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A BIM-based model for constructability assessment of conceptual design

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Abstract. The consideration of constructability issues at the design stage can lead to improved construction performance with smooth project delivery and savings in time and money. Empirical studies demonstrate the value obtained by integrating construction knowledge with the building design process, and its benefits for owners, contractors and designers. However, it is still a challenge to implement the concept into current design practice. There is a need for a decision support tool to aid designers in reviewing their design constructability, deploying current technological tools, such as BIM. Such tools are beneficial at the conceptual design stage when there is a room to improve the design significantly with less incurred cost. This research investigates how current process- and object-oriented models can be used to assess design constructability. It proposes a BIM-based model using embedded information within the design environment to conduct the assessment. The modelling framework is demonstrated in four key parts; namely, the conceptual design model, the constructability assessment model, the assessment process model and the decision-making phase. Each is associated with a set of components and functions that contribute towards the targeted constructability assessment outcomes. The proposed framework is the first to combine a numerical assessment system and a rule-based system, allowing for both quantitative and qualitative approaches. The modelling framework and its implementation through a prototype are described in this paper. It is believed that this framework is the first to enable users to transfer their construction knowledge and experience directly into a design platform linked to BIM models. The assessment criteria can be customised by the users who can reflect their own constructability preferences into various specialised profiles that can be added to the constructability assessment model. It also allows for the integration of the assessment process with the design phase, facilitating the optimisation of constructability performance from the early design stage.

Keywords: design constructability; constructability assessment; building design; BIM

1. Introduction

The constructability concept aims to integrate engineering, construction and operation knowledge and experience to better achieve project objectives (Arditi *et al.* 2002). The term is defined by the Construction Industry Institute (CII 1986) as “the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve

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overall project objectives". Similarly, the Construction Industry Research and Information Association (CIRIA) defines buildability as "the extent to which the design of a building facilitates ease of construction, subject to overall requirements for the completed building" (CIRIA 1983).

The significance of designing for constructability is universally acknowledged in the construction industry. Many studies were conducted to investigate how to implement the concept. They took different approaches to benchmark the constructability of design solutions and to enable the objective evaluation of abstract concepts. One key approach to improve and enhance constructability is through a quantified assessment of designs (Wong *et al.* 2007).

The importance of deploying the constructability concept at the early design stage stems from the criticality of this phase in any architectural, engineering and construction (AEC) industry project. Most influential design decisions are made at this stage regarding the design shape, layout, sizes, dimensions or material selection. It is therefore vital to use our construction knowledge and experience when making such decisions. This includes the consideration of design constructability, which is often ignored by designers and building clients until the commencement of the construction phase - when it is too late to make significant improvements with less costs (Fadoul and Tizani 2017).

Barriers to implementing constructability vary from one project to another and from one company to another. However, the required effort in terms of time and manpower largely impedes the actual implementation of the concept (Hancher and Goodrum 2007). Another dominant factor in most construction projects is the lack of formal, explicit constructability knowledge bases that can connect observed constructability issues and the design processes. These knowledge bases can be provided as online repositories to be accessible by project partners at the right time in the decision-making process (Jergeas and Put 2001). Therefore, devising a tool that can build such knowledge bases based on experts' inputs, and then applying them back on relevant cases, will significantly facilitate concept implementation, which is not currently the case (Gambatese *et al.* 2007).

BIM technologies can play a vital role in improving design constructability through a collaborative process with early input into the design options. It facilitates the integration of the design and construction processes that consequently leads to improved quality of building with savings in project cost and time taken (Eastman *et al.* 2008). Object-oriented models have real potential in quantifying constructability application, where designers can draw out related constructability factors using a fast, simple and precise tool. In addition, BIM has the ability to electronically model and manage the vast amount of information encapsulated in the building design, from its conception to end-of-life. Such information can be employed to estimate, schedule, detail, advance bill production, automate shop drawing, and construction planning for all of the trades. Furthermore, the integration of time into the design solution to build a 4D BIM model could help significantly in conducting visual analyses of constructability status. Design teams can now simulate the entire construction process virtually, leading them to identify what could go wrong during the process. Crucial constructability aspects such as materials and labours accessibility, construction sequences and activities interdependency can be qualitatively analysed and assessed - giving a room to constructors to optimise the construction schedule (Hijazi *et al.* 2009).

This paper evaluates the practice of assessing design constructability and its associated challenges by reviewing currently adopted approaches and methods to appraise design constructability. The evaluation covers recently developed assessment tools presented to benchmark design constructability, whereby designers can use obtained feedback to improve design solutions. It then identifies a set of requirements that should characterise any decision-support tool for assessing design constructability and deploying advanced technologies. A model-based approach is proposed to enable the use of current information technologies to assess design constructability. Such a model can contribute significantly to address the identified gaps in the evaluation process. The proposed framework and its components are described and its potential in improving design constructability is explained.

2. Benefits of improved constructability

Previous studies explored the implementation of constructability assessments and recognized the potential benefits for owners, contractors and designers. Table 1 below shows some of these identified benefits in terms of cost, time, quality and safety in addition to other benefits that could contribute directly or indirectly to the success of considered project.

Nevertheless, benefits of constructability implementation may have further implications on the whole project and not only on the construction process, this includes the improvements in the conceptual planning, procurement, construction methods and stakeholder involvement and satisfaction (Griffith and Sidwell 1997).

Table 1 Benefits of improved constructability (Wong *et al*. 2007)

Domain	Impact	References
Cost	Saving 1-14% of capital cost	(Gray 1983)
	Saving on total project cost	(Jergeas and Put 2001, Elgohary *et al.* 2003, Trigunarsyah, 2004b)
	Lower cost of bidding	(Gibson Jr. *et al.* 1996)
	Reduced site labour	(Lam 2002)
	Increased cost-effectiveness	(Low and Abeyegoonasekera 2001)
	Better resources utilisation	(EldinF 1999)
Time	Early competition	(Griffith and Sidwell 1997, Eldin 1999, Low and Abeyegoonasekera 2001, Elgohary *et al.* 2003, Trigunarsyah 2004b)
	Increased productivity	(Poh and Chen 1998, Low and Abeyegoonasekera 2001)
	Reduced outage duration	(Eldin 1999)
Quality	Higher quality of built products	(Eldin 1999, Low and Abeyegoonasekera 2001, Low 2001, Elgohary *et al.* 2003)
Safety	Safer environment on site	(Francis *et al.* 1999, Eldin 1999, Trigunarsyah 2004a)
Other	Reduction in unforeseen problems	(Francis *et al.* 1999, Low and Abeyegoonasekera 2001)
	Improvements in industrial relations, teamwork, communication and client satisfaction	(Francis *et al.* 1999, Eldin 1999, Geile 1996)

3. Adopted approaches for improving constructability

By reviewing different developed tools benchmarking design constructability, it was found that the common employed approaches are: Quantitative assessment of constructability of design, constructability review and implementing constructability programs as Table 2 illustrates.

Table 2 Design constructability evaluation approaches pros and cons (Wong 2007)

Adopted approach	Pros	Cons
Quantitative assessment of constructability of design	• More practical and manageable in focusing the assessment at the design output instead of the design process	• Difficult to comprehensively include all substantial factors influencing constructability under the appraisal system
Constructability review	• Ensures all design errors are captured in the design documents, including drawings and specification. • Aims to identify any potential constructability issues that may arise prior to commencing actual site work.	• Incurs additional time and resources. • There might be a resistance from some design stakeholders regarding the subjective review.
Implementing constructability programmes	• Embodies all factors affecting constructability, including interactions between stakeholders	• Any programme involves process factors which make performance assessment appear subjective and complicated. • Tracking the entire process of design is not feasible, whereas snapshots observed during parts of the process may not be representative.

4. Evaluation for current studies in quantifying design constructability

The quantitative approach was previously identified as the most practical method among others to assess the design constructability. Studies that employed such approach applied various principles and had various assessment scopes as shown in Table 3, which reviews current constructability assessment tools and compares their adopted concepts. Aspects of the comparison included the content of model, scope of application, assessment principles, assessment aspects and the basis of assessment criteria. This helps in understanding what current tools offer for improving design constructability and, hence, identifies gap areas that need to be addressed in further studies.

5. Requirements for Modelling Constructability in Buildings

A comprehensive review of related literature was undertaken to identify the shortcomings of current assessment tools and challenges to be addressed in this area, particularly with regards to potential and actual deployments of recent advanced technologies. Subsequently, this study defines seven requirements that need to be available in appraisal systems in order to facilitate the constructability assessment process and deliver it in an effective, fast and accurate way (Fig. 1).

6. A proposed framework for constructability assessment of buildings design

Based on the above derived requirements for modelling constructability in buildings, the study proposes a BIM-based model that seeks to satisfy these requirements. The aim is to integrate the constructability assessment process with current BIM-authoring tools, allowing the design team to consider the concept in the early design stages.

This section presents the constructability modelling framework and its implementation. It discusses the components of the framework and how the various constituent parts relate to the operation of the model.

Table 3 Review of constructability assessment tools

Constructability tool	Paper Title	Reference	Country	Content	Scope of application	Assessed aspects	Surveys Used	Interview approach used
Constructability Assessment Using BIM/4D	Quantitative Assessment of Building Constructability Using BIM and 4D Simulation	(Zhang *et al.*, 2016)	China	It proposes a methodology to quantitatively assess the building constructability using BIM and 4D simulation.	Used to evaluate the constructability of the completed design proposal for new buildings.	Design attributes (Prefabrication, Grid Layout, Standard Dimensions, Resources' Availability, Labour's Skills), Construction attributes (Construction Sequence, Time under Ground, Building Envelope, Weather Effect, Safety, Material Access, Personnel Access, Equipment Access), Site Impacts (Adjacent Structures)	Yes (To identify factors affecting construc tability)	No
The Empirical Assessment Model	The Assessment of Constructability: BIM Cases	(Tauriainen *et al.*, 2014)	Finland	It introduces an experimental constructability assessment method (ECAM) using building information models (BIM).	Used to analyse and assess the constructability at the design and construction stages of a project with building information models.	Fluctuation of foundation, footing, ground and intermediate floor levels (CF1), Standardization and prefabrication of elements (CF2), The geometry and dimensionality of elements (CF3), Reinforcements in elements (CF4), Formwork for concrete elements (CF5), Holes, slots and penetrations (CF6)	Yes	Yes
The Scheme Design Buildability Assessment Model (SDBAM)	A scheme design buildability assessment model for building projects	(Lam *et al.*, 2012)	Hong Kong	It depicts the developmental process of a buildability assessment model for use at the scheme design stage (equivalent to design development stage in RIBA 2007) of building projects.	Used to evaluate the buildability of buildings at the early design stage.	Construction systems (Structural frame, Slab, Building envelope, Roof, Internal wall), Buildable and non-buildable features, Innovative or obstructive elements	Yes	Yes
Constructability Assessment Using BIM/4D	Constructability Assessment Using BIM/4D CAD Simulation Model	(Hijazi 2009)	Canada	To propose a new methodology to evaluate the level of application of constructability principles in residential buildings using the object-oriented Building Information Model (BIM) and the 4D CAD simulation model.	Used for completed design of residential buildings.	Design attributes (Prefabrication, Grid Layout, Standard Dimensions, Resources' Availability, Labour's Skills), Construction attributes (Construction Sequence, Time under Ground, Building Envelope, Weather Effect, Safety, Material Access, Personnel Access, Equipment Access), Site Impacts (Adjacent Structures)	Yes	No
Buildability assessment model (BAM)	Implementing a Buildability Assessment Model for Buildability Improvement	(Lam and Wong 2008)	Hong Kong	Buildability Assessment Model (BAM) has been developed for use in Hong Kong by adapting the Buildable Design Appraisal System of Singapore.	It is intended to be used use before statutory plan submission, when the design of buildings is almost complete.	Construction systems (Structural frame, Slab, Building envelope, Roof, Internal wall), Finishing systems, Building features, Building services aspects, Innovative ideas of improving buildability	Yes	Yes

Table 3 Review of constructability assessment tools (continued)

Buildable Design Appraisal System (BDAS)	Code of Practice on Buildability	(BCA 2005)	Singapore	Developing a system to calculate the buildability score of buildings in Singapore.	Developed as an incentive and becomes a prerequisite for granting design approval. Nearly for all new residential, commercial and industrial buildings.	The computation of scores is based on the 3s principles (standardisation, simplicity, and single integrated elements) for: Structural systems and roof systems, wall systems (including finishing systems used), other buildable features bonus provisions for single integrated components	Not explicit	Not explicit
Buildability Multi-Attribute System (BMAS)	Constructability assessment framework	(Zin *et al*. 2004)	Malaysia	Developing measures for assessing the buildability of designs in Malaysia.	This study outlines the buildability in design stage.	Number of assembly or construction process Difficult of rebar assembly Variability of building elements size/ shape/ Materials usage/ detailing Number of offsite assemblies Location of building elements Availability of skills required Suitability of materials	Not explicit	Not explicit

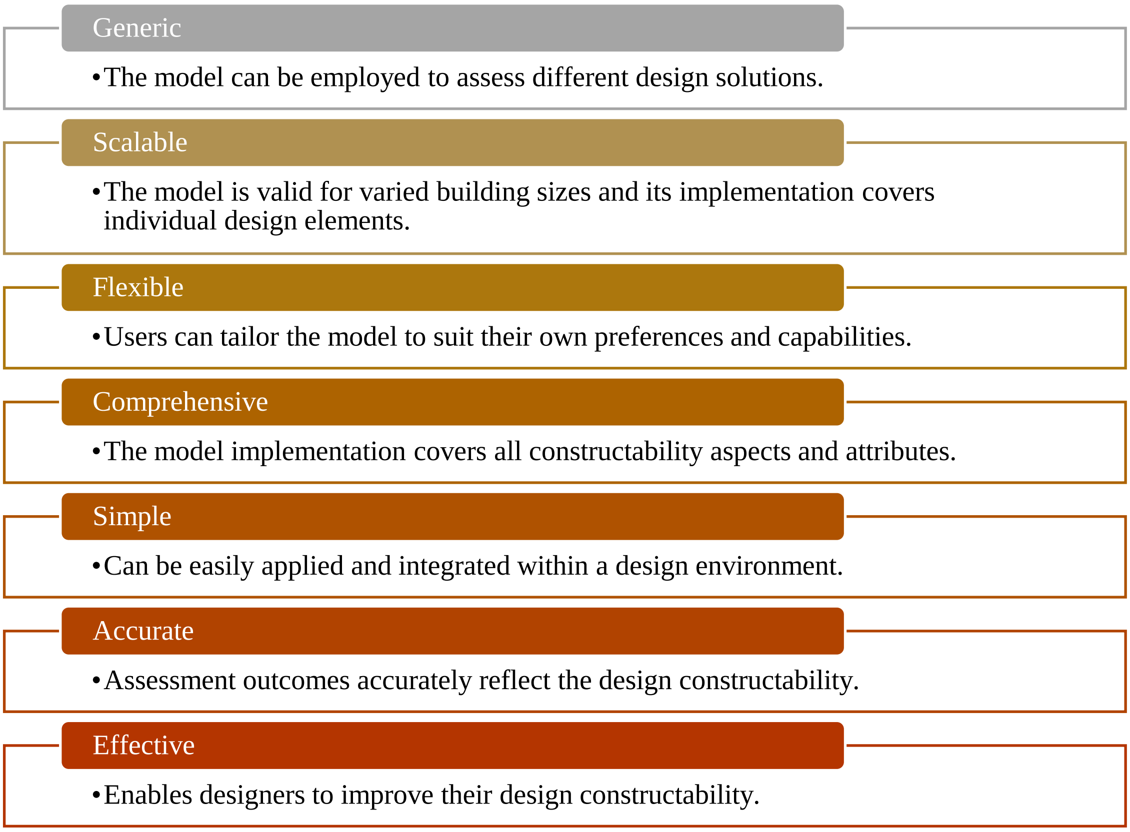

Fig. 1 Requirements of constructability appraisal system (Fadoul *et al*. 2017)

6.1 Modelling framework

Fig. 2 illustrates the proposed methodology to assess design constructability using the embedded information within a BIM. It demonstrates the modelling framework in four parts: The conceptual design model, the constructability assessment model, the assessment process model and the decision-making phase.

6.1.1 The conceptual design model

The conceptual design model refers to the digital building model that needs to be assessed for its constructability. At this stage, designers build their conceptual model using BIM software and provide the necessary information that the model should contain according to the agreed level of details (LoD). Users will get different assessment outcomes for different model input.

6.1.2 The constructability assessment model

This is used to benchmark the constructability of considered conceptual models. It is typically customised by the design team to suit their design objectives and to meet requirements, storing their construction capabilities. A specialised model would typically be authored once for every type of project (e.g. multi-storey office buildings, multi-story car parks, residential buildings, etc.) and is used many times for similar projects type.

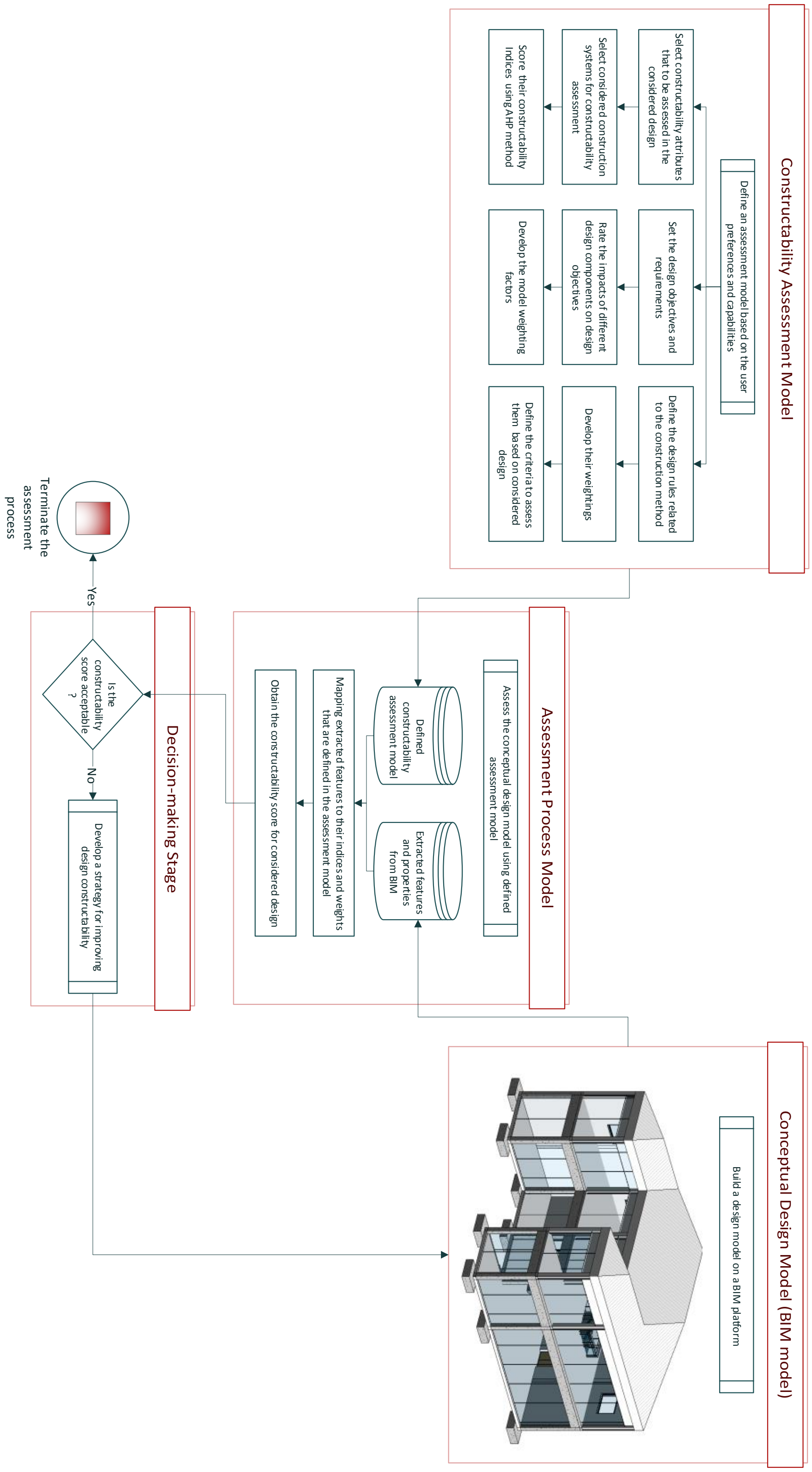

Fig. 2 Constructability assessment methodology

The assessment model has four main components, as shown in Fig. 3, namely: AEC systems, rules of thumb, complexity and location. The model components are designed to accommodate both quantitative and qualitative assessment of the design constructability. They contain customised model configurations input by users to be used for the assessment process. Such configurations may include: Constructability aspects to be assessed and their weights, constructability indices of materials, rates of design components and values of any restricted design parameters to be verified in the design under assessment. The importance of these components are balanced using weighting factors assigned based on their contribution towards satisfying the design objectives.

AEC Systems

This part of the model is used to assess the design construction systems (slabs, floors, foundations, etc.). It is designed to ensure the constructability of their design elements given the available resources (tools, equipment, skills, etc.).

The model provides a numerical system to score the constructability of different design elements with respect to selected constructability attributes (Fig. 4). It employs the analytical hierarchy process (AHP) method (Saaty 2008) to develop such scores. Obtained scores rank the constructability of design elements from users' perspectives and hence enable users to input their design preferences and constraints.

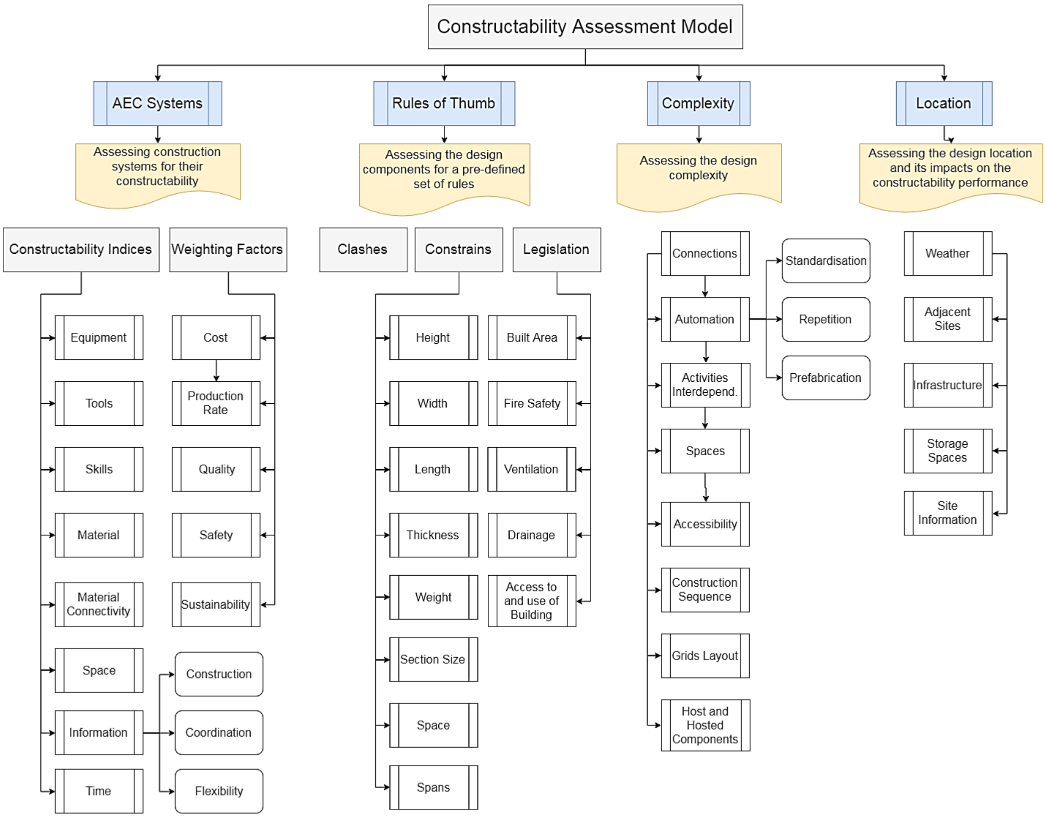

Fig. 3 Proposed constructability assessment model

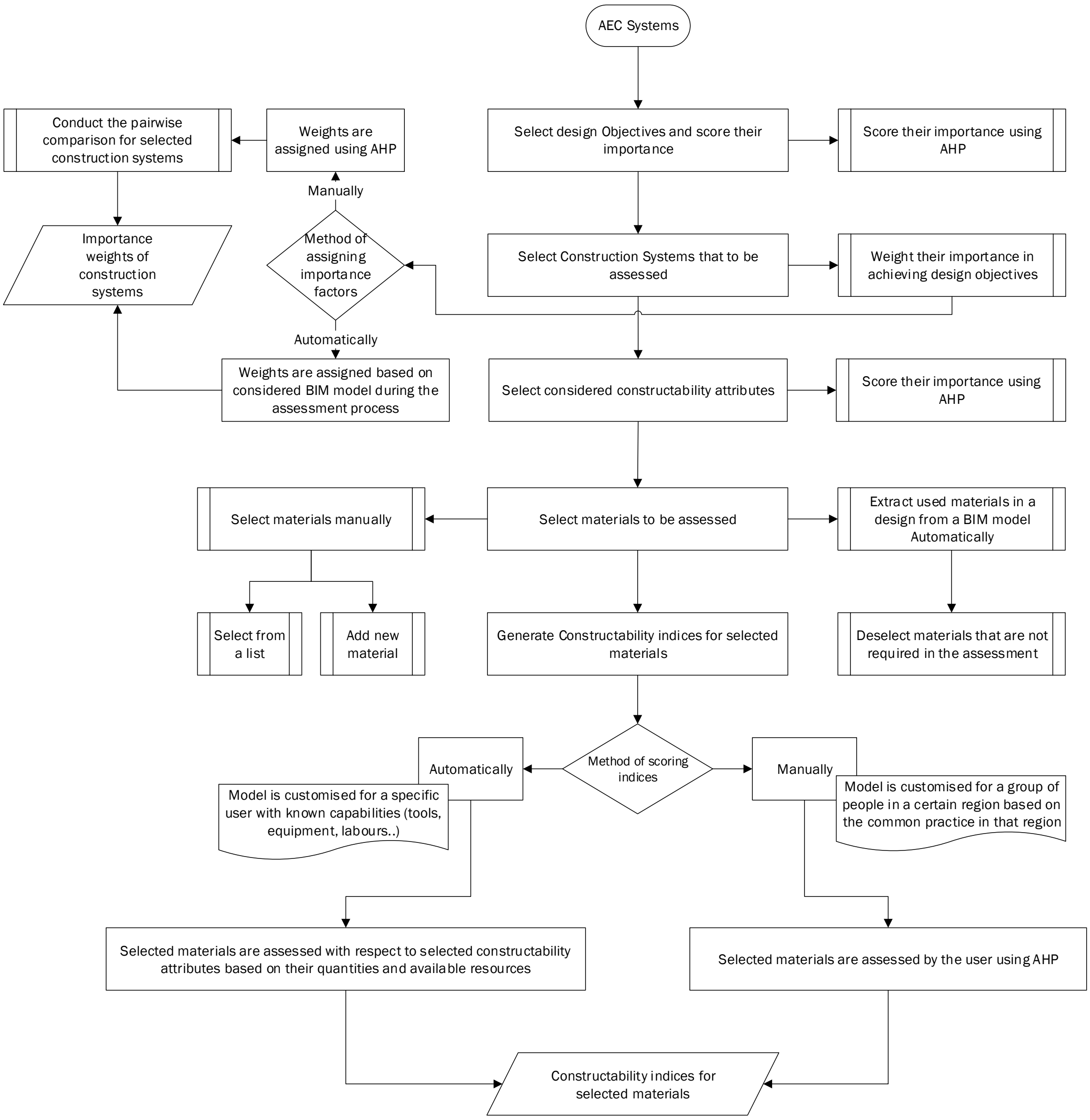

Fig. 4 Customising AEC systems in constructability assessment model

It also facilitates the transfer of relative construction knowledge and experience from users into the design platform, enabling designers to quantify what is not quantifiable at the moment, which usually requires manual reading and interpretation. It also enables users to decide between alternative designs based on available resources and their capabilities to construct. The idea of assessing the design constructability based on its used construction systems was inspired by the scheme design buildability assessment model (SDBAM) (Lam 2012). This ensures that constructability is directly reflected in design elements rather than being ambiguously assessed using constructability factors, as was adopted in some previous tools. Users will be able to choose which attributes in their design are considered for assessment, as this may vary from one design to another.

Rules of Thumb

This feature of the model allows users to assign a set of rules that need to be satisfied in their considered design. It takes advantage of a rule-based system to assess the design constructability based on available information in the design platform. These rules are applied to impose the design limitations and constraints in terms of spacing, layout or dimensions, which may later affect the construction process.

When customising this part of the assessment model, if selected to be assessed, users are able to enable rules that impose design constraints (restrictions of weight, height, length, width, etc.). Such restrictions could be applied bearing in mind resources such as availability of elements, mode of transportation, site accessibility, available storage space, methods of constructions/installation and available working space. The rules to apply for a specific design can be activated from the assessment model (not all rules need to be applied for all designs) to suit the given conditions. Although users could always opt to extend the package to include more rules, this might require some programming skills. During the assessment process, the process model verifies the compliance of assessed designs with enabled rules, assigns them weights (as specified by the user in the assessment model) and then determines a final score representing the constructability index based on these rules. By adding the design rules feature, the proposed framework is the first of its type to combine a numerical assessment system and a rule-based system, allowing for both quantitative and qualitative approaches when assessing design constructability.

Complexity

This category is provided to accommodate impacts of the design solution on facilitating various constructability aspects during the construction process, such as the simplicity of the design, automation of the process and flexibility associated with its different aspects. These are observed and assessed by users using available tools within the BIM environment, such as 4D animation (or even AR and VR capabilities) to evaluate design constructability. Although the scope of implementation in this research does not currently cover this, the feature is included in the framework as planned work and in order to demonstrate its potential use for the ultimate benefits of BIM in achieving a constructible design.

Location

This part of the model assesses the design considerations for the project location and its surrounding environment. Aspects such as weather in the region and site conditions should be catered for in selected design elements and how they are installed. Additionally, site accessibility and its proximity to delivery sources play a vital role in choosing construction methods (i.e., precast or cast in situ for concrete components).

In the proposed model, the assessment of these components is based on available information within the BIM model that can be employed for this part, with some user inputs. This includes:

1. The construction schedule to be linked with weather forecasts to decide on suitable construction methods, appropriate working hours and avoid working in anticipated extreme weather.

2. Selected construction materials and components within the design, and their delivery requirements given site accessibility and the availability of storage space. Alternatively, coordinating for just-in-time deliveries to avoid double lifting.
3. Selected foundation system and its suitability for site soil conditions.
4. Compliance of the design with legal requirements for its adjacent buildings (i.e., the Party Wall Act in the UK which prevents and resolves disputes in relation to party walls, boundary walls and excavations near neighbouring buildings).
5. Any other restrictions laid on the design due to its surrounding environment, the availability of utilities and accessible infrastructure facilities.

However, the impact of project location on the design solution could be better observed and assessed by integrating GIS (Geographical Information System) applications into the BIM model. Such integration incorporates more data into the assessment process (such as access to the construction site, traffic data, the topography of the area and soil condition) which would enable deeper insight for better decision-making.

Weighting Factors

These factors shape the assessment model's priorities by assigning weights for its considered components (AEC systems, rules of thumb, complexity and location). The weights are assigned to represent the contribution of such components towards achieving the design objectives in terms of cost, time and safety, etc. As can be seen in Fig. 4, the AHP method was used to obtain weights and rates for different components of the assessment model. The technique structures a decision problem into a hierarchy of criteria, sub criteria and alternatives, followed by a series of pairwise comparisons to derive prioritised scales (Saaty 2008). This enables model users to have the control of customising their assessment models. They can decide what to assess and score them accordingly, imposing their own constructability conditions.

6.1.3 Assessment process model

This process consists of mapping customised assessment model on the actual design model to benchmark its constructability. The design model will be assessed based on its: AEC systems, satisfaction for assigned rules, complexity and considerations for the project location. Different design elements will be assigned scores and weights as rated earlier in the model or their satisfaction to set assessment criteria. These scores and weights make up for the total score of each considered assessment model components (AEC systems, rules of thumb, complexity and location) as Fig. 5 illustrates. This is balanced by the weighting factors, imposing the importance of each component in affecting the constructability performance of a design from the user's perspective. The summation of these factored scores delivers the final constructability score of the examined design. This informs its overall constructability status.

6.1.4 Decision-making phase

Based on the obtained feedback, designers can decide whether an improvement in their design constructability is needed. They will be able to observe problem areas, if there are any, which are indicated by the output scores. This system paves the way for optimising their constructability performances.

6.2 Framework Implementation

The proposed framework is implemented through a prototype using Application Programming

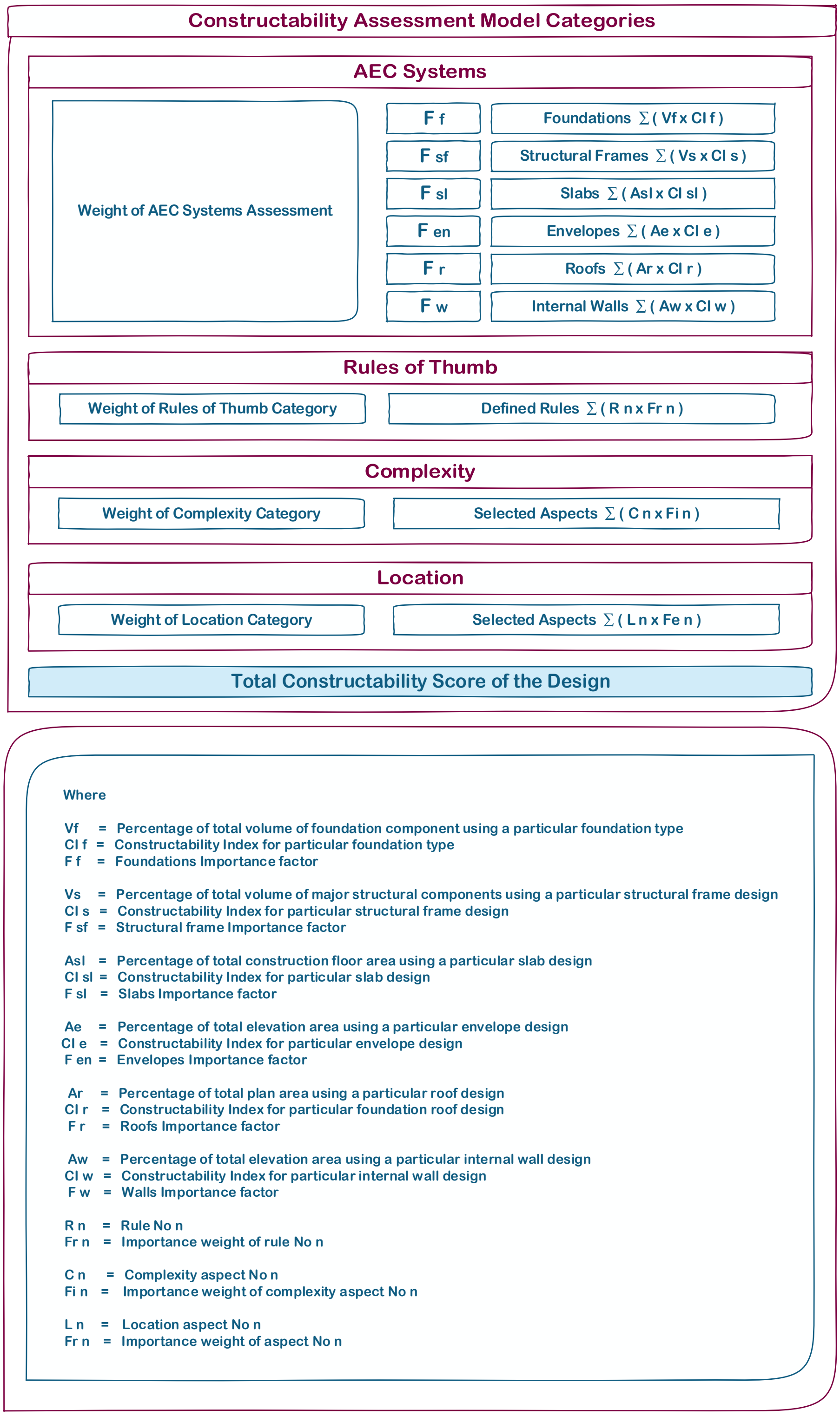

Fig. 5 Equation framework for calculating the constructability score using the proposed model

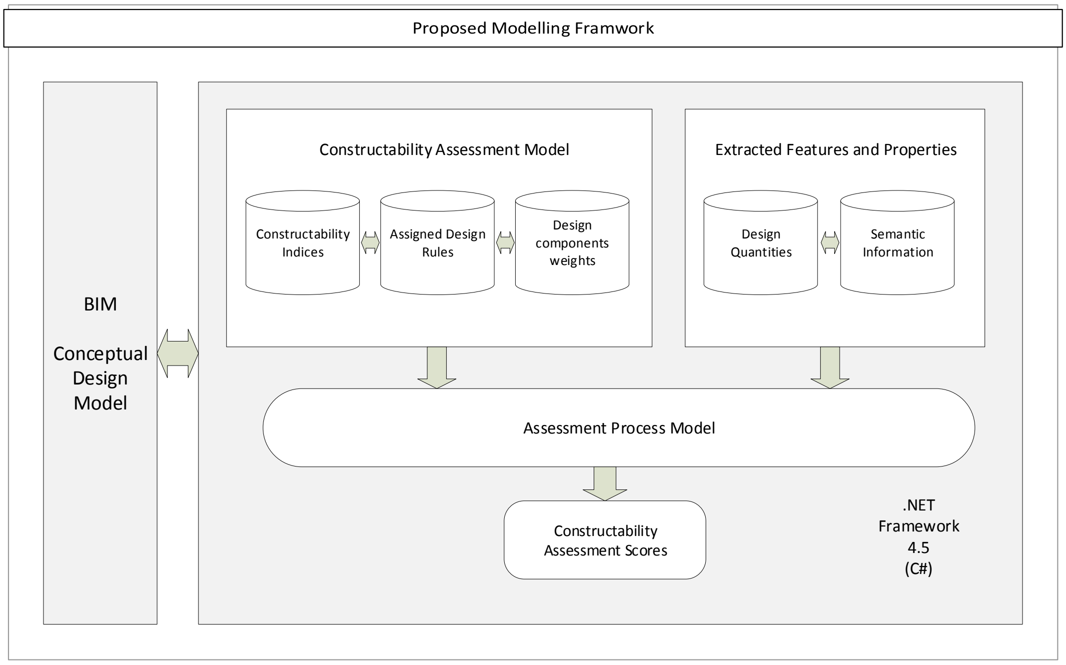

Fig. 6 Implemented framework

Interface (API) as a BIM extension, as illustrated in Fig. 6. The plug-in software for Revit is implemented in the .NET Framework environment using the C# programming language. The assessment process model acts as an inference engine that synthesises extracted features and properties from the conceptual BIM model (e.g. quantities, dimensions and elements' properties etc.) and applies onto them the knowledge embedded in the constructability assessment model. It then verifies the defined rules and assigns the weighting factors and indices to the extracted features and properties and determine the constructability scores.

The elicitation of a use-case guiding the programming direction is shown in Fig. 7. It demonstrates the prototype functioning in four parts, namely: Customising a new constructability model, modifying the customised model for another use, interacting with the uploaded BIM model (initial analysis for its quantities) and assessing the design constructability.

The implemented prototype allows users to explore different design alternatives and decide on a design based on its constructability performance (Fig. 8). This will enable design optimisation by examining different construction systems and then observing their impacts on design constructability.

The proposed system satisfies the earlier specified requirements for modelling constructability in buildings, Fig. 1. Its concept and implementation are generic and can be applied to different types of buildings. This is due to the separation of the 'knowledge' in the constructability assessment model, the data embedded in the BIM model and the reasoning implemented in the assessment process model. While the BIM model contains semantic information on the conceptual design, the assessment model stores user requirements and construction capabilities.

Furthermore, the ability to use the prototype throughout the design process with different LoD stems from its flexibility to carry out the assessment with available information in the model. Users can decide on what to assess based on what they have in the model. For example, missing

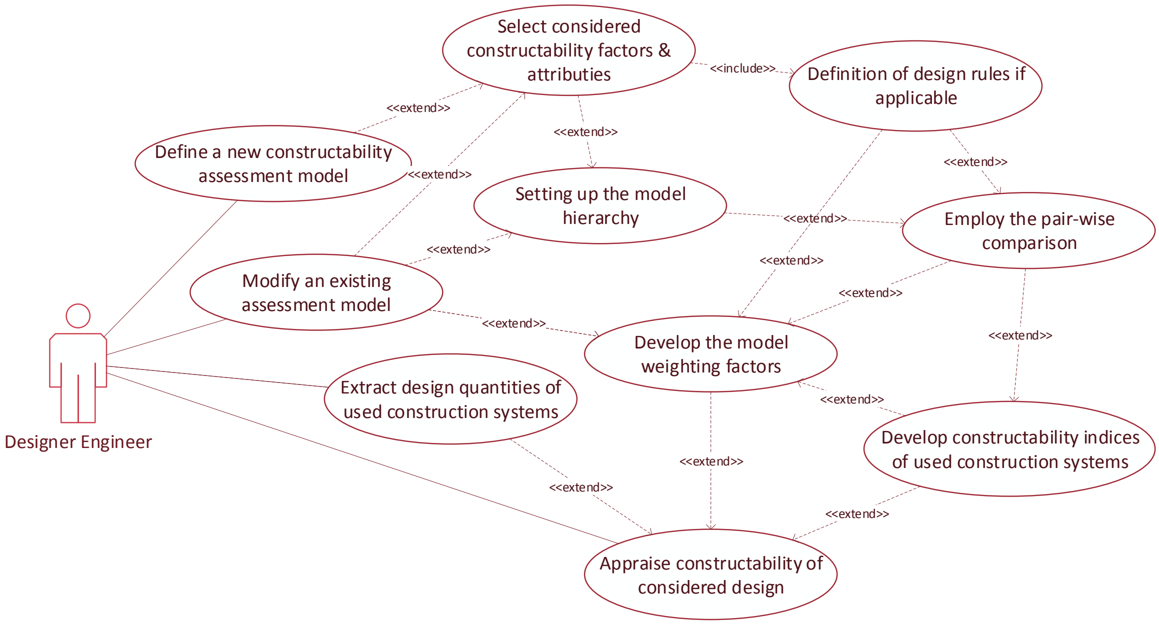

Fig. 7 Use case (Fadoul *et al.* 2018)

sizes and dimensions in the BIM model will not be checked against their defined rules—if there are any. Once the information is made available in the model, they will be part of the next assessment checks. The usefulness of such a feature enables designers to carry out the assessment with a multilevel of design details throughout various stages of the design process.

The scalability of the model is demonstrated in its ability to assess varying building sizes as long as they satisfy the required level of details. However, users should use an assessment model that is suitable for the design solution at hand. It is envisaged that users will create a number of assessment models each could be specialized to suit specific size or type of construction. An example of this could be a model to use for the assessment of small building projects that use prefabrication techniques.

The model is also designed to accommodate various constructability aspects within the assessment process and from different perspectives. It has four different parts covering all potential constructability issues which are identified in literature as well as current practice. While this indicates the comprehensiveness of the model, users are not obliged to use all parts. This gives the users the flexibility to tailor their model and only include critical aspects that they usually face during the construction phase.

The integration of the implemented prototype with a BIM authoring tool (in this case, Revit software) facilitates its use. Also, the customised assessment could be used for similar types of building for which it was tailored originally, or modification can be made to model to suit and possibly saved as another model. These features simplify the assessment process and save time and effort in using the software.

In addition, the assessment process delivers meaningful feedback that assists in improving design constructability. It enables the assessor to use the presented scores to clearly observe design elements that need consideration based on their constructability performance. It also indicates how each construction system performs with respect to what is expected, and what its final contribution

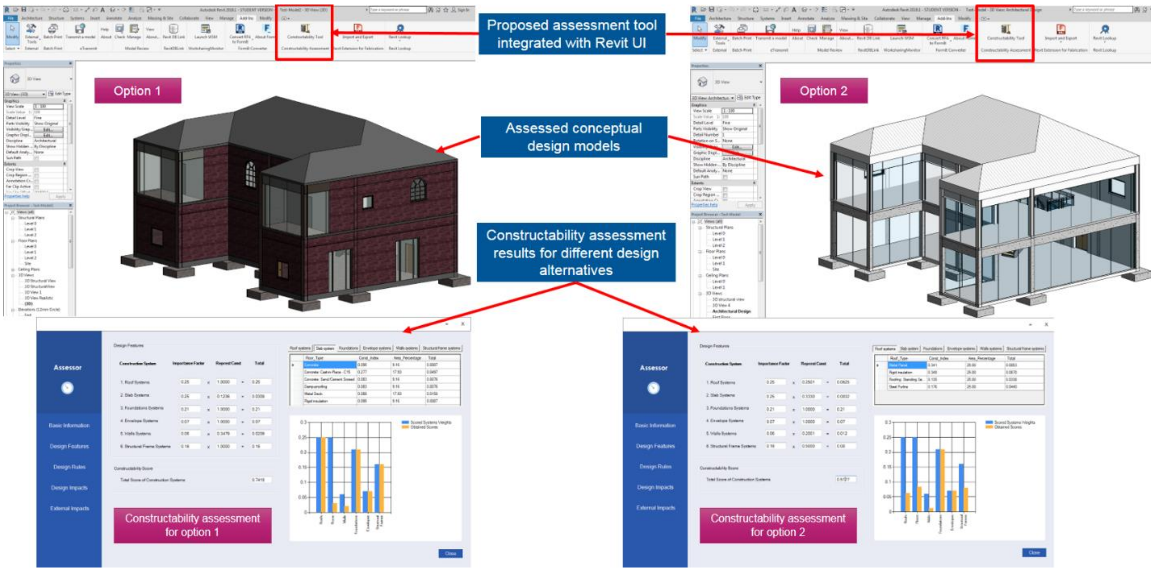

Fig. 8 Constructability scores of design alternatives

towards fulfilling the desired design objectives in terms of cost, time, etc. The detailed working of the system is outside the scope of this paper.

7. Conclusion

Despite awareness of the potential benefits of designing for constructability, it remains very challenging to devise tools that can implement the concept. The use of new technology-based tools to assess the constructability of designs has not been fully realised. The challenge has been how to build a tool that assesses design constructability and quantifies its abstract nature, while making use of current information technologies such as BIM.

This paper reviewed current conventional methods for assessing design constructability. It studied various approaches adopted for constructability assessment. Aspects of the study included the model content, scope of application, assessment principles, assessment aspects and the basis of assessment criteria. The shortcomings of current assessment systems and the challenges that need to be addressed in this area has been identified. Consequently, it defined a set of modelling requirements that should characterise an ideal constructability tool, namely by being: Generic, scalable, flexible, comprehensive, simple, accurate and effective.

This paper then proposed a BIM-based model to quantify the constructability of design. The potential of the model stems from its employment of the latest design techniques and contemporary information modelling technology, which facilitates its integration with current design tools. The proposed modelling framework consists of four parts: The conceptual design model, the constructability assessment model, the assessment process and the decision-making phase. The proposed model and its components are described, and its implementation using the BIM concept is explained. It satisfies the modelling requirements for potential assessment tool derived from evaluating current ones. It is believed that this framework is the first to combine a numerical assessment system and a rule-based system, allowing for both quantitative and qualitative approaches and the first to enable users to transfer their construction knowledge and experience directly into a design platform linked to BIM models.

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