevators	1.000	.706
B1.4	Centralization of material transportation systems	1.000	.641
C1.1	Construction method for core structure and formwork operations	1.000	.422
C1.2	Concrete pumping methods	1.000	.603
C1.3	Rebar placing and splicing methods	1.000	.736
C1.4	Zoning for concrete placement (i.e., construction joints)	1.000	.682
C1.5	Facade protection during structural work	1.000	.565
D1.1	Method of surveying and sensor embedment	1.000	.712
D1.2	Access roads and pits for permanent measurement	1.000	.691
D2.1	Vertical transportation plan by construction stage	1.000	.664
D2.2	Space zoning between built and working zones	1.000	.551
D2.3	Evacuation routes and spaces	1.000	.623
E1.2	Ventilation and dust reduction in working zones during internal finishing work	1.000	.539
E2.1	Switching between temporary and main water tank according to water supply capacity	1.000	.796
E2.2	Switching between temporary and main septic tank according to sewage capacity	1.000	.725
E4.2	Temporary access control system and CCTV layout	1.000	.722
E5.1	Electric power supply and distribution system, and electric room	1.000	.724
E5.3	Lighting for collision prevention (tower cranes, airplanes, etc.)	1.000	.750

Table 4.7 shows the explanation of the total variance. It shows the eigenvalue of each factor and its explanatory power (% of variance). The eigenvalue represents the amount of variance explained by the factor; larger values mean that the factor explains the variance of the variables well (Lee and Lim, 2005). In this study, the number of factors was

determined based on the commonly used eigenvalue 1, and 21 tasks (variables) were extracted as a total of five factors. Rotation sums of squared loading was 66.12%, so this is the total explanatory power of the five factors. Thus, the factor analysis of the initial 26 tasks showed a slight decrease from the explanatory power of the seven factors (70.68%). The results of the final factor analysis were slightly lower than the explanatory power (70.68%) of the seven factors in the initial 26 tasks. However, even though the number of factors decreased from seven to five and the number of tasks decreased from 26 to 21, the explanatory power was still more than 60%, indicating that this analysis summarized the information efficiently.

Table 4.7. Total variance explained

Component	Total variance explained								
	Initial eigenvalues			Extraction sums of squared loading			Rotation sums of squared loading		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	7.554	35.973	35.973	7.554	35.973	35.973	3.982	18.961	18.961
2	2.246	10.695	46.668	2.246	10.695	46.668	3.694	17.592	36.553
3	1.574	7.495	54.163	1.574	7.495	54.163	2.312	11.010	47.563
4	1.326	6.312	60.475	1.326	6.312	60.475	1.975	9.405	56.968
5	1.186	5.646	66.121	1.186	5.646	66.121	1.922	9.153	66.121
6	.928	4.417	70.538	-	-	-	-	-	-
7	.800	3.811	74.349	-	-	-	-	-	-
8	.699	3.331	77.680	-	-	-	-	-	-
9	.629	2.996	80.676	-	-	-	-	-	-
10	.593	2.825	83.501	-	-	-	-	-	-
11	.577	2.748	86.249	-	-	-	-	-	-
12	.474	2.259	88.508	-	-	-	-	-	-
13	.415	1.975	90.484	-	-	-	-	-	-
14	.369	1.755	92.239	-	-	-	-	-	-
15	.325	1.550	93.788	-	-	-	-	-	-
16	.309	1.469	95.257	-	-	-	-	-	-
17	.288	1.371	96.629	-	-	-	-	-	-
18	.210	1.001	97.630	-	-	-	-	-	-
19	.201	.958	98.588	-	-	-	-	-	-
20	.157	.745	99.333	-	-	-	-	-	-
21	.140	.667	100.000	-	-	-	-	-	-

Table 4.8 shows factor loadings and reliability coefficients (Cronbach's α) for each of the five factors in the final rotated matrix. The factor loading represents the degree of correlation between each variable and factor, and each variable belongs to the factor with the highest factor loading. Usually, the criterion of factor loading is 0.4 or more, and variables (tasks) with high factor loadings are important variables in the factor (Jung et al., 2007). The factor loadings of each task were 0.4 or more in all five factors, indicating that each factor consisted of significant variables. In the reliability analysis results, the reliability coefficient of four of the factors was 0.7 or more, and the coefficient of the other factor was also very close to the criterion. Thus, reliability was ensured because there are no tasks to hinder reliability. As the Cronbach's α if an item is deleted is also lower or slightly higher than the coefficient value of the factor, all tasks that hinder reliability have been removed. Therefore, the comprehensive factor analysis results show that the factors have been properly refined and classified.

Table 4.8. Rotated component matrix and reliability statistic

Component	Code	Factor loading	Cronbach's α	Cronbach's α if item deleted
1	D1.2	.824	0.894	.886
	C1.4	.768		.875
	D1.1	.703		.871
	C1.3	.640		.868
	D2.1	.608		.875
	D2.3	.569		.883
	C1.1	.542		.897
	C1.5	.414		.887
2	B1.3	.788	0.826	.772
	B1.4	.773		.802
	B1.1	.721		.774
	B1.2	.641		.817
	C1.2	.634		.797
3	E4.2	.810	0.69	0.559
	E1.2	.644		0.636
	D2.2	.589		0.601
4	E2.1	.869	0.76	-
	E2.2	.820		-
5	A1.1	.865	0.716	.593
	E5.3	.836		.451
	E5.1	.530		.752

In this section, 27 initial preliminary engineering tasks were refined into 21 tasks through factor analysis. In addition, the five categories based on the literature review and expert group interviews (Table 4.1) were reclassified into five categories using similar characteristics of factors: ‘Structural method and surveying’, ‘Vertical transportation of resources’, ‘Space zoning’, ‘Water supply’, ‘Temporary facilities and services’ (Table 4.9). ‘Surveying’-related tasks were classified into the same factor as the ‘Structural method’, as it seems more efficient in improving the constructability to perform the surveying plan at the same time as the structural framework plan. The lifting equipment and the concrete pumping plan were classified as the same factor for similar reasons. The factors related to ‘Space zoning’, ‘Water supply’ and ‘Temporary facilities and services’ are not factors directly affecting the construction work, but they enable efficient utilization of resources and most of the detailed tasks are used in the construction work. Therefore, the following factors can be seen as tasks that easily satisfy the requirements after completion of construction.

Table 4.9. Final task factors for constructability improvement

Group	Code	Tasks
Structural method and surveying	D1.2	Access roads and pits for permanent measurement
	C1.4	Zoning for concrete placement (i.e., construction joints)
	D1.1	Method of surveying and sensor embedment
	C1.3	Rebar placing and splicing methods
	D2.1	Vertical transportation plan by construction stage
	D2.3	Evacuation routes and spaces
	C1.1	Construction method for core structure and formwork operations
	C1.5	Facade protection during structural work
Vertical transportation of resources	B1.3	Lifting plans for tower cranes, hoists, and elevators
	B1.4	Centralization of material transportation systems
	B1.1	Location of lifting equipment in consideration of finishing work
	B1.2	Other machinery for on-site materials handling (gantry cranes, monorails, fork lifts, trucks, etc.)
	C1.2	Concrete pumping methods
Space zoning	E4.2	Temporary access control system and CCTV layout
	E1.2	Ventilation and dust reduction in working zones during internal finishing work
	D2.2	Space zoning between built and working zones
Water supply	E2.1	Switching between temporary and main water tank according to water supply capacity
	E2.2	Switching between temporary and main septic tank according to sewage capacity
Temporary facilities and services	A1.1	Standardization and fire code requirements of temporary facilities
	E5.3	Lighting for collision prevention (tower cranes, airplanes, etc.)
	E5.1	Electric power supply and distribution system, and electric room

5. Process Development of CI integration in the Design Phase

5.1. Design Process Review

It is necessary to investigate the existing design process to reflect the engineering tasks in the design phase effectively. However, because of the lack of open data on the design process, this study assumes a design process based on data from domestic design offices and existing literature (Kim, 2005; Shon, 2013).

(1) Schematic design process

The schematic design stage gives shape to a plan based on consultations about the planning work, sets the design goals of size, budget, function, quality, and aesthetics of the building, and selects the best possible alternative. Accordingly, at the schematic design stage, architectural design concepts should be set up to clarify the requirements of the client and the basic system review of the related specific fields (such as structure, machinery, electricity, civil engineering, and lighting) should be conducted to select the actual design alternatives. In the schematic design, it is necessary to determine the construction method and equipment as well as to estimate the construction costs and the process schedule, so that it is necessary to apply the engineering tasks reflecting the constructability (Figure 5.1).

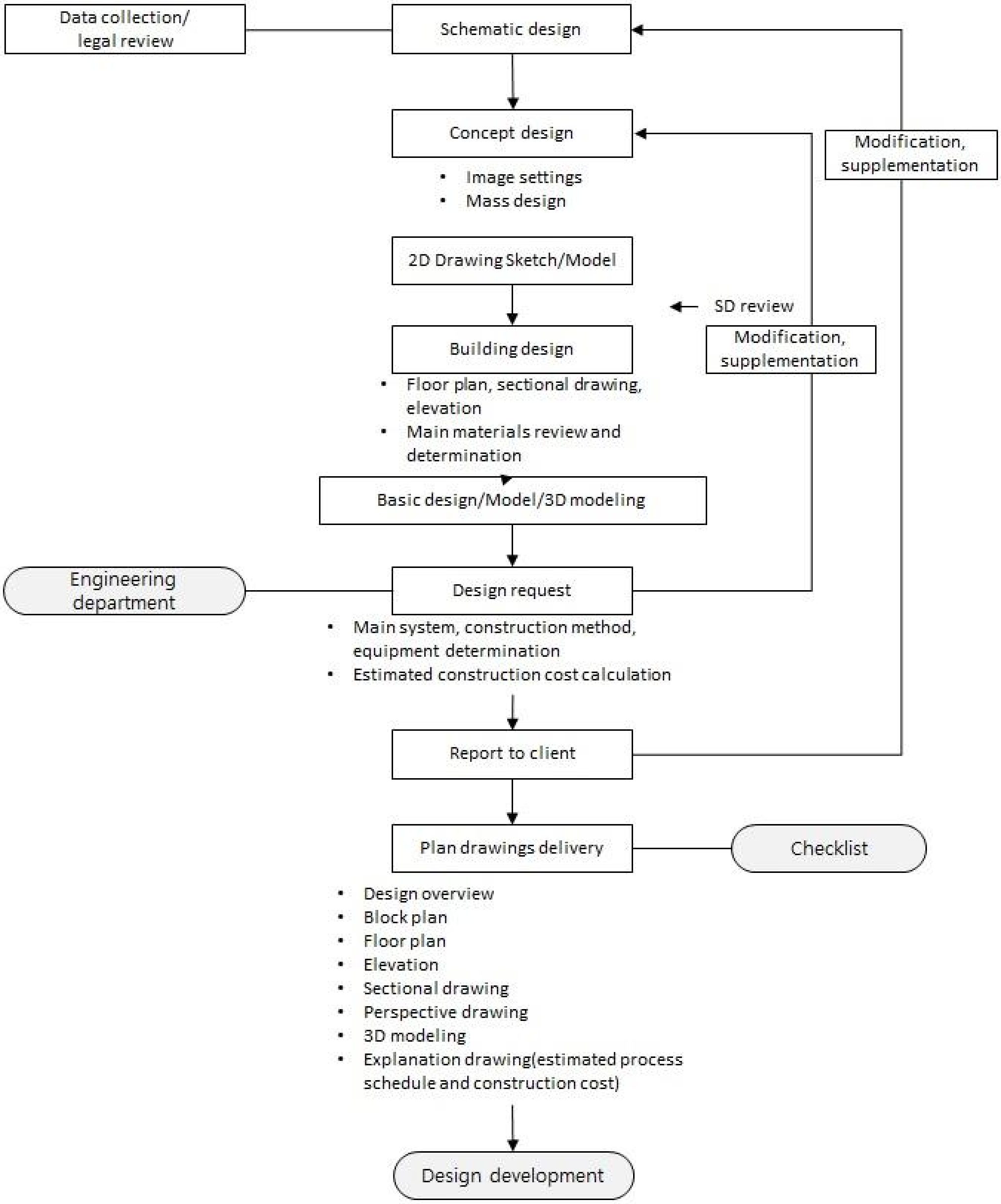


Fig. 5.1. Schematic design process (modified from Kim, 2005)

(2) Design development process

Design development is the step of specifying the type of building and developing the building components. It embodies the design model approved by the client in the schematic design stage. Figure 5.2 shows that it is difficult to examine various problems that occur during construction because the scope of the design development process participants is limited to the structure, civil engineering, mechanical, electrical, and fire protection parts. Therefore, engineering application is required, and constructability should be reviewed.

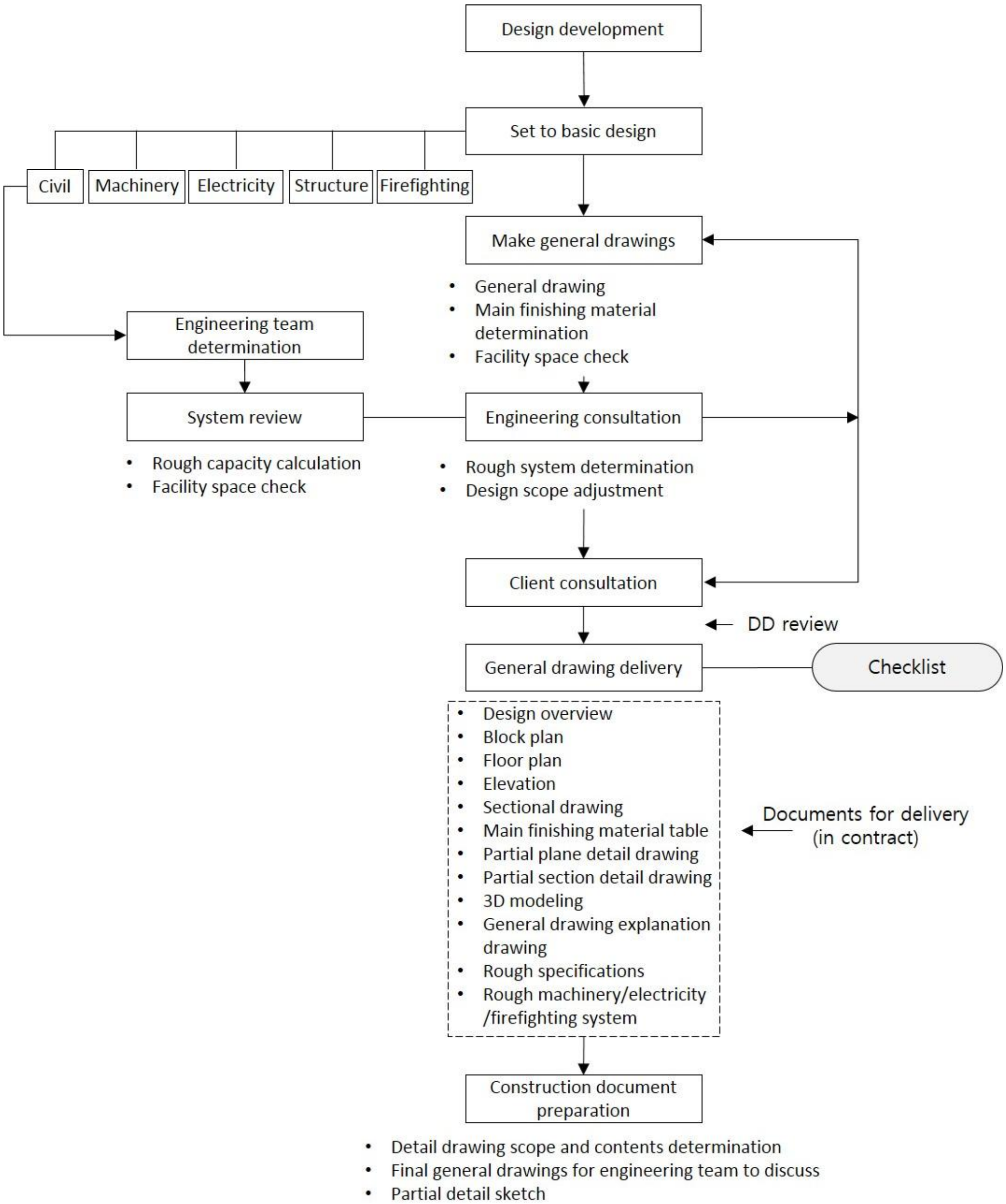


Fig. 5.2. Design development process (modified from Kim, 2005)

(3) Construction documentation process

The construction documentation stage completes the design to the optimal levels for bidding and construction by determining all the information of building range, size, quality, location, texture, and color. Engineering tasks related to each field apply in the construction document process because there are participants in the fields of civil engineering, construction, machinery, electricity, and firefighting. Improved constructability can be obtained in this stage by improving communication between participants in each field (Figure 5.3).

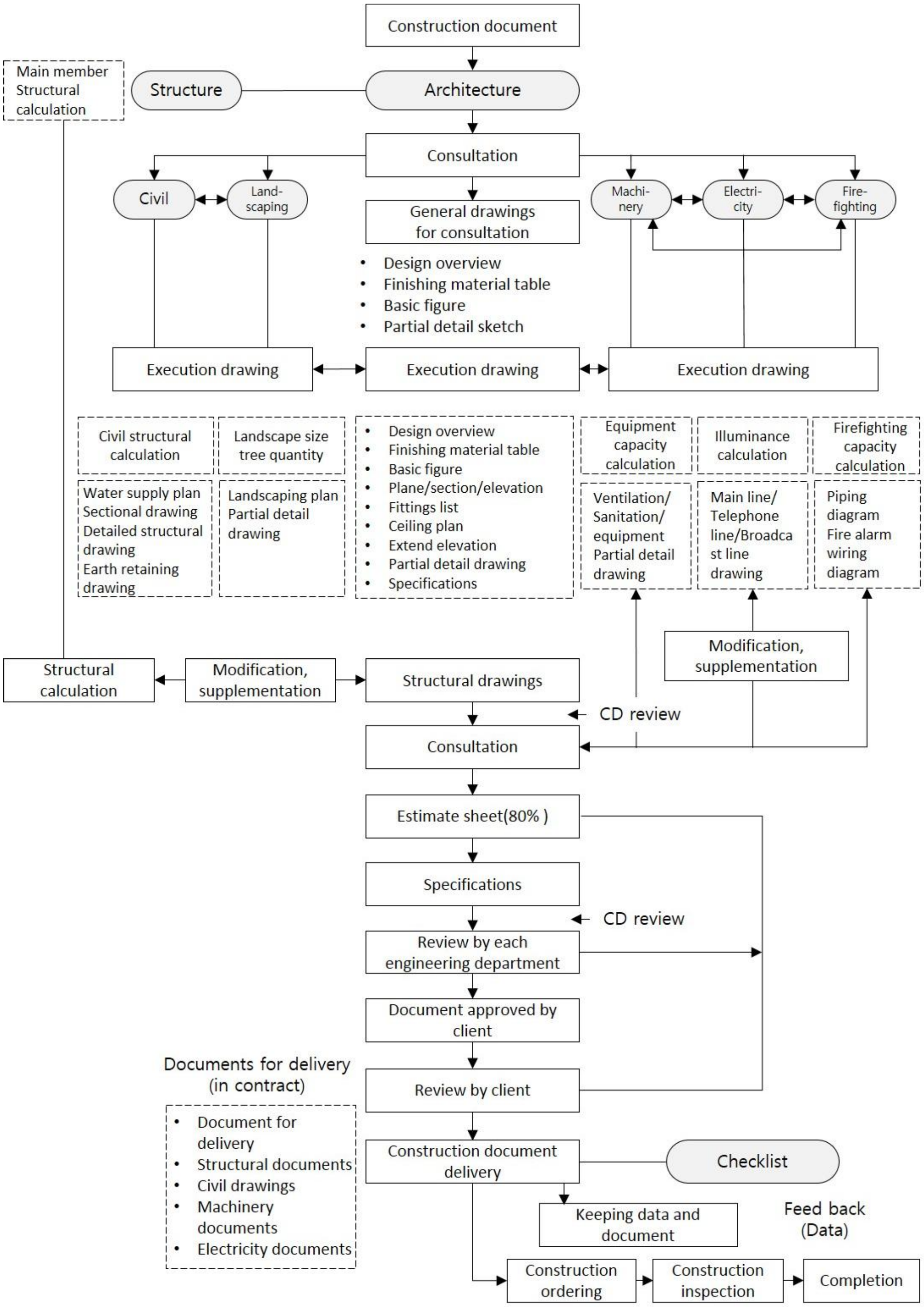


Fig. 5.3. Construction document process (modified from Kim, 2005)

5.2. Application Period and Participants in Engineering Tasks

To reflect the engineering tasks effectively in the design phase, it is necessary to determine the execution subject and the proper execution point in time for each construction engineering task. In this section, based on the construction engineering tasks derived from section 4, the application period and execution subjects of each task were analyzed through interviews with experts (Table 5.1). The design phase includes only the three phases of schematic design, design development, and construction document phase except for the predesign, which has limited applications of construction engineering tasks, and a shop drawing step is additionally proposed considering the tasks that must be reflected in the drawings after the design phase.

The subjects of each task are classified into architecture, construction, structure, machinery, electrical, and fire/disaster prevention. The architects and constructors should participate in all tasks in common because of the characteristics of the engineering tasks. In addition, in the existing task ‘Construction method for core structure and formwork operations (C1.1)’, it was difficult to reflect the engineering efficiently when considering the application point in time and the execution in the design phase; therefore, the existing task C1.1 was separated into ‘Selection of core construction method (C1.1)’ and ‘Plan for formwork operations (C1.6)’.

Table 5.1. Application period by design stage and participants of engineering tasks

Category	Code	Construction engineering task	Application period				Participant			
			SD	DD	CD	SH	S	M	E	F
Structural method and surveying	D1.2	Access roads and pits for permanent measurement	◎	●			√			
	D1.1	Method of surveying and sensor embedment	◎	●			√			
	C1.4	Zoning for concrete placement (i.e., construction joints)		◎	●		√			
	C1.3	Rebar placing and splicing methods		◎	●		√			
	C1.6	Plan for formwork operations		◎	●		√			
	D2.3	Evacuation routes and spaces		◎	●					√
	C1.1	Selection of core construction method	◎	●			√			
	D2.1	Vertical transportation plan by construction stage			◎	●	√			
	C1.5	Facade protection during structural work			◎	●	√			
Vertical transportation of resources	B1.3	Lifting plans for tower cranes, hoists, and elevators		◎	●		√	√	√	
	B1.4	Centralization of material transportation systems		◎	●		√			
	B1.1	Location of lifting equipment in consideration of finishing work		◎	●		√			
	C1.2	Concrete pumping methods		◎	●		√	√	√	
	B1.2	Other machinery for on-site materials handling (gantry cranes, monorails, fork lifts, trucks, etc.)			◎	●	√			
Space zoning	E4.2	Temporary access control system and CCTV layout			◎	●			√	
	E1.2	Ventilation and dust reduction in working zones during internal finishing work			◎	●		√	√	
	D2.2	Space zoning between built and working zones	◎	○	●					
Water supply	E2.1	Switching between temporary and main water tank according to water supply capacity		◎	●			√	√	
	E2.2	Switching between temporary and main septic tank according to sewage capacity		◎	●			√	√	
Temporary facilities and services	A1.1	Standardization and fire code requirements of temporary facilities			◎	●		√	√	√
	E5.3	Lighting for collision prevention (tower cranes, airplanes, etc.)		◎	●				√	
	E5.1	Electric power supply and distribution system, and electric room		◎	●				√	

Note: SD = Schematic design, DD = Design development, CD = Construction documents, SH = Shop drawing,
S = Structure, M = Machinery, E = Electricity, F = Fire and disaster prevention
◎ = Discuss rough plans and methods, ○ = Presentation and organization of plans,
● = Final plan confirmation and drawing reflection

Based on the above results, similar tasks were regrouped to reflect the engineering tasks in the design process (Table 5.2) efficiently. There are limitations in reflecting the tasks at the design stage because the application period and subject of each task are not considered in the five groups derived from Section 4. In addition, the derived tasks are less applicable in terms of the efficiency and necessity of performing tasks when the 22 tasks are individually performed at the design stage. Therefore, the tasks were regrouped considering the similarity of task characteristics, application periods, and subjects. In addition, grouped tasks were subdivided so that the subdivided tasks (22 tasks) could be performed in the design process. For example, the task ‘Main construction method for framework’ includes three engineering tasks: ‘Zoning for concrete placement (C1.4)’, ‘Rebar placing and splicing method (C1.3)’ and ‘Plan for formwork operations (C1.6)’. Following the subdivided tasks, comparison of alternative construction methods is performed in the design development stage, and the final selection of construction method is carried out in the construction document stage.

Therefore, the 22 subdivided tasks can be reflected more efficiently in the design process than the existing categories derived from Section 4 because they were selected considering the appropriate point in time and subject in the design phase.

Table 5.2. Regrouping results of tasks for effective integration with design activities

Category	Code	Regrouping	Subdivided task
Structural method and surveying	D1.2 D1.1	Surveying	Comparison of surveying plans Selection of surveying plans and locations
	C1.4 C1.3 C1.6	Construction methods for rebar, formwork, and concrete operation	Comparison of alternatives for construction methods for rebar, formwork, and concrete operation Selection of construction method for rebar, formwork, and concrete operation
	D2.3	Evacuation	Review of evacuation floor and route Selection of evacuation plan
	C1.1	Core construction method	Comparison of alternatives for core construction methods Selection of core construction method
	D2.1	Vertical transportation of resources	Plan for vertical transportation of resources
	C1.5	Facade protection	Facade protection plan
Vertical transportation of resources	B1.3 B1.4 B1.1 C1.2	Lifting equipment and concrete pumping	Comparison and review of the lifting equipment and concrete pumping plans Selection of lifting equipment and concrete pumping plan
	B1.2	Machinery for on-site materials handling	Plan for materials handling machinery
Space zoning	E4.2 E1.2	Security and ventilation	Space plan for Security and ventilation systems
	D2.2	Separation between built and working zones	Analysis of separation plans between built and working zones Select alternatives for separation between built and working zones Selection of separation plan between built and working zones
Water supply	E2.1 E2.2	Water supply	Comparison of alternatives water supply plans Selection of water supply plan
Temporary facilities and services	A1.1	Temporary facilities	Review of standardization and fire protection for temporary facilities
	E5.3 E5.1	Electricity and lighting	Comparison of alternatives for electric power supply and lighting plan Selection of electric power supply and lighting plan

5.3. Integrated Process for CI and Design Activities

5.3.1. Dependency structure matrix

There are many ways to model the design process, among which the critical path method (CPM) has visual clarity and can measure work time, but it is difficult to express the precedence relationships between tasks clearly. Integration definition functional modeling is designed to model the decisions, actions, and activities of an organization or system. It is an analytical theory developed to extract problems and design an improved model through model analysis (Shin, 2006). However, it is not suitable for design process modeling because it is difficult to represent if there are two or more repetitive tasks. DSM, on the other hand, has been primarily used as a design process management tool and can visualize the independence, sequencing, and interrelationships of tasks. It also has the advantage of representing precedence relationships through segmentation of activities, so that the flow of information can be grasped and marking of simultaneous tasks is possible (Jang, 2009).

The DSM methodology is expressed as an $n \times n$ matrix that represents the network between activities, and it can show the flow of complex information between n activities in a binary representation. The DSM also shows the relationship between the activities as parallel (independent), sequential, coupled (interdependent), as shown in Figure 5.4 (Park et al., 2012; Ahn et al., 2013).

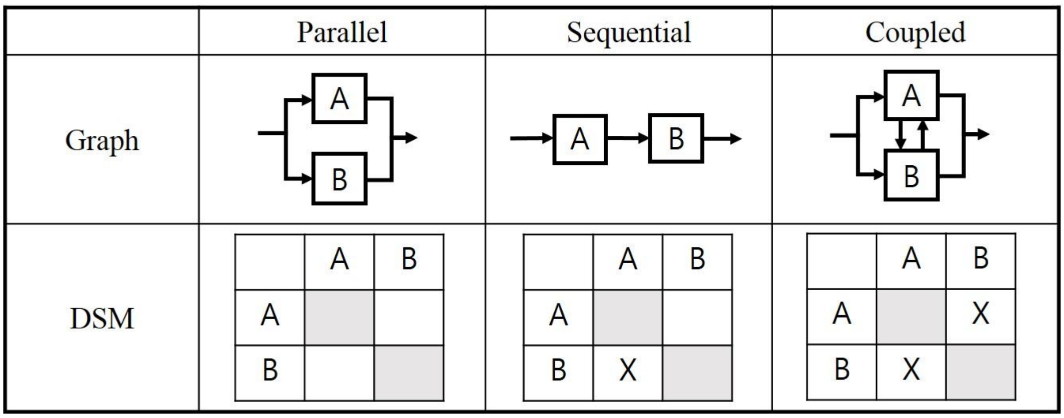


Fig. 5.4. Relationships between activities A and B (modified from Park et al., 2012)

In the graph in Figure 5.4, 'Parallel' shows no interaction between A and B activities, and there is no information to be exchanged, so there are no X marks that indicate the relationship of activities in the DSM. This shows that activities A and B are independent. 'Sequential' indicates that only one of the activities A and B affects the other activity, and the graph indicates that information is transferred from activity A to activity B. Therefore, activity B is dependent on activity A, and the X mark in DSM means that activity A gives information to activity B. 'Coupled' represents the exchange of information between activity A and activity B and can be expressed in an interdependent relationship between the two activities. On the DSM, both activities are indicated by an X mark.

The DSM generated through the above process can be analyzed by using partitioning, tearing, and/or clustering algorithms. These algorithms are used for different purposes according to the application subject (Browning, 2001; DSMweb.org, 2017). In this study, a partitioning algorithm was used to optimize information flows between CI and design activities. The partitioning algorithm is a method for analyzing the entire process with an emphasis on independent and sequential relationships. Figure 5.5 shows a simple example of the partitioning algorithm (Maheswari et al., 2006; Jang et al., 2009).

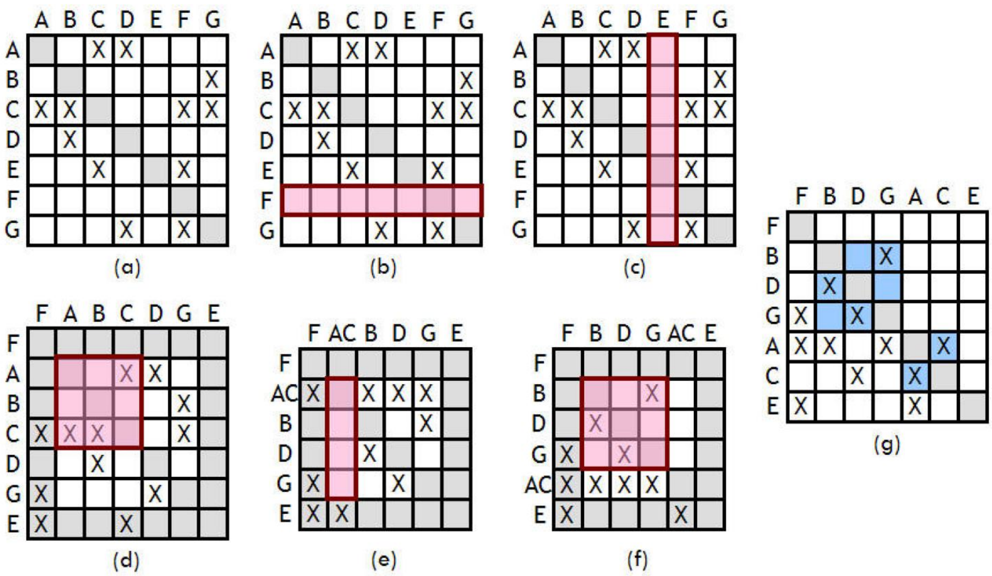


Fig. 5.5. Partitioning algorithm method (Jang et al., 2007)

(a) The first matrix, not yet partitioned.

(b) Activity F is independent because all cells of the row are empty and there is no information received from other activities. Therefore, activity F should be placed at the front of the matrix and excluded.

(c) Activity E has no information to deliver to other activities since all cells of the column are empty. Thus, activity E is placed at the end of the matrix and excluded.

(d) Except for the already excluded activities F and E, there are no more empty rows or columns in the matrix. Activities A and C are mutually dependent because they exchange information with each other. Thus, activities A and C can be grouped into a single activity AC for simplicity.

(e) Activity AC has no information to deliver to other activities because all cells of the column are empty. Thus, place the activity AC at the end of the matrix and exclude it.

(f) Of the remaining activities, activity B delivers information to activity D and activity D delivers information to activity G. In addition, activity G delivers information to activity B, so that the information is circulated. Thus, activities B, D, and G are interdependent.

(g) This is the matrix after the partitioning process has been completed.

5.3.2. Integrated process based on information flow

This study suggests a CI integration process based on information flow using DSM that improves productivity by improving communication among task performers through application at the points in time of engineering tasks. Figure 5.6 shows the steps to build a CI integration process into the design phase.

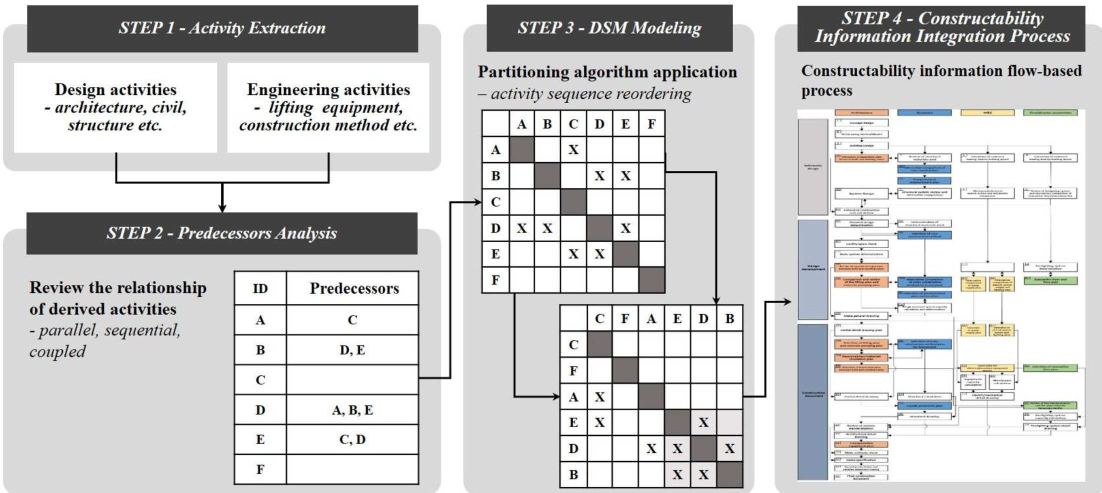


Fig. 5.6. Steps to build a constructability information integration process

In Step 1, design activities and engineering activities are derived based on previous sections and the activities can be divided into architecture, structure, Mechanical and Electrical (M&E), and fire/disaster prevention tasks. In Step 2, the dependencies of the activities derived in Step 1 are analyzed to utilize DSM. The precedence relationships between design activities and engineering activities are analyzed and activities are classified into independent, sequential, and interdependent relationships. In Step 3, the dependencies obtained in Step 2 are assigned to the matrix. The assigned activities are optimized and rearranged by a partitioning algorithm. In Step 4, the CI integration process is created by analyzing the results of Step 3 to visualize the feedback between the task performers, which can reduce wasteful factors such as design changes and rework and can contribute to improvements in constructability.

(1) Step 1 - Activity extraction

Design activities (Section 5.1) and engineering activities (Section 5.2) are derived from literature reviews and interviews with experts. These activities are divided into architecture, structure, M&E, and fire/disaster prevention in consideration of the task performers. Activities are also divided into schematic design phase, design development phase, and construction document phase considering the appropriate performance periods. Table 5.3 shows the derivation of the design activities.

In the schematic design phase, tasks related to architecture include mass design, legal review, and system design, together with defining the image of the building. Structural tasks involve reviewing the structural materials used, reviewing structural systems, and comparing alternatives. M&E and fire/disaster prevention tasks involve calculation of estimated loadings by building layout, reviewing the facilities systems, and comparing alternatives.

In the design development phase, the tasks related to architecture are to make detailed design decisions, to make main system decisions, and to create general drawings. Facilities and fire/disaster prevention tasks include rough calculation of facility system capacities, firefighting equipment determination, and evacuation simulation. Tasks related to the structure include determining the structural materials to be used and determining the rough system structure. At this time, to determine an efficient structural system, there should be consultations between architects, facility experts, and structural task performers.

In the construction document phase, tasks related to architecture are performed, such as partial detailed plans, detailed design drawings, and final construction document creation. The tasks related to the structure include the structural calculations and structural drawing tasks, and the tasks related to the M&E include the equipment capacity calculation and illuminance calculation tasks. Fire/disaster prevention tasks include firefighting system capacity calculation and firefighting system detailed drawing tasks, which will be included in the final construction document.

Table 5.3. Design activities extraction

Phase	Subject	Activity name
SD	A	Concept design (image setting, mass design, space program, legal review, transportation plan)
		2D drawing sketches/study models
		Building design (floor plan, sectional drawings, elevation, color plans, main material review and decision, rough specification)
		System design (outline main system determination)
		Estimated construction cost calculation
	S	Review of structural materials used
		Structural system review and alternatives comparison, wind tunnel tests
	M&E	Calculation of estimated loading dose for M&E system by building layout (loading dose reduction plan)
		Mechanical/electrical system review and comparison of alternatives (ecofriendly design review, vertical transportation plan)
	P	Calculation of estimated loading dose for firefighting system by building layout (loading dose reduction plan)
		Review of firefighting system and alternatives comparison of evacuation floor/evacuation line, evacuation simulation review
DD	A	Detailed design determination, legal review, transportation plan drawing
		Facility space check
		Main system determination (machinery, electricity, firefighting room area and location negotiation)
		Make general drawings (main finishing material determination, block plan, perspective drawing, model, rough specifications, estimated construction cost review, etc.)
	S	Determination of structural materials used
		Rough structural system capacity calculation and determination (column shortening analysis, structural health monitoring review)
	M&E	Calculation and determination of rough machine/electric system capacity, ecofriendly design
	P	Firefighting system determination, evacuation simulation

(Continued)

CD	A	Partial detailed drawings
		Partial detail drawings (curtain wall, windows and doors, chimney effect, architectural acoustics, building waste, Intelsat Business Service, security, finishing materials)
		Review of various standardizations
		Architectural detail drawings
		Make estimate sheets
		Make specifications
		Quantity calculations and detailed statement preparation
		Final construction documents
	S	Structural drawings
		Structural calculation
		Structural drawings
	M&E	Equipment capacity calculation
		Illuminance calculation
		Electric/mechanical detail drawings
	P	Firefighting system capacity calculation
		Firefighting system detail drawings

Note: A = Architecture, S = Structure, P = Fire/disaster prevention

Table 5.4 shows the derivation of the engineering activities. In the schematic design phase, there should be a rough discussion of the separation plan between built and working zones. The separation plan between built and working zones should be considered in the early design stage because it has a great influence on the improvement of constructability through efficient separation of resources (materials and manpower). The engineering tasks related to the structure include tasks to compare core construction method alternatives and compare measurement plans.

In the design development phase, the engineering tasks related to the architecture include the selection of the separation plan alternatives between built and working zones, review and comparison of the lifting equipment plan and concrete pumping plan, and the engineering tasks related to the structure, include the selection of the core construction method and comparison of the main construction methods for framework. Engineering tasks related to M&E and fire/disaster prevention include comparison of alternative water supply plans, comparison of alternative electric power supply and lighting plans, and evacuation floor and flow plans. Most tasks consist of planning and comparison of alternatives.

In the construction document phase, the engineering tasks consist of the final determination of the planned and alternative comparisons in the design development phase and the tasks that can be done in the shop drawing phase after the construction document phase. Engineering tasks related to the architecture include selection of a concrete pumping plan and a lifting plan, resource circulation plan, and structural engineering tasks include the selection of the main construction method for framework and a facade protection plan. Engineering tasks related to M&E include selection of a water supply plan, selection of an electric power supply and lighting plan, and selection of an evacuation plan. The engineering task related to fire/disaster prevention is the selection of an evacuation plan.

Table 5.4. Engineering activities extraction

Phase	Subject	Activity name
SD	A	Analysis of separation plans between built and working zones
	S	Comparison of alternatives for core construction methods Comparison of surveying plans
DD	A	Comparison and review of the lifting equipment and concrete pumping plans Select alternatives for separation between built and working zones
	S	Selection of core construction method Comparison of alternatives for construction methods for rebar, formwork, and concrete operation Selection of surveying plans and locations
	M&E	Comparison of alternatives water supply plans Comparison of alternatives for electric power supply and lighting plans
	P	Review of evacuation floor and route
CD	A	Selection of lifting equipment and concrete pumping plan Plan for vertical transportation of resources Selection of separation plan between built and working zones Plan for materials handling machinery
	S	Selection of construction method for rebar, formwork, and concrete operation Facade protection plan
	M&E	Selection of water supply plan Selection of electric power supply and lighting plan Space plan for electrical/machine equipment systems
	P	Selection of evacuation plan Review of the standardization and fire protection for temporary facilities

(2) Step 2 - Analysis of predecessors

In Step 2, the precedence relationships among the activities derived in Step 1 are classified as independent, sequential, or interdependent. The interdependence of each activity should be analyzed with a focus on the relationships between design activities and engineering activities, and the relationships between engineering activities, to reduce rework and waste in the design phase. The precedence relationships among the activities were analyzed through interviews with experts in design and construction and are shown in Table 5.5.

Table 5.5. Analysis of the precedence relationships among the activities

Discipline	Subject	Activity Name	ID	Predecessors
Design activity	A	Concept design	1	–
	A	2D drawing sketch/study model	2	1
	A	Building design	3	1,2
	S	Review of structural materials used	4	3,35
	M&E	Calculation of estimated loading dose for M&E system by building layout	5	3
	P	Calculation of estimated loading dose for firefighting system by building layout	6	3
	S	Structural system review and alternatives comparison, wind tunnel tests	7	3,4,10,36,37
	M&E	Mechanical/electrical system review and alternatives comparison	8	3,5
	P	Review of firefighting system and alternatives comparison of evacuation floor/evacuation line, evacuation simulation review	9	3,6
	A	System design	10	3,7,8,9
	A	Estimated construction cost calculation	11	7,8,9,10,35
	A	Detailed design determination, legal review, transportation plan drawings	12	10,11
	S	Determination of structural materials used	13	4,12
	A	Facility space check	14	7,8,9,12,37,38
	A	Main system determination	15	10,12,13,14,42
	S	Rough structural system capacity calculation and determination	16	7,13,15,17,18,38, 39,40,41
	M&E	Calculation and determination of rough machine/ electric system capacity, ecofriendly design	17	5,8,14,15,43,44
	P	Firefighting system determination, evacuation simulation	18	6,9,14,15,45
	A	Make general drawings	19	3,12,15,16,42
	A	Partial detail drawings plan	20	19
	P	Firefighting system capacity calculation	21	18,20,52,54
	M&E	Equipment capacity calculation	22	8,17,20,46,51
	M&E	Illuminance calculation	23	8,17,20,47,51
	S	Structural calculation	24	16,20,48
	A	Partial detail drawings	25	19,20,48,49
	S	Structural drawings	26	16,19,24,25,48,53
	M&E	Electric/mechanical detail drawings	27	17,19,22,23,46,47,51
	P	Firefighting system detail drawings	28	18,19,20,21,52
	A	Review of various standardizations	29	25,26,27,28,54
	A	Architectural detail drawings	30	26,27,28

(Continued)

Design activity	A	Make estimate sheets	31	29,30,55,56
	A	Make specifications	32	29,30,56
	A	Quantity calculations and detailed statements	33	30,31
	A	Final construction document	34	30,32
Engineering activity	A	Analysis of separation plans between built and working zones	35	3,4
	S	Comparison of alternatives for core construction methods	36	3,4
	S	Comparison of surveying plans	37	3,4,36
	S	Selection of core construction method	38	12,13,36
	S	Comparison of alternatives for construction methods for rebar, formwork, and concrete operation	39	12,13,38,40
	A	Comparison and review of lifting equipment and concrete pumping plans	40	12,13,14,38,39
	S	Selection of surveying plans and locations	41	16,37,38,39
	A	Select alternatives for separation between built and working zones	42	12,15,35
	M&E	Comparison of alternatives water supply plans	43	17
	M&E	Comparison of alternatives for electric power supply and lighting plans	44	17
	P	Review of evacuation floor and route	45	18
	M&E	Selection of water supply plan	46	17,19,43
	M&E	Selection of electric power supply and lighting plan	47	17,19,44
	S	Selection of construction method for rebar, formwork, and concrete operation	48	19,39,49,50
	A	Selection of lifting equipment and concrete pumping plan	49	20,40,48,50
	A	Plan for vertical transportation of resources	50	19,48,49
	M&E	Space plan for electrical/machine equipment systems	51	17,19
	P	Selection of evacuation plan	52	18,19,45
	S	Facade protection plan	53	25,48
	P	Review of the standardization and fire protection for temporary facilities	54	55
	A	Selection of separation plan between built and working zones	55	19,42
	A	Plan for materials handling machinery	56	30,48,50,53

(3) Step 3 - Partitioning algorithm application

The results of the activity predecessor analysis in Step 2 are applied to the DSM matrix, as shown in Figure 5.7. IDs 1–35 are design activities, and 36–56 are engineering activities, which are colored gray. Figure 5.8 shows the matrix with the partitioning algorithm applied to the DSM matrix of Figure 5.7 and Table 5.6 show the results of applying the partitioning algorithm. Some activities are clearly interdependent.

First, in block A of the schematic design phase, the tasks ‘Review of structural materials used (4)’ and ‘Analysis of separation plans between built and working zones (35)’ have a feedback relationship. The work space can be separated according to the structural materials and the construction period can be shortened and the work efficiency can be improved through efficient resource allocation. In block B, suitability review and alternatives comparison of structural system and system design are performed to obtain various design alternatives and structural performance at the same time. Because the design of the building must meet the structural performance requirements, information must flow between the two tasks.

Second, in the design development phase, block C represents the feedback relationship between the tasks ‘Main system determination (15)’ and ‘Select alternatives for separation between built and working zones (42)’. This is because the construction efficiency can be improved by separating the construction working zones according to the main system of the building, while selecting the main system of the building considering the separation of the construction working zones can result in a more efficient architectural design. In block D, the task ‘Calculation and determination of rough machine/electric system capacity (17)’ has a feedback relationship with the task ‘Comparison of alternatives water supply plans (43)’. This is because the rough water supply planning task must be considered when calculating the capacities of the septic tank and water supply tank. In addition, the relationship between the two tasks is interdependent because the capacity of the water supply tank and the septic tank must be reflected to propose alternatives to the water supply plan. Task 17 also has a feedback relationship with the task ‘Comparison of alternatives water supply plans (43)’, for similar reasons. Block E has a feedback relationship between the tasks ‘Firefighting system determination, evacuation simulation (18)’ and the ‘Review of evacuation floor and route (45)’. This is because the two tasks must be considered to determine the appropriate fire protection facility for the evacuation route, and it is possible to establish an effective evacuation floor/evacuation route plan setting according to the fire protection facilities decision. In block F, the construction method for the framework and the concrete pumping plan must collaborate to minimize waste factors such as rework in the design stage, and thus a feedback relationship is established. In block G, the tasks ‘Selection of surveying plans and locations (41)’ and ‘Rough structural system capacity calculation and determination (16)’ have a feedback relationship, and these tasks must be considered together to prepare for column shortening effectively.

In block H, the tasks ‘Selection of construction method for rebar, formwork, and concrete operations (48)’, ‘Selection of lifting equipment and concrete pumping plan (49)’ and ‘Plan for vertical transportation of resource (50)’ have a feedback relationship. This is because the resource transportation and the construction methods for structural work should be considered in the selection of lifting equipment and concrete pumping method while the concrete pumping method and location of lifting equipment should be considered when selecting the structural methods. In addition, the lifting equipment and the resource movement according to construction method should be considered for the resource circulation plan. Collaboration in these three tasks can be expected to improve the constructability in the construction phase.

In general, there is a great deal of information exchange in the design development phase. This is because after the rough design and form of building are derived from the schematic design phase, the engineering tasks should be reflected from the design development phase beforehand to reduce waste factors such as rework and design changes. Step 4 presents the CI integration process based on the results of Step 3.

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
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Fig. 5.7. Applying activities to the DSM matrix

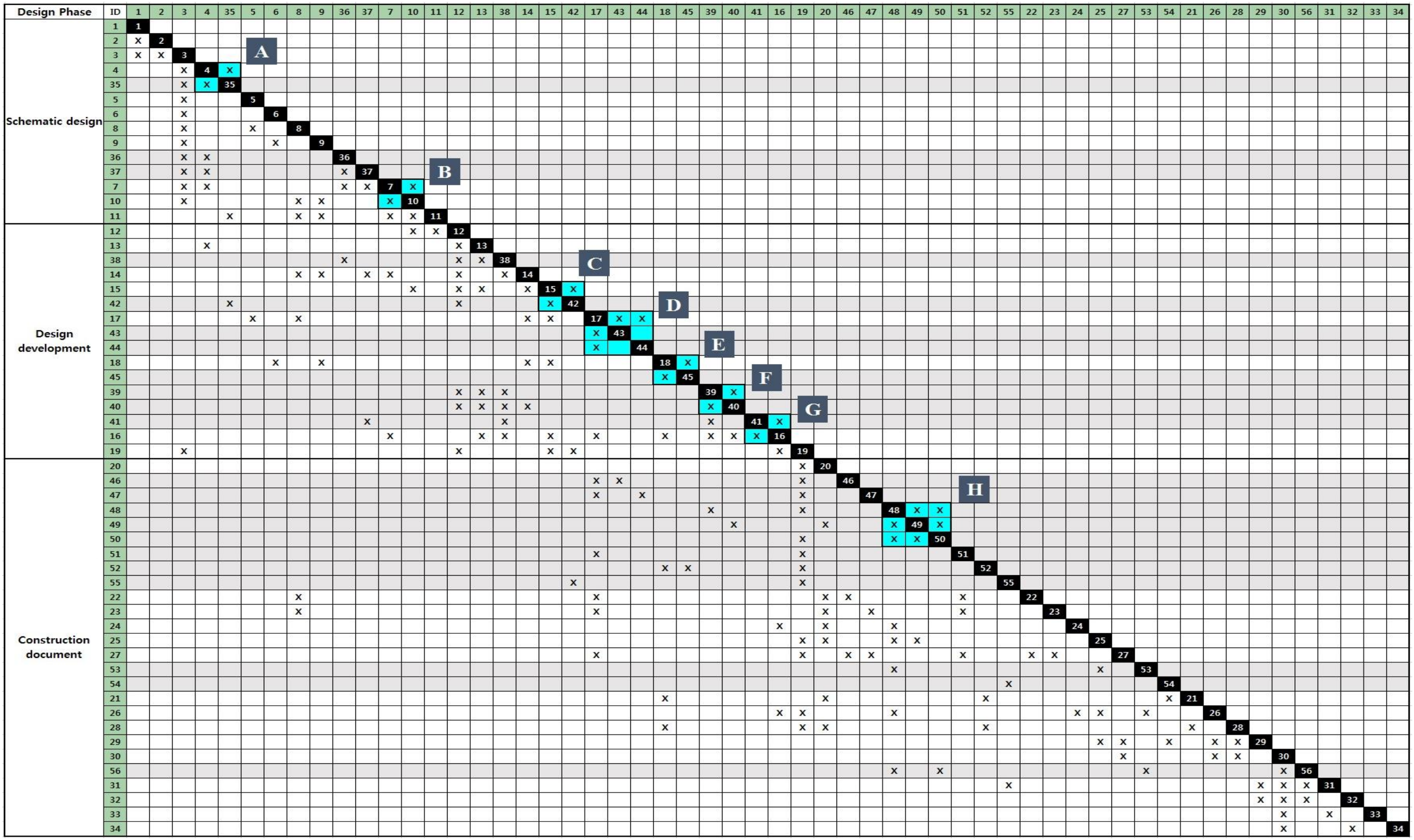

Fig. 5.8. Partitioning algorithm application

Table 5.6. Results of applying the partitioning algorithm

Phase	Block	Discipline	Subject	ID	Activity name
Schematic design	A	Design	Structure	4	Review of structural materials used
		Engineering	Architecture	35	Analysis of separation plans between built and working zones
	B	Design	Structure	7	Structural system review and alternative comparison, wind tunnel tests
		Design	Architecture	10	System design
Design development	C	Design	Architecture	15	Main system determination
		Engineering	Architecture	42	Select alternatives for separation between built and working zones
	D	Design	M&E	17	Calculation and determination of rough machine/electric system capacity, ecofriendly design
		Engineering	M&E	43	Comparison of alternatives water supply plans
		Engineering	M&E	44	Comparison of alternatives for electric power supply and lighting plans
	E	Design	Fire/disaster prevention	18	Firefighting system determination, evacuation simulation
		Engineering	Fire/disaster prevention	45	Review of evacuation floor and route
	F	Engineering	Structure	39	Comparison of alternatives for construction methods for rebar, formwork, and concrete operation
		Engineering	Architecture	40	Comparison and review of lifting equipment and concrete pumping plans
	G	Engineering	Structure	41	Selection of surveying plans and locations
		Design	Structure	16	Rough structural system capacity calculation and determination
Construction document	H	Engineering	Structure	48	Selection of construction method for rebar, formwork, and concrete operation
		Engineering	Architecture	49	Selection of lifting equipment and concrete pumping plan
		Engineering	Architecture	50	Plan for vertical transportation of resources

(4) Step 4 - CI integration process

In Step 4, a CI process that reflects the engineering tasks is proposed based on the results of the partitioning algorithm in Step 3 (Figure 5.9). Unlike existing design processes (Figures 5.1, 5.2, and 5.3), the proposed process clearly specifies the engineering task and the task subjects, so that the workflow sequence can be planned and rework can be reduced because interference between tasks can be avoided. In addition, it is possible to recognize beforehand when a decision must be made, so it is possible to carry out the task promptly by making quick decisions during the project. The engineering tasks are reflected at the appropriate point in time in the design phase, so that decision-making between the practitioners is performed efficiently. Through this process, it is possible to minimize the inefficient exchange of information that may occur during collaboration, thereby eliminating obstacles to design productivity. Therefore, the CI integration process based on the information flow using DSM can improve the productivity of the overall construction project by improving communications among the subjects of each task and helping the project manager to manage the engineering tasks efficiently.

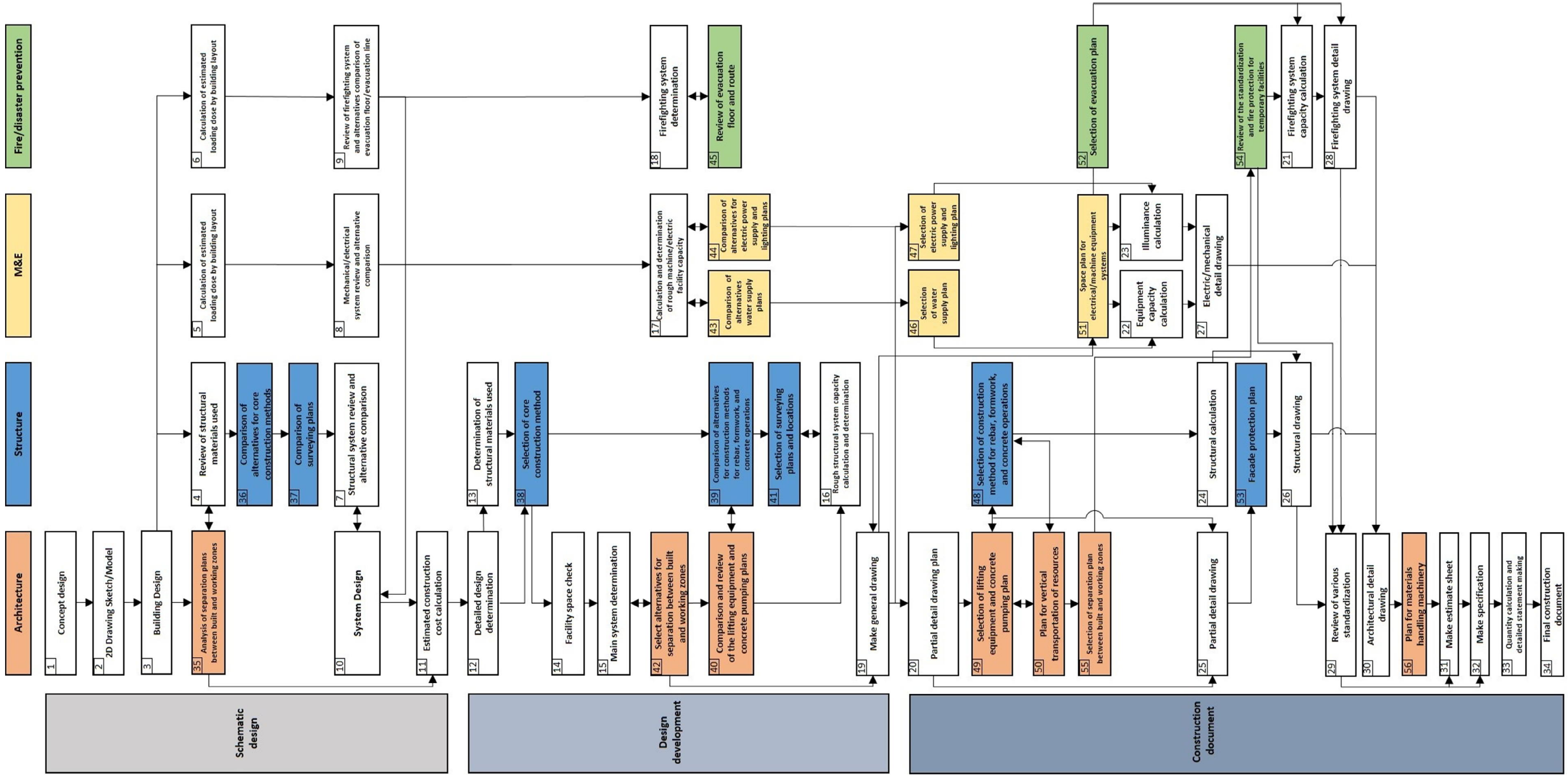

Fig. 5.9. Constructability information integration process

6. Conclusion

With the increasing number of high-rise building construction projects, reflecting construction knowledge and expertise during the design phase has a significant effect on successful project completion. It enables the minimization of inefficiencies such as design changes and rework, and allows improvements in constructability in the construction phase. There have been considerable efforts to make more buildable designs by using CI. Most previous approaches, however, are relatively unstructured, inefficient, and often lead to rework in design. To utilize this knowledge and expertise most effectively, the right information should be provided to the design teams at the proper time and at the appropriate levels of detail for successful integration with design activities.

Therefore, this study proposes a CI integration process model to improve constructability in the design phase in high-rise building construction. The proposed model organizes engineering tasks based on appropriate timing and levels of detail considering information flows of the existing design activities.

The main outputs of this study and their contributions are as follows:

1) The necessity and effects of introducing construction engineering in the design phase were investigated through a literature review and a questionnaire survey. The survey results showed that the proper application of CI in the design phase could have the greatest impact on constructability improvement and construction cost reduction. It also showed that engineering reflecting CI can be implemented well in the project deliveries based on integration of design and construction in the DB method. In addition, establishing an efficient work process was identified as the one of the important necessary activities.

2) Twenty-one engineering tasks, which have high importance and necessity for constructability improvement, were clearly presented from group interviews with experts, questionnaires, and statistical analysis. Those tasks can be used as basic data for introducing the CI integration process in the design phase. Based on these results,

practitioners can easily examine the necessary engineering tasks according to the conditions of the project.

3) The application period, work scope, and participants for each engineering task were investigated, and 22 regrouped engineering activities were derived. The activities consider the appropriate levels of detail that can be integrated with specific design activities, and thus they can be reflected more effectively in each design stage. These results can be used as a reference to organize project teams to maximize the efficiency of collaboration and knowledge sharing.

4) The CI integration process was developed by using the DSM technique. This focuses on optimization of information flows between design activities and CI. Thus, it can contribute to minimizing inefficient information exchanges that may occur during the design process, thereby eliminating obstacles to design productivity. The right CI with the appropriate levels of detail can also be provided to the design participants at the appropriate points in time. This helps to utilize the CI most effectively during the decision-making processes in the design phase. Moreover, the proposed process can provide a useful mechanism to organize constructability issues according to level of detail and the phase of the project.

The limitations of this study and future research needed on this topic are as follows:

1) This study focused on constructing an efficient process for utilizing CI in each design stage based on interviews and feedback with experts. However, the quantitative effectiveness of applying the proposed process was not fully investigated. Thus, it is necessary to verify how useful the proposed tasks and processes are in terms of reduction of rework, time, cost, and so on. There is also a need for further investigation of additional activities and interrelationship between design and CI. In addition, further study will be required to improve legal and institutional strategies to ensure practical use of the proposed model.

2) The model proposed in this study specified timing and related participants for each

activity, and interrelationships among activities. Although it is helpful to recognize decision-making 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 project participants and use information at each point of design to optimize decision-making processes. This model will help utilize the CI most effectively.

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