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CONSTRUCTABILITY IMPLEMENTATION MODEL USING DEPENDENCY STRUCTURE MATRIX

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ABSTRACT: Utilizing construction knowledge and experiences in design phase can reduce change orders and improve productivity in construction phase. To do so, information must be made available to the design team in time. Current approaches for effective utilization of constructability knowledge, however, only focus on the formalization of constructability knowledge such as a checklist, which lacks the consideration of the appropriate use at the proper point in time. The inadequate use of constructability knowledge can result in unnecessary reworks. To deal with this problem, the design team needs to know what constructability knowledge is required for specific design activities in the design process. This paper presents a constructability implementation model using the dependency structure matrix (DSM) that focuses on information flows between design activities and constructability knowledge. For this objective, design activities in the design process are modeled in a matrix form based on their dependency. Then, constructability knowledge, which needs to be considered in the design stage, is mapped into activities and incorporated into the matrix, creating Constructability-DSM (C-DSM). Next, the partitioning algorithm is applied to C-DSM for optimal information flow. The Partitioned C-DSM is then analyzed based on the relationship between activities. Finally, the optimal utilization of construction knowledge in the design process is determined by identifying what constructability knowledge is required for each design activity, and how and when it is reflected to design for constructability. Thus, this research can help provide robust control actions to reduce unnecessary iterative cycles in design process for efficient constructability implementation.

Keywords: Constructability, Design Process, Dependency Structure Matrix (DSM)

1. INTRODUCTION

As construction projects have become complicated and design and construction technique have advanced, design significantly depends on construction technique and performance. Design results reflecting construction knowledge and experience will contribute to more efficient construction and improve productivity by minimizing change orders and eliminating unnecessary costs [6]. To achieve these objectives, designers need to utilize the constructability knowledge necessary for design decision making at the proper point in time through collaboration with construction organizations [4].

Previous approaches to the utilization of the constructability knowledge in design stage have mainly focused on formalization of the constructability knowledge such as checklists necessary to be considered in each design stage: schematic design, design development, working drawing, shop drawings, etc. However, these lack consideration of the constructability knowledge in the level of activities, which are the unit for design decision making [9]. This may lead to productivity declines in overall design process. For instance, to reflect the constructability knowledge to the design after the relevant design has proceeded, designers have to rework not only just the related-design, but also other designs affected by the related-design [1]. To improve design productivity by minimizing this kind of inefficiency, design activities requiring the constructability knowledge need to be verified through design management from the perspective of design process [7].

Thus, this study is to suggest constructability implementation model using the dependency structure matrix (DSM) based on information flows in consideration of relationships between design activities, the unit for design decision making, and the constructability knowledge necessary to be considered in design stage. By doing this, the optimal utilization of construction knowledge in the design process is determined and it can help provide robust control actions for efficient constructability implementation.

2. LITERATURE REVIEW

2.1 Constructability

The concept of constructability was first coined based on a study in 1960s in the UK, and initially it was a narrow concept, focusing on productivity to figure out hidden inefficient factors throughout the construction industry. Thereafter, it developed into current principles and concept of integration of each construction production stage such as planning, design, and construction to improve cost–effectiveness and quality of the construction industry through studies in the US, UK and Australia in 1970s to 1990s. In addition, its practical principles, procedure and implementation methods were established and being used in construction projects. In this study, based on the definition by the Construction Industry Institute (CII) [3], constructability is defined as an optimized utilization of construction knowledge and experience in the phase of planning, design and construction to achieve overall project objectives.

Major positive effects by applying constructability to design stage are as follows:

- Improved construction efficiency by quality design reflecting constructability
- Cost reduction or waste factor removal by minimizing change orders
- Motivating contractors by giving them opportunity to contribute to a project

2.2 Previous Research

Researchers have been well aware of the importance of considering constructability in design stage and conducted related studies for an effective utilization of construction knowledge. Fischer and Tatum [4] noted that inefficient works occur because the constructability knowledge is not properly conveyed to designers and the major reason is lack of explicit and formal constructability knowledge. Thus, they set the foundation for an effective using the constructability knowledge by formalizing construction knowledge which is used in preliminary design stage.

Pulaski and Horman [11] suggested the level of constructability knowledge necessary for each design stage as a conceptual matrix model based on the integrated building process model (IBPM) and the product model architecture (PMA). Then, he formalized the constructability knowledge, promoting its effective use.

Park [10] suggested an improvement measure after analyzing constructability for a steel structure work and then, for an effective implementation of the improvement measure, he presented a checklist to improve constructability for a wide range of project participants including designers.

Review of previous studies reveals the following limitations. First, focusing on analysis and formalization, such as a checklist, of the constructability knowledge necessary for each design stage, they lack consideration of constructability in the level of activities, the unit for design decision making process. The constructability knowledge considered improper point in time may hinder productivity in design stage. For example, if designers want to reflect the constructability knowledge related to the load in design stage after the relevant design has proceeded, designers have to rework not only just changing a material strength for columns, but also column section, column layout, and accompanying HVAC layout to reflect this constructability knowledge. In addition, previous studies lack consideration on the ways to cooperate between designers and construction organization. The constructability knowledge is communicated in design stage through the cooperation between designers and construction organizations, but inappropriate way to cooperate may lead to inefficiency. For instance, if meeting is held whenever any collaboration is necessary, this is a waste of time and costs. To minimize these inefficiencies and improve design productivity, design management focusing on information flow between activities in design process is necessary.

2.3 Dependency Structure Matrix (DSM)

DSM, suggested by Steward in 1965, has been widely used for design process management in various industries such as semi-conductor or auto industry [12]. In construction industry, there have been studies on the usability of DSM and its application to architectural design process. DSM is a process analysis tool by modeling the relations between activities in the form of square matrix. If there is an information dependency between two random activities on each row and column, it is expressed as "×", and if there isn't, it is expressed as blank. Fig. 1 shows three types of relationships between activities for the modeling: parallel, sequential, and coupled relationship.

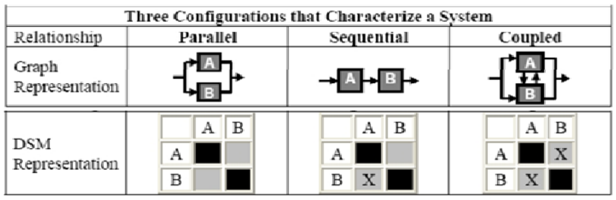

Fig.1. Types of relationships between the activities[14]

Parallel relationship means a relation without any communication between activities and sequential relationship means a relation that one activity has one way effect on the other activity, resulting in one way information flow. Lastly, coupled relationship means a relation that two activities are mutually dependent to each other, resulting in two way information flows.

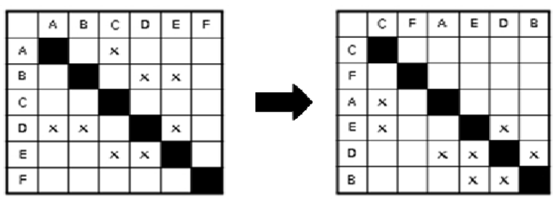
Fig.2. Partitioned DSM [8]

DSM made by this process goes through the process for optimal activity layout by various algorithms such as partitioning, tearing, and clustering algorithms [2]. Each algorithm has its own objective, depending on an application subject. This study focuses on partitioning algorithm, which was used here. The goal of partitioning is to resequence the design tasks to maximize the availability of information required at each stage of the design process [5]. Fig. 2 shows an example of the partitioning algorithm.

Unlike other process management methods such as network method or bar-chart, DSM can show mutually dependant information flow between activities in process, and based on this and analyzing information flow, various strategic approaches are possible [13]. Given the characteristics of a design process having a lot of repetitive work due to mutually dependant information flow, DSM is a proper process management method to show correlations between activities based on information flow of a design process [2].

3. Constructability Implementation Model

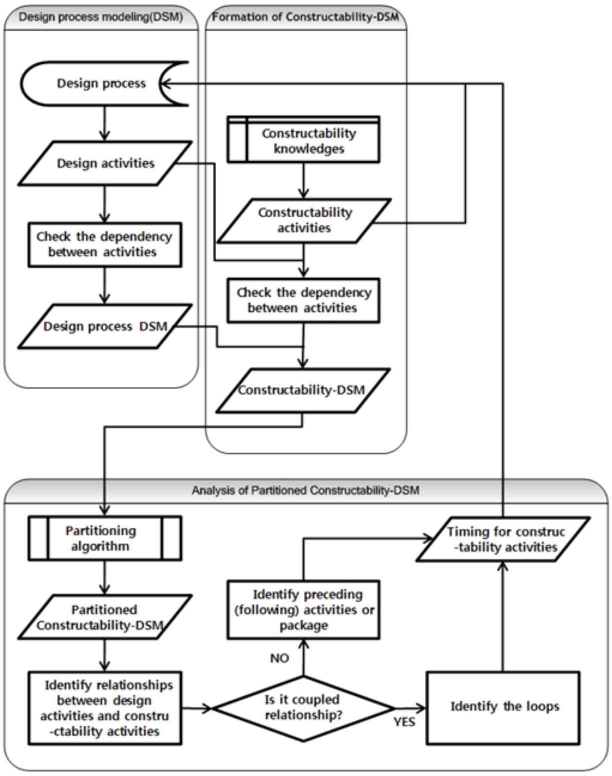

Fig.3. Conceptual model scheme

Architectural design process is relatively typical. However, inefficiency may occur in the process of information exchange among different participants, for instance, as in collaboration between designers and construction organization. To minimize this kind of inefficient information exchange and improve design productivity, information flow between collaboration participants at an activity level needs to be efficiently managed.

Thus, this study suggests information flow based constructability implementation model using DSM as a means to minimize productivity barrier in design stage which may occur by considering the constructability knowledge at improper point in time. Figure 3 shows a conceptual model for information flow-based constructability implementation model. The model consists of three modules. Each module receives necessary information, processes it, and sends the processed information to the next module.

3.1 Design Process Modeling

To manage design process, first, modeling the design process is necessary. In this study, design activities of design process are modeled based on dependency between activities. Major concepts are as follows.

-Design activities: information flow between activities is the subject for management of this study, and thus the scope is limited to unit work that has information flow with other work in the process. In other words, only the work to create design information, which has effect on design decision making, is considered.

-Dependency: this means forward and backward information flow between any two activities.

3.2 Formation of Constructability-DSM

This study assumes that constructability knowledge which needs to be considered in design stage can be expressed on activities in the process. Thus, constructability activity is defined as an activity perceiving the constructability knowledge through the collaboration between designers and construction organization. For instance, an activity, perceiving by a designer in column design process that the rebar placing distance needs to be adjusted so that concrete pouring is possible, is regarded as an activity for design process.

Based on this, constructability activities are created by figuring out the construction experience and knowledge which needs to be considered in design stage. Then, dependency with design activities are verified as described in previous chapter. In other words, how constructability activities relate to design activities in a sense of information flow is verified.

Then, Constructability-DSM(C-DSM) is made by adding the constructability activities to the design process matrix in the previous chapter. Thus, C-DSM has not just information flow between design participants, but also information between designers and construction organization through the collaboration of the two. C-DSM created can be used as a material to figure out the proper point in time for specific constructability knowledge to be used in design process at an activity level.

3.3 Analysis of Partitioned Constructability- DSM

To find out the proper point in time when specific constructability knowledge needs to be considered in design process at an activity level, partitioning algorithm is applied to C-DSM. The partitioning algorithm re-lays out activities from the perspective of information feed-forward to optimize the information flow on a matrix.

(1) Constructability activities in coupled relationship with design activities

Constructability activities, in coupled relationship with design activities, have two-way information flow between construction organization and designers. These constructability activities deal with variable knowledge affected by design results such as construction planning or efficiency depending on construction methods or materials. Construction planning is hard to be precisely planned in advance in design stage, but given the definition of constructability in this study and that construction planning can be a condition for design through the collaboration with construction organization, the knowledge of constructability can be considered in design stage.

These constructability activities are coupled to design activities in two-way information flow, forming a repetitive work package. Activities in a repetitive work package have information flowing from and to each other. Thus, constructability activities in a repetitive work package must be performed together with design activities in the package. Therefore, these constructability activities need to be considered at a work package level.

(2) Constructability activity in sequential relationship with a design activity

Constructability activity in sequential relationship with a design activity has a one-way information flow from construction organization to designers. These constructability activities generally deal with the constructability knowledge relating to design constraints such as accessibility of men, material or equipment during construction. Constructability activities in a sequential relationship with design activities can be determined for their time to be used by verifying preceding or following activities or work package.

4. CASE STUDY

To prove the applicability and effectiveness of information flow based constructability implementation model using dependency structure matrix, a case study has been conducted. The case project was Daewoo construction, a multipurpose building project, Nonhyun-dong, Inchon, Korea.

In this study, the example of design process is only about structural design process for basement columns and foundation among the whole design processes. Design activities, constructability activities, and information dependency between activities for each module are confirmed by analyzing work process of architectural design firms and surveying design and construction experts. Design-build or CM contract is assumed as a delivery system because they have a smooth operation of design work in consideration of constructability.

Design activities in the design process are created for modeling, and their dependency is verified. (Table 1) Then, based on the dependency, design process is modeled into activity-based matrix. Figure 4 shows a modeling of design activities A~L with their dependency.

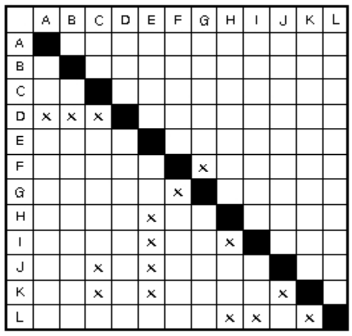

Fig.4. Design process modeling

Table 1 shows constructability activities M~P necessary to be considered in design process and their dependency with each design activity. Based on this, Figure 5 shows C-DSM. This C-DSM is the matrix in the previous chapter incorporating constructability activities. Dark part in the matrix represents constructability activities. "×" represent information flow between design participants and "⊚" signs represent information flow between designers and construction organization.

Table 1. The information dependency relationships with activities

Classification	Activity ID	Activity Name	Predecessors
Design activities	A	Understanding of owners needs	-
	B	Review of design guide	-
	C	Geotechnical investigations	-
	D	Review of foundation type(Preliminary foundation plan)	A, B, C
	E	Load calculation	M
	F	HAVC layout planning	G
	G	column, beam, slab layout planning	F
	H	steel column(basement) design	E, N, O
	I	S. R. C column design	E, H, N, P
	J	Determination of foundation type	C, D, E
	K	Determination of foundation size & penetrated depth	C, E, J
	L	Determination of the strength of materials	H, I, K, P
Constructability knowledge	M	Low rise construction plan	K
	N	Consideration of physical interferences in column	-
	O	Application of Skip Floor	H
	P	Consideration of concrete construction efficiency	I, L

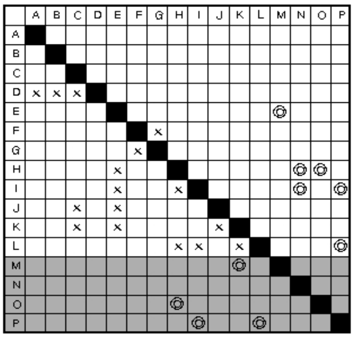

Fig.5. Constructability-DSM

Figure 6 shows C-DSM with activities re-laid out by the partitioning algorithm. As a result, constructability activities M~P are re-laid out on specific points of matrix depending on information dependency with design activities. Then, the relationship between constructability activities and design activities can be verified in design process. Constructability activities have sequential or coupled relationships with design activities.

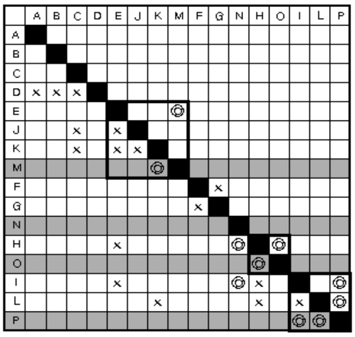

Fig.6. Partitioned Constructability-DSM

The case design process as in Figure 6 shows the sequential relationship between constructability activity N and design activities H and I, the coupled relationship between constructability activity M and design activities E, J, and K, the coupled relationship between constructability activity O and design activity H, and the coupled relationship between constructability activity P and design activity I and L.

(1) Coupled relationship with design activities

Constructability activities, in coupled relationship with design activities, have two-way information flow between construction organization and designers.

For instance, among design process for an urban construction project where underground and over the ground constructions are simultaneously performed, the activity determining foundation size, penetrated depth and type (design activity J, K) and Load calculation (design activity E) is coupled to low level construction planning (constructability activity M). There wouldn't be a problem if permanent foundation is built from the beginning, but in many cases, depending on the state of ground for foundation, temporary foundation such as pier foundation is built first instead of permanent foundation. Until permanent foundation by mat foundation to support the whole building is constructed at the end of underground construction, underground and over the ground construction have to be constructed together up to the floor that the temporary foundation can bear. Thus, at the time when the lowest basement is constructed, construction planning relating to how many over the ground floors is to be constructed (design activity E) and determining foundation size and penetrated depth have two-way information flow.

On top of that, when the basements are excavated at a time to shorten the construction period using skip floor method (constructability activity O), buckling by axial load may occur and thus, structural stability of steel columns (design activity H) must be reviewed.

Lastly, in designing column sections (design activity I) and selecting material's strength (design activity L), if each floor has its own different concrete column strength and section for optimal design, there would be inefficiency in concrete procurement or other work (constructability activity P), and thus, this kind of inefficiency must be minimized through the collaboration with construction organization.

Then, constructability activities in a repetitive work package must be performed together with design activities in the package in that these constructability activities are coupled to design activities in two-way information flow, forming a repetitive work package. If constructability activity M in the case design process is conducted together with design activities E, J, and K, the work will become effective. In the same way, by checking a design activity having a coupled information flow with the constructability activity, time for remaining constructability activities O and P to be considered can be verified. For example, if constructability activity P in the case design process is conducted together with design activities I and L, the work will become effective.

(2) Sequential relationship with a design activity

Constructability activity in sequential relationship with a design activity has a one-way information flow from construction organization to designers. For example, considering physical interference in column structural design (constructability activity N) has a sequential relationship to determining a column section (design activity H, I). In other words, a designer must determine a column section, considering whether there is a physical interference among reinforcement cage, steel column, tremie pipe, toe grouting pipe and stiffener in a casing.

Constructability activities in a sequential relationship with design activities can be determined for their time to be used by verifying preceding or following activities or work package. Constructability activity N in the case study can be effectively used if it is performed before a work package (activity H~O) having design activity H.

5. CONCLUSIONS

The discoveries in this research are as follows:

To begin with, the constructability activities created from the constructability knowledge and the proper point in time to consider constructability knowledge verified by partitioning algorithm tells designers about which constructability knowledge should be used and when to use. This is reflected in design process, enabling maximum utilization of the constructability knowledge to decision makings in design stage. Through this process, by minimizing inefficient information exchange that may occur in collaboration between designers and construction organization in design process, design productivity can goes up.

In addition, depending on the relationship between constructability activities and design activities, what way of using specific constructability knowledge would be efficient can be determined. The constructability knowledge is communicated to designers through the collaboration with a construction organization. In case of repetitive work package involving constructability activities, repetitive information exchanges are necessary and thus, active collaboration such as regular meeting between designers and construction organization is necessary. However, for constructability activities in a sequential relationship with design activities has one-way information flow, and thus one-way collaboration such as information delivery is enough for communication rather than an active collaboration such as a meeting. Thus, DSM enables an efficient collaboration between designers and construction organization by informing a project manager of a proper way of collaboration to use particular constructability knowledge to the design.

Meanwhile, this study has a limitation in that it is hard to provide a concrete information flow between design and constructability activities in case of small number of design activities due to low level of detail and large number of constructability activities because one design activity may have dependency with multiple constructability activities. To prevent this, future studies need to be done on a process to subdivide design activities in design process. Lastly, the case of this study only considered a structural design process among the whole design process, and more specifically, only basement column and foundation design process was considered. Thus, more case studies are necessary to test the applicability and utility of the concept in this study and these will contribute to overall management relating to the whole processes of a project for rationalization of construction production.

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