A Constructability Assessment Framework for Buildings Design Using Building Information Modelling (BIM)

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Abstract:
Implementation of constructability principles in the construction industry has a potential return on investment concerning time and money. Prior research shows that reviewing the design constructability at the early design stages provides benefits to owners, contractors and designers. Considering the complexity of current building design processes, there is a need to provide a decision support tool that can help designers in reviewing the design constructability based on embedded information within the design model. Such a tool would be most beneficial at the conceptual design stage so that constructability is factored into the design solution starting from its inception.

Therefore, this research investigates how contemporary process- and object-oriented models can be used to assess design constructability to enable improvements. It proposes a model-based approach using the information within a BIM model to conduct such assessment. The modelling framework and its implementation through a prototype are described in this paper. It concludes that the proposed method, quantifies the abstract nature of constructability and use it to assess alternative designs, thereby serving as an incentive for constructability improvement.

Keywords: Constructability assessment, Buildings design, assessment framework, BIM, constructability attributes.

1. INTRODUCTION

The Construction Industry Institute (CII) defines the term constructability as “The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives” (CII, 1986). Similarly, the Construction Industry Research and Information Association (CIRIA) defines term buildability as, “The extent to which the design of a building facilitates ease of construction, subject to overall requirements for the completed building” (Johnson and Jardine, 1995).

The design phase is a critical part of any project in the architectural, engineering, and construction (AEC) industry. Although the design process itself constitutes just 5% of the costs associated with a typical construction project, its success affects the build cost and the quality of the remaining 95% of the project (Egan and Williams, 1998). This includes the consideration of design constructability, which is often ignored by designers and building clients until the commencement of the construction phase when they are confronted by the reality (CIRIA, 1983).

In recognition of the importance of designing for constructability, many studies were conducted to investigate the implementation of the concept. Various approaches were employed to benchmark the constructability of design solution and enable an objective evaluation of the abstract concept. One of the key approaches to improve and enhance constructability is through a quantified assessment of designs (Wong et al., 2007).

This paper reviews current adopted approaches and methods used in assessing design constructability and the associated challenges within such process. The review covers recently reported assessment tools to benchmark design constructability, and that designers could use to obtain feedback to improve their design solutions. It then identifies a set of requirements that should characterize any decision-support tool for assessing design constructability. It goes further to propose a model-based approach that can be utilized to employ current information technologies to assess design constructability. Such model can contribute significantly to address the identified gaps from the evaluation process. A proposed framework and its components will be described as well as the direction for future work.
2. EVALUATION OF CURRENT CONSTRUCTABILITY ASSESSMENT TOOLS

Table 1 below summarizes the assessment of 12 constructability tools. These tools employ two approaches for benchmarking design constructability, they are the Knowledge-Based Systems (KBSs) and the Qualitative Modelling Analysis. They also adopted different elicitation methods for constructability knowledge such as interviews and questionnaires.

By reviewing and evaluating those assessment tools, current limitations can be identified as:

I. The interview approach is the common way to acquire constructability knowledge from design and construction experts which doesn’t necessarily reflect anyone else’s preferences and capabilities.

II. The focus on single design elements, instead of considering a building design as a whole to make necessary trade-offs to optimize the constructability overall.

III. The application time indicates that the assessment process lacks inputs of construction knowledge at early design stages.

IV. Nine out of the 12 tools are systems that lack the capability of visualization, which can cause communication issues and waste time during decision-making (Golparvar-Fard et al., 2013).

3. REQUIREMENTS FOR MODELLING CONSTRUCTABILITY IN BUILDINGS

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

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Generic</td>
<td>The model can be employed to assess different design solutions at the various stages of the design process.</td>
</tr>
<tr>
<td>Scalable</td>
<td>The model is valid for varied building sizes and its implementation covers individual design elements.</td>
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<td>Flexible</td>
<td>Users can tailor the model to suit their own preferences and capabilities.</td>
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<td>Comprehensive</td>
<td>The model implementation covers all constructability aspects and attributes.</td>
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<tr>
<td>Simple</td>
<td>Can be easily applied and integrated within a design environment.</td>
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<td>Accurate</td>
<td>Assessment outcomes accurately reflect the design constructability.</td>
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<tr>
<td>Effective</td>
<td>Enables designers to improve their design constructability.</td>
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</tbody>
</table>

Figure 1: Requirements of constructability appraisal systems (Fadoul et al., 2017)
Table 1. Summary of current constructability tools (Jiang, 2016)

<table>
<thead>
<tr>
<th>Constructability Tools</th>
<th>No.</th>
<th>Name</th>
<th>Constructability Knowledge Elicitation Methods</th>
<th>Level of Detail of Constructability Knowledge</th>
<th>Application Timing</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Building Site</td>
<td>System</td>
<td>Sub-System</td>
<td>Component</td>
</tr>
<tr>
<td>Knowledge-Based Systems (KBSs)</td>
<td></td>
<td></td>
<td>N/A</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>(1) Structural frame selection system</td>
<td>1</td>
<td></td>
<td></td>
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<td>(2) Modular Construction decision support system</td>
<td>2</td>
<td></td>
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<tr>
<td>(3) Automated constructability assessment system for structural steel design</td>
<td>3</td>
<td></td>
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<tr>
<td>(4) Knowledge representation space for constructability analysis of concrete beam design</td>
<td>4</td>
<td></td>
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<tr>
<td>(5) Formwork selection system</td>
<td>5</td>
<td></td>
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<tr>
<td>(6) Designer Fabricator Interpreter (DFI) system</td>
<td>6</td>
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<td>(7) Automated retail constructability diagnosis system</td>
<td>7</td>
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<tr>
<td>(8) Fabrication issues checking system</td>
<td>8</td>
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<tr>
<td>(9) Construction Knowledge Expert System (COKE)</td>
<td>9</td>
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<tr>
<td>Qualitative Modeling Analysis</td>
<td></td>
<td></td>
<td>Literature review, Interview</td>
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<td></td>
<td></td>
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<tr>
<td>(10) Buildable Design Appraisal System (BDAS)</td>
<td>10</td>
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<tr>
<td>(11) Comparative analysis system of building upper structural systems</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(12) Automated measurement of buildability factors affecting edge formwork labor productivity</td>
<td>12</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

References:
- Salazar & Brown (1988)
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- Navon et al. (2000)
- Ernst & Roddis (1994)
- Fischer (1993)
- CIDB (1993), Pho & Chen (1990)
- Lam et al. (2007)
- Jarkas (2010)
4. CURRENT LIMITATIONS AND EMERGING CHALLENGES

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 constructability of designs has not been fully realized. The challenge now is how to utilize BIM capabilities to assess design constructability.

This study proposes a constructability decision-support tool. It provides a mechanism to assess the design constructability at an early design stage and deliver feedback to enable designers to optimize their designs and make necessary changes with minimum disruption and maximum efficiency.

5. A PROPOSED FRAMEWORK FOR CONSTRUCTABILITY ASSESSMENT OF BUILDINGS DESIGN

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

5.1 Modelling Framework

Fig 2 illustrates the proposed methodology 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 and the decision-making phase.

Figure 2: Constructability assessment method
For a particular project, the typical process will be:

1. Build the conceptual design model using a BIM software and provide the necessary information that the model should contain according to the agreed level of details (LoD).

2. Customise the constructability assessment model to suit the design objectives. The model assesses the constructability of four components in the conceptual design model, they are design features, design rules, design impacts and external impacts. These components are balanced with weighting factors assigned based on their importance in achieving a constructible design.
   - The design features component assesses the constructability of selected design elements based on available resources and imposed design constraints. This is achieved by identifying the considered constructability factors and attributes in the assessment process from the users' perception, and then calculating constructability indices of different design elements using analytical hierarchy process (AHP) method (Saaty, 2008). It ranks the elements based on their constructability from users’ perspectives and hence enabling them to decide between alternative designs.
   - The design rules allow users to define a set of rules that need to be satisfied in their considered design. These rules are applied to impose the design limitations and constraint in terms of spacing, layout or dimensions, which may affect the construction process later. The system verifies the satisfaction of such rules, assigns them weights scored by the user, and then obtains a final score that is combined with scores from other categories.
   - The design impacts feature assesses the effects of selected design solutions in facilitating various constructability aspects during the construction process, such as the complexity of the design, automation of the process and uncertainty associated with its different aspects. The research is currently investigating this feature and how to attain the full potentiality of BIM in capturing such aspects during the assessment process. For example, visualization and interaction with the BIM model within a 3D environment provided by a game engine, which can be enhanced to an augmented or fully immersion virtual reality environment, may help the users to better assess their designs interactively. Detailed construction simulations or simpler 4D animations may also support in the decision-making process of the designer to improve constructability.
   - The external impacts component assesses the influence of surrounding environment factors on the construction process and how that is factored in the considered design. Such factors include infrastructure, site conditions, and adjacent buildings. Although the scope of implementation in this research does not cover this, the feature was included in the framework description to demonstrate its ability to accommodate such aspects in the assessment process, enabling users to achieve accurate and reflective constructability assessment outcomes.

Usually, the definition of the assessment model is done once and used to assess many similar projects. Adjustments may be necessary for projects of different types.

3. The process model extracts semantic information from BIM model and analyses its constructability by applying the constructed assessment model. It incorporates scores obtained from the different components of the assessment model (design features, design rules, external and internal impacts) as per user choice, as shown in Fig 3.

4. Based on the obtained feedback from 3 above, the design could be modified and the assessment cycle is run again.

5.2 Framework Implementation

The proposed framework is implemented through a prototype using Application Programming Interface (API) as a BIM extension, as Fig 3 illustrates. The assessment process model acts as inference engine that synthesizes extracted features and properties from the conceptual BIM model (quantities, dimensions and elements properties etc.). It then applies the rules and indices from the constructability assessment model to such features and properties and determines the constructability scores.
The proposed model is currently being implemented in the .NET Framework environment using C# programming language. The elicitation of a use-case guiding the programming direction is shown in Fig 4.
6. CONCLUSIONS

The current practice of designing for constructability fails to meet expectations and is in need of improvement. The implementation of a constructability concept is quite complicated and requires more serious efforts, resources and time than have hitherto been devoted to it.

This paper reviewed current methods in assessing design constructability. It defines a set of modelling requirements that should characterize an ideal constructability tool. It also proposes a model-based approach to quantify constructability of design. The potential of such model stems from its employment of the latest design techniques and contemporary information modelling technology, which means its integration with current design tools. The proposed model and its high-level components are described, and its implementation using the BIM concept is explained. The proposed system would assist in design automation where the constructability of a design can be automatically assessed and the outcome be used to improve it. Future work will involve completing the implementation part followed by its validation and evaluation with practising engineers.

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