THE ASSESSMENT OF BUILDING DESIGNS CONSIDERING CONSTRUCTABILITY FACTORS

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Abstract: *The application of the constructability concept in building designs at the design stage increases the efficiency of projects in terms of time, cost and quality. Many researches on the constructability and its implementation in practice have been conducted in various countries. However, this concept is still novel for construction research and practice in Vietnam. Traditionally, engineers often review project designs by using 2D-CAD drawings. This seems to be a manual, complicated and time-consuming work. The requirement of developing effective constructability assessment tools for projects in Vietnam arises. This paper aims (1) to discuss the current practices of the constructability assessment in Vietnam, (2) to discuss the ability of 4D-BIM model in analyzing the constructability of designs and (3) to identify the factors which may affect the constructability and to propose the procedure for assessing designs considering those factors by using 4D-BIM model. The results of this paper will be considered as the foundation for further researches on the development of a constructability quantitative assessment framework by using 4D-BIM model for projects in Viet Nam.*

Keywords: *Constructability, BIM, building design, construction, constructability assessment, constructability factor.*

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1. Introduction

A construction project includes two main processes, which are design and construction, whereby designers and contractors rarely communicate before the initiation of the execution process. In many cases, due to the lack of construction knowledge and experience, designers often make mistakes that may lead to the unexpected illogicality and difficulties in carrying out construction activities. Normally, the designs are assessed before the construction stage; however, this process cannot always detect all mistakes. As a result, changes in designs during the execution phase can be required, which may extend the project duration and cost.

The concept of constructability was first introduced in the 1980s for the purpose of minimizing the gap between designs and construction [1,2]. The Construction Industries Research and Information Association (CIRIA) defined the constructability of designs as “the extent to which the design of a building facilitates ease of construction, subject to overall requirements for the completed building” [3]. Since then, many researchers have conducted research on constructability concept and how to implement it in practice. Recently, many researchers suppose that the constructability of designs not only ensures the ability to construct the project, but also facilitates easy, efficient, economical and safe construction [4,5]. The benefits of applying constructability are demonstrated in many case studies, which show that as much as 10.2 percent in project time and 7.2 percent in project cost can be saved when the assessment of constructability of designs are performed [2].

The concept of Building Information Modelling (BIM) was introduced in the 1970s [6]. With the continuous development in computing technologies, BIM is promised to be a powerful tool to solve project management problems. BIM provides an effective environment that allows constructors to share information with designers. In BIM, construction products are simulated as 3D model along with relevant digital information.

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Furthermore, timeline schedule can be added to 3D model to create 4D model which shows visually how buildings can be constructed in reality. Therefore, with BIM model, the process of assessing the constructability of designs becomes easier and more feasible.

In Vietnam, the instruction to assess building designs stated in current legal documents does not provide clear assessment criteria as that in Hong Kong, Singapore or the United States. In Singapore, for example, the Building and Construction Authority provides the requirement of constructability scores for construction projects [7]. Hence, projects that meet the score required can get the permission to construct. Besides, the constructability of designs has not been emphasized appropriately in researches in Vietnam. Nguyen Hai Loc and Nguyen The Quan discussed the concept and advantages of assessing constructability of designs at the design stage in their research [1]. However, there seem to be no study conducted to explore the implementation of BIM model on assessing the constructability of designs at the design stage for projects in Vietnam. The main objectives of this paper are: (1) to discuss the current practices of constructability assessment in Vietnam, (2) to discuss the ability of 4D-BIM model in analyzing the constructability of designs and (3) to identify the factors of designs which may affect their constructability and to propose the procedure for reviewing designs considering those factors by using 4D-BIM model. To achieve the research objectives, the research methodology used is the comprehensive study and analysis of relevant researches. The results of this paper will be considered as the foundation for further researches on developing a constructability quantitative assessment framework using 4D-BIM model.

2. The current practices of constructability assessment in Vietnam

Traditionally, many construction projects in Vietnam use the design-bid-build delivery method [1], where the owner contracts separately with a designer and a contractor. With this delivery method, there is the lack of communication chances for designers and constructors at the design phase. Therefore, the accuracy of designs depends just on professional skills and experience of the designers. During the design stage, design drawings are first assessed within the designer's team, and after that together with other designers in the group of the architect, structural and MEP engineers. Before tendering, designs are inspected by assessment agencies as required by relevant legal documents. However, these documents has not clearly provided assessment criteria or required the minimum constructability score for designs. Therefore, the assessment and approval of designs are normally subjectively dependent on the assessment agencies.

Besides, for most projects in Vietnam, the constructability of designs is normally reviewed by using 2D-CAD drawings. The main reason is that many design companies are now representing design work in 2D-CAD drawings. Some large companies, e.g. Coteccons, Fecon, Hoa Binh, may use BIM software to implement their designs. However, for projects having numerous design contractors, the assessment of designs is commonly performed on 2D-CAD drawings as the standard platform, because these contractors may apply different design software, e.g. BIM and CAD. Engineers have to find out conflicts or mistakes among many drawings of structure, architecture, and MEP designs. It can be seen clearly that this is a manual, complicated and time-consuming work, especially for large projects.

In reality, many projects in Vietnam face the problems of multiple design modification during the construction phase [1]. This is one of main reasons for construction time extension, cost overrun or low product quality. Tran Hoang Tuan proposed that changes in designs at the execution phase is the third ranking factor causing cost overrun and the forth ranking factor causing time extension for projects in Can Tho [8]. In his research, Lam reported that 30.4 % of survey respondents agree that mistakes of design cause delay and cost overrun for projects in Vietnam [9]. Based on the results of a survey, Luu Truong Van and Nguyen Chanh Tai concluded that the correctness and logic of designs play the second important success factors of construction projects in Vietnam [10].

Consequently, the requirement of providing criteria or constructability score for designs is necessary for construction projects in Vietnam. Also, it is needed to develop more effective assessment tools to assist designers in checking building designs.

3. Constructability tools

Since years, constructability assessment of designs has been discussed in many researches. A number of tools have been proposed to facilitate the implementation of constructability in reality. These tools can be categorized into three groups including knowledge-based systems, quantitative analysis systems and BIM-based assessment systems. Knowledge-based systems rely on the database to generate constructability sets of rules for assessment and automated decision-making [11]. Murtaza et al. developed a knowledge-based system for preliminary design use [12]. This system was designed for owners to determine whether the constructability concept of modularization is feasible for a petrochemical or power plant. In another research, Ugwu et al. developed a knowledge-based model for structural steel design assessment following schematic design [13]. Some other researchers proposed the integration between knowledge-based systems and CAD models to better analyze the constructability of designs. Ernst and Roddis integrated a CAD with a rule-based expert system to perform automated checking of fabrication-related issues before the information is transferred to fabricator [14].

Quantitative analysis system is a more common method to analyze the constructability of designs. Quantitative analysis is an effective approach for evaluating alternatives, solving problems, and making decision [11]. With this method, the constructability score for a concerned project design is generated. By comparing this score with alternative designs, designers can decide the most constructible design. Lam et al. used Analytic Hierarchy Process (AHP) to evaluate the most constructible design for common construction systems in a building superstructure with respect to constructability factors [15]. Common systems considered are structural frames, slabs, envelops, roof and internal walls. The research established constructability scales of construction systems, which are used to quantify the constructability by applying them to the amalgamation of construction systems in any given design. More recently, Zolfagharian and Irizarry developed a quantitative constructability assessment model for commercial projects in the United States [16]. The main contribution of this research is to develop constructability indexes for building components and their construction systems and to create a model for measuring the constructability of commercial building designs.

Knowledge-based systems and quantitative analysis systems proposed by previous research mainly focus on a single aspect of structural design, unable to visualize and mostly applied in late design development phase [11]. Therefore, the implementation of these approaches in practice is limited. Another constructability tool that has proved to be more effective is the BIM-based assessment systems [2,6,17,18]. Tauriainen et al. proposed an experimental constructability assessment method using BIM as a source of constructability information applied for projects in Finland [18]. Thereby, the model can measure the constructability score of a structural element or a building. The validation of the proposed model is made in seven BIM-based building models. In another method, Zhang et al. developed a constructability assessment platform which derives data from the BIM and 4D simulation integration model [17]. The overall constructability assessment value provided by the platform assists designers in deciding the most constructible design proposal.

4. 4D-BIM model and constructability

Construction project designs are conventionally reviewed based on 2D CAD drawings. It has been proved that such review work is difficult and not efficient. Difficulties in presenting spaces, conflicts between design and construction, complicated modifications of drawings, design changes, miscommunication and information gap can cause mistakes for 2D-CAD designs [6]. This leads to poor constructability of designs. To improve this problem, Building Information Modelling (BIM) technology has been introduced as an effective solution. BIM is a technology of computer-aided modelling for the purpose of managing projects focusing on building information, models, production, communication and analysis [19]. In BIM environment, buildings are created as 3D model, where building components like walls, foundations, columns, slabs, etc. are identified and drawn as object oriented elements. As shown in Fig. 1, building construction data like resources, material, costs, construction method, etc. can be assigned to corresponding building element in 3D-BIM model. 3D-BIM model can be generated using Autodesk Revit, Tekla, etc.

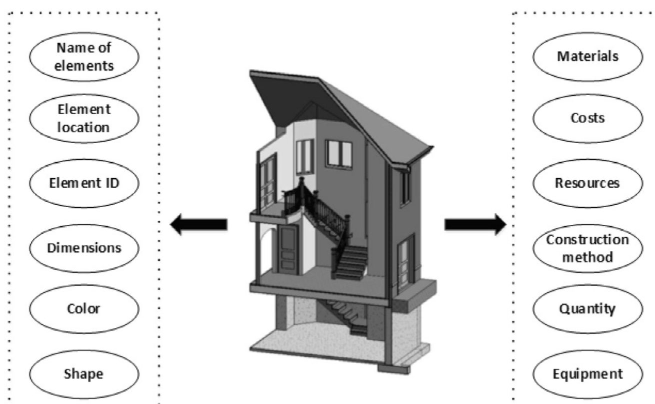


Figure 1. *Building data model*

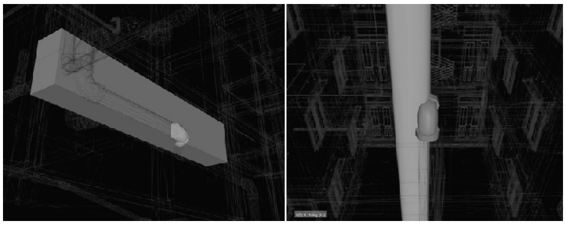
4D-BIM model is the model that link the 3D model and a time-scaled schedule using BIM software such as Naviswork Manage, Ceapoint, Tekla BIMsight etc. Hence, the construction process of building can be simulated in 4D-BIM model as it will be built in reality so that every design component is tested and evaluated, minimizing unexpected problems at the construction phase. The common construction problems that can happen to designs can be classified into three types including space, measurement and clash [6]. With its many advantages, BIM technology can facilitate the review of these constructability issues.

Spatial allocation presented in designs is one of main issues that should be reviewed. The space mentioned refers mainly to the net space used inside the building, for example the distance between furniture, distance between furniture and windows, etc. To review the spatial allocation, it is required to integrate different design areas including architecture, structure and interior decoration. BIM provides a high performance solution for reviewing the integrated design content. Utilizing BIM model, the reviewing of space will be much easier. The visualization is a good approach to facilitate the identification of poor spatial allocation design (See Fig. 2).

Figure 2. *Visualization of BIM model for space review*

Measurement design refers to the annotation of the measurement of building components in all drawings for showing their relationships in the space. For example, when a designer changes the number of staircase steps, he should consider the clear height for user climbing. If the designer cannot handle the relationships among plan, elevation and section, the errors of measurement annotation will cause problems after the construction, i.e. the clear height is not enough at the staircase for user climbing [6]. BIM technology will facilitate the reviewing of measurement design. Designers can ensure the consistency between design drawings thanks to the database of BIM models. When the position or properties of an object is changed in a plan view, all other drawings of this object will change automatically at the same time. Furthermore, the measurement annotations are also changed if they were assigned to the object.

Clashes are common issues that represent the inconsistency of design areas including architecture, structure and MEP. Detecting conflict problems of designs using 2D-CAD drawings is a difficult work for engineers. Engineers cannot find all clashes from the integrated 2D-drawings because they are too complicated. Utilizing the clash detection function of BIM software will make the finding of conflict problems much easier. Fig. 3 shows examples of clash detection for a 3D building model using detection function of Naviswork Manage software. The software will produce a clash detection report, so that engineers can analyze the conflict problems and eliminate them. Furthermore, the visualization of BIM model is an important advantage that supports engineers much in viewing and analyzing clashes.



(a) *(b)*

Figure 3. *Clash detection by using Naviswork Manage*
a) Clash between ground beam and pipeline;
b) Clash between pipelines

In conclusion, the application of the BIM technology can enhance the design quality by supporting the constructability assessment of designs. Through BIM model, engineers can also detect construction problems such as the insufficiency of construction space, which enhances the quality of construction process.

5. The assessment of building designs considering constructability factors

5.1 Identification of constructability factors

During the construction process, contractors have to deal with many design-related problems which can affect the construction productivity. These issues can be the complexity of designs, the unavailability of resources, the poor organization of site temporary facilities, the low capacity of public road for material transportation, the impact of new construction on adjacent structures, etc. In the early design stages, if designers are able to consider all factors that can affect the constructability of project designs, then the designs are more feasible and the problems arising during the construction stage can be minimized or eliminated. In order to support the constructability assessment of designs, constructability factors are identified and discussed in this research. As a result of a comprehensive literature review [2,15-18,20-23], 3 groups of constructability factors along with 18 common factors are identified as shown in Fig. 4.

Constructability factors		
Design factors (DFs)	Construction factors (CFs)	External factors (EFs)
• DF1: Prefabrication • DF2: Grid layout • DF3: Standard dimensions • DF4: Design flexibility • DF5: Simplification • DF6: Resource availability • DF7: Labor skill availability	• CF1: Construction sequence • CF2: Time under ground • CF3: Weather effect • CF4: Safety • CF5: Personnel access • CF6: Space for material • CF7: Space for equipment	• EF1: Site facility availability • EF2: Road use ability • EF3: Site impact to structures • EF4: Site impact to infrastructure

Figure 4. *Factors affecting constructability of designs*

The design factors (DFs) include 7 factors that relate to the designs of building components. Factor DF1 shows whether the building component is prefabricated. Component that is manufactured offsite and is not a complete system is considered to be prefabricated. From the constructability point of view, the more fabricated components are involved in project designs, the more the positive impact is on the constructability [17]. Besides, the design of grid layout (DF2) should be considered because a repeated grid layout will facilitate faster construction when precast concrete is used. A design which has modularized grid layout will facilitate faster fabrication process of components and reduce material waste [2].

Standard dimensions (DF3) refers to the dimensions of building components, which should be designed considering the sizes of material and minimizing the demand of labour. The standard dimensions of components will reduce the waste of materials [17]. Another aspect considered is the flexibility of design (DF4), which shows the ability to adapt to any design change of building components such as change in dimensions, position, materials, etc. Flexible designs will reduce the cost and time of rework [17]. Besides, building designs should be not only flexible but also simple. The simplification of designs (DF5) reflects the difficult degree of construction details of designs. A simple design will facilitate the construction productivity.

Resource availability (DF6) shows the availability of resources, such as materials, equipment and labours, which is a key factor for the ability to perform construction. When resources are not available, construction activities cannot be performed, which causes activity delay. In addition, the construction of some particular building components may require special skill workers. The ability to construct of designs decreases when the designs require the high number of these workers. Therefore, designers also need to consider the availability of labor skill (DF7).

The construction factors (CFs) show the factors that relate to the construction process. The first factor to be considered is the installation sequence of building components (CF1) [2,17]. Thereby, the construction sequence should ensure the relationships between components such as the spatial relationships. Besides, the free-interference path for transporting any building component around jobsite should be guaranteed. This ensures no disruption for the installation process due to the lack of components. Also, construction sequence should be designed to ensure safe working condition [24]. Construction duration for underground structure (CF2) must be considered because this value will affect the overall constructability assessment of designs [17]. The underground construction is often a complex process, which should take as short time as possible. The factor CF3 considers the effect of bad weather on the construction process. Bad weather conditions are one of the main reasons that cause project delay. The number of bad-weather days expected to happen during the construction process should be aware [17].

In order to ensure a safe working environment for site personnel, safety issues (CF4) must be considered in all design areas, such as the distance between the high voltage power lines and cranes, or the locations of chemical materials, gas container, unsafe openings onsite, etc. This issue also relates to the access path for site personnel (CF5) to different site locations. Designers should ensure that personnel can access safely to all site locations required. The space for material (CF6) shows all issues related to the material access path, site storages, unloading areas, prefabrication areas, staging areas, working areas and protected areas. The space for equipment (CF7) refers to the space occupied by a resource or temporary facility that is used to support construction activity. The analysis of equipment space can lead to the consideration of the equipment access that relates to the equipment storage area, working area, unloading area and equipment occupied space [17].

The external factors (EFs) shows factors of external conditions that should be noticed when designing. The factor EF1 mentions the availability of government facilities such as water, electricity at the site area. Availability of government facility systems saves time and costs for building new facility systems. Road use ability (EF2) reflects the applicability of public roads at site local area. A high applicability of public roads will facilitate the transportation of materials to site. Traffic conditions will affect the time point and duration of material transport. For example, the concrete mixer trucks are normally not allowed to travel during daytime, especially in the rush hour. Therefore, pouring concrete work is normally performed in the evening. The factor EF3 considers the impact of current construction on the adjacent structure, e.g. building foundations, basements, while the factor EF4 considers the impact on the infrastructure, e.g. the adjacent pipeline systems or sewage systems [2]. Designers should identify adjacent structures or infrastructure systems that can be impacted, the distance between those systems and new building and the expected effect level.

5.2 Proposed procedure for assessment of designs considering constructability factors

As discussed above, BIM technology can be applied to assess the constructability of designs. This paper proposes a procedure for reviewing building designs using 4D-BIM model considering constructability factors as shown in Fig. 5. This assessment procedure can be considered a basis for the development of a BIM-based quantitative assessment framework in order to assist designers to assess their design proposals at the design stage.

The architecture, structure and MEP designs of a building are created in 3D-BIM model. The 3D-BIM models of all building design disciplines are later integrated into one unified 3D model. By adding construction schedule to the integrated 3D model, the 4D-BIM model is achieved. Thereby, each schedule activity links to its building components. It should be noted that the more detail the schedule has, the better output data from 4D model is.

For every specific project, at the beginning, designers should identify the constructability factors that need to be considered. This consideration depends on unique project conditions and should consider the client requirements. Those factors will be assigned to corresponding building components in the 3D-BIM model or identified from the 4D-BIM model. Thereby, the DFs and EF1 are integrated into the 3D-BIM model by defining them as shared parameters with input types represented in Table 1. In 3D-BIM model, shared parameters are kinds of component properties, which can be flexibly defined and assigned to every building components. Therefore, designers can add accurate constructability information for components easily.

With the help of BIM software, e.g. Naviswork, simulation video or snapshot pictures of 4D-BIM model can be produced easily. The analysis of this visual output will provide information about CFs and EFs. Thereby, the relationship between the time duration and each building component is used to study the following factors: CF1, CF2 , CF3 , CF4 , EF2 , EF3 and EF4. Meanwhile, the space allocations and resource

Table 1. *Definition of constructability factors as shared parameters*

No.	Constructability factors	Shared parameters	Input type
1	DF1 - Prefabrication	Prefabrication	Yes/No
2	DF2 - Grid layout	Grid repetition	High/Moderate/Low
3	DF3 - Standard dimensions	Standard dimension	Yes/No
4	DF4 - Design flexibility	Change potential Change readiness Change effect	Yes/No Yes/No High/Moderate/Low
5	DF5 - Simplification	Simplification degree	High/Moderate/Low
6	DF6 - Resource availability	Material availability Equipment availability Labor availability	Yes/No Yes/No Yes/No
7	DF7 - Labor skill availability	Special skill needed Special skill availability	Yes/No Yes/No
8	EF1 - Site facility availability	Facility availability	Yes/No

accessibility can be studied from the 4D model through the analysis of construction schedule and working space in 3D model. This information is necessary for assessing CF5, CF6 and CF7.

In order to assess the constructability of design proposals, all output data from the 3D and 4D model are exported. The assessment criteria for each CF are required for the assessment process. In reality, for each project, stakeholders tend to have different interpretations on how constructability factors impact on building designs. However, at the end, they have to follow a generic construction knowledge based on a specific project situation to perform the design and construction properly [17]. Based on the definition of the factors, each factor with its evaluation criteria are provided as shown in Table 2. Using these criteria, designers can evaluate their design proposal. If the constructability evaluation meets the designers' requirements, then the design proposal can be approved; otherwise, changes in designs and/or construction sequences should be made.

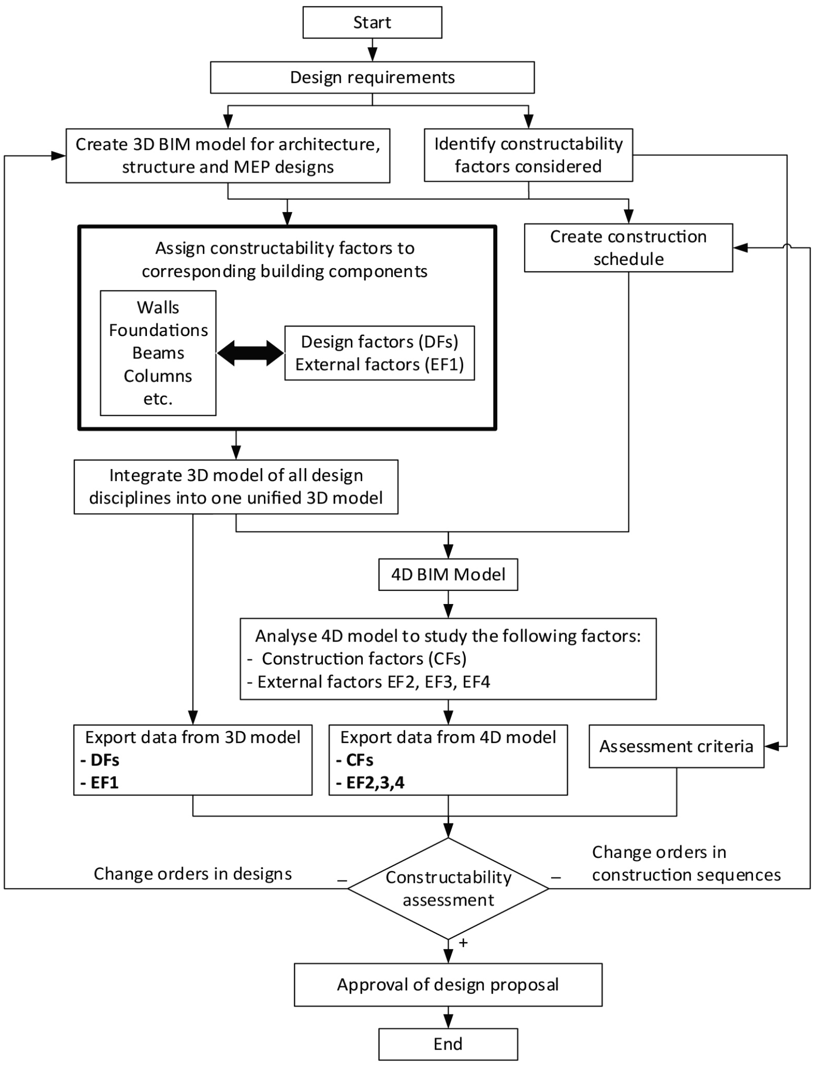


Figure 5. *Procedure for assessment of designs considering constructability factors*

6. Conclusion

Since its first introduction, the constructability concept has been discussed by many researchers in the world. The benefit of the constructability assessment of designs at the early stage has been proved in various case studies. Applying this concept in a project will enhance the design quality; hence, facilitating the construction process. This leads to benefit in project cost, time and quality. Among the many constructability tools proposed, BIM is proved to be a powerful tool to examine the ability to construct of the designs. This paper discussed the current status of the constructability assessment in Viet Nam. The main advantages of

Table 2. *Assessment criteria for constructability factors*

No.	Data	Assessment criteria
DF1	% of prefabricated components (with YES input type)	The higher the percentage, the better the constructability
DF2	% of high/moderate/low grid repetition	The higher the percentage of “high” repetition, the better the constructability
DF3	% of standard components (with YES input type)	The higher the percentage, the better the constructability
DF4	% of components that are potential to changes	The lower the percentage, the better the constructability
	% of components that are ready for changes	The higher the percentage, the better the constructability
	% of components, which are potential to changes, have high/moderate/low change effect	The higher the percentage of low change effect, the better the constructability
DF5	% of components that have simple construction details	The higher the percentage, the better the constructability
DF6	% of components that have resource availability (with YES input type)	The higher the percentage, the better the constructability
DF7	% of components that require special labor (with YES input type)	The lower the percentage, the better the constructability
	% of components, which require special skill, have required labors (with YES input type)	The higher the percentage, the better the constructability
CF1	Visual analysis of 4D model	Activity sequence has to respond to the relationships of components, the effect of trade interaction and the interference-free path for installation of any component
CF2	% of project days during which activities are performed under ground level	The lower the percentage, the better the constructability
CF3	% of project days with planned activities expect to have bad weather	The lower the percentage, the better the constructability
CF4	% of checked criteria follow safety checklist	The higher the percentage, the better the constructability
CF5	% of checked criteria follow personnel safety checklist	The higher the percentage, the better the constructability
CF6	% of checked criteria follow material checklist	The higher the percentage, the better the constructability
CF7	% of checked criteria follow equipment checklist	The higher the percentage, the better the constructability
EF1	% available facilities (with YES input type)	The higher the percentage, the better the constructability
EF2	N/A	The more road applicability, the better the constructability
EF3	Number of detected components	If 1 clash is detected then constructability is very bad If 0 clash is detected then constructability is very good
EF4	Number of detected components	If 1 clash is detected then constructability is very bad If 0 clash is detected then constructability is very good

BIM in reviewing constructability issues are found out, including spatial allocation, measurement design and design clashes. 18 constructability factors that should be considered in the design stage are also identified and classified into three groups: design, construction and external. When designers consider these factors, the building designs may be more feasible and quality. The procedure for assessing the constructability by using 4D-BIM model considering these factors are then introduced in this paper. Thereby, the method of integrating constructability factors into 3D/4D model as well as the assessment criteria of those factors are presented. This procedure may be one effective approach of the constructability assessment for construction organizations in Vietnam where there is no available clear criteria for this problem and BIM is considered as a new technology. This procedure also provides a foundation for the development of a quantitative constructability assessment framework of building designs. For further research, the importance of constructability factors should be investigated and ranked considering Vietnamese conditions. From the findings of this investigation, a framework for constructability assessment of building designs will be developed.

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