Department of Civil Engineering

A BIM-BASED MODEL FOR CONSTRUCTABILITY ASSESSMENT OF BUILDINGS DESIGN

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Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy

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Declaration

I hereby declare that this thesis entitled "*A BIM-Based Model for Constructability Assessment of Buildings Design*" is the result of my own research, except for commonly understood and accepted ideas, or where specific reference has been made to the work of others. This thesis has not been submitted to any institution other than the University of Nottingham for the degree of Doctor of Philosophy.

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Abstract

Implementation of constructability principles in the construction industry has a potential return on investment concerning time and money. Existing empirical studies demonstrate that incorporating these principles into the initial stages of design maximises outcomes for all stakeholders, including designers, contractors, and clients. However, constructability encounters many challenges in practical implementation. One of the main obstacles is knowledge acquisition and representation, leading to the lack of a knowledge-based tool to model design constructability. Current methods demand laborious efforts and resources to execute assessment calculations and interpret their outcomes. The dynamic design process and the need for ongoing modifications in designed products necessitate revision of the constructability assessment routine, whenever design changes are introduced, and it is highly desirable that these revisions should be automated.

This research, therefore, investigates design-stage assessment of design constructability by examining contemporary process and object-oriented models. The study reviews currently employed approaches for assessing design constructability and highlights their shortcomings. Based on this, it presents an original assessment framework to measure constructability of BIM-based design solutions. The proposed mechanism separates the formulation of construction knowledge from carrying out the assessment processes. The modelling framework is composed of three key parts: the *Constructability Model (CM),* which formulates user-based knowledge; the *BIM Design Model,* which provides required data for the assessment; and the *Assessment Model (AM),* which reasons the formulated knowledge into design features.

The model was implemented in a prototype, using object-oriented programming in a C# application. The prototype was developed using .NET Framework as a plug-in to BIM software, Revit, to operate on the design models created. The prototype was tested using typical design case studies, which have proved its usefulness in informing constructability decision-making. The process also enabled the exploration and evaluation of what-if scenarios in design iterations, and construction methods.

A developed BIM-based constructability assessment model was validated through different approaches, including interviews with experienced practitioners and a focus group comprising experts from industry and academia. As a result, the model has been found to provide the capability to represent constructability assessment knowledge within its Constructability Model. In addition, it demonstrated the ability to employ the knowledge-bases produced to reason about the constructability of alternative designs. Furthermore, practitioners have confirmed that the model is highly applicable in the industry and greatly needed to improve the practice of designing for constructability.

The research concludes that the introduced assessment framework effectively enables modelling of buildings' design constructability. The implemented prototype is found to provide qualities lacking in current constructability tools. These include the qualities of being *generic*, *scalable*, *flexible*, *comprehensive* (both quantitatively and qualitatively), *simple* to use, *accurate*, and *effective* in delivering meaningful results that enable constructability improvement.

In addition, the separation between knowledge acquisition and knowledge reasoning processes simplifies the assessment procedure and saves the user time and effort. It allows for the reuse of formulated knowledge (i.e., CM) to model the constructability of multiple designs and at different stages. It also eliminates any potential bias that could arise during constructability assessment, given the subjectivity of the problem. Furthermore, the use of the BIM-based assessment tool automates the process and delivers an instant feedback on constructability performance.

Keywords: Constructability assessment, BIM, building design, assessment model

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Abbreviations

2D	Two dimensional
3D	Three dimensional
4D	Four-dimensional spacetime Three-dimensional plus time
AEC	Architecture, engineering, & construction
AHP	Analytical hierarchy process
AI	Artificial intelligence
AM	Assessment Model
BDAS	Buildable design appraisal system
BIM	Building information modelling
BCA	Building and Construction Authority, Malaysia
BPS	Building performance simulation
CAD	Computer aided design
CM	Constructability Model
CII	Construction Industry Institute
CIRC	Construct for excellence
CIRIA	Research and Information Association
DBMS	Database management system
ICT	Information and communications technology
IFC	Industry foundation classes
KM	Knowledge management
LOD	Level of detail/ development
SDBAM	Scheme design buildability assessment model
SWOT	Strengths, weaknesses, opportunities, and threats
NBIMS	US National Building Information Modelling Standard Version
NBS	US National Building Specification
UI	User interface

1. Introduction

1.1. Background

The traditional design process often overlooks necessary design solution considerations during the construction process (Faniran et al., 2001). Historically, it was seen as the remit of architects and engineers to design projects, and then their role ended, and contractors took over to work out how to actually build the designs during the construction process (Zin, 2004). Due to the fundamental separation between design and construction activities, many construction issues and challenges are experienced, resulting in most projects exceeding their budget or construction schedule (Gray, 1983b, Hassan, 1997). Addressing the critical waste of the construction industry, constructability concepts have been developed to minimise design-related problems and inefficiency, seeking to integrate design with the construction process to minimise potential challenges that may arise during the construction phase (CIRIA, 1983, Hon et al., 1988, CII, 1986, CII, 1987b).

Constructability principles can be incorporated at any stage of the project lifecycle, but their deployment at the design stage has the most significant improvement on constructability performance (Kifokeris and Xenidis, 2017). The design stage is critical, and has profound impacts on the entire performance of construction projects throughout their lifecycle (Gerold et al., 2012). The design stage accounts for only 5% of capital costs in typical construction projects, but it impacts the remaining 95% of the project building cost and quality (Egan and Williams, 1998, Latham, 1994).

Constructability aims to minimise all construction issues, including design-related problems (Jergeas and Put, 2001). Consequently, focusing on the design stage effectively implements constructability to improve projects in general. Constructability is particularly concerned with crucial parts of designs where designers can act to influence constructability (Hassan, 1997). These include aspects such as deciding on the facility shape, layout, sizes, dimensions, or materials selection. Constructability seeks to ensure that construction knowledge and previous experience are considered when making such decisions (Fadoul et al., 2018a).

The significance of designing for constructability is globally recognised in the construction industry (McGeorge et al., 1992). To date, several studies attempted to address the subject and accommodate its controversy aspects (Wong et al., 2007b). They adopted different approaches to benchmark design constructability and to enable the objective evaluation of abstract concepts. As a result, various techniques and methods have been developed to improve design constructability, including developing guidelines, checklists, expert systems, and empirical formulas (Fischer, 1991, Pheng Low, 2001, Fox and Hietanen, 2007, Lam and Wong, 2009). However, barriers to implementing constructability still stand as a challenge to design practice, as evidenced by the significant efforts, time, and human resources required to implement the concept within the design environment, which discourages many practitioners from considering constructability in their designs (O'Connor and Miller, 1995).

Researchers have investigated the employment of advanced ICT capabilities within the architecture, engineering, and construction (AEC) industry to address gaps. Building information modelling (BIM) is the most powerful technique available to effectively implement information modelling. BIM design tools offer great capabilities in managing vast amounts of information embedded in building model, from initiation to demolition. This has enabled its adoption for assessing aspects such as cost, energy, functionality, aesthetics, and constructability (Eastman et al., 2011). In addition, the capability of implementing parametric design rules associated with buildings elements allows for dynamic changes during design development to explore various alternatives (Michael, 2016). However, the exploitation of such technologies for implementing constructability is not fully realised (Hijazi et al., 2009).

This study evaluates the current practice of designing for constructability and its associated challenges. An extensive review of studies in the area was conducted to identify shortcomings and what the industry lacks, in order to fully implement constructability. These include the requirements of any design tool that may assist designers in modelling their design constructability. It will pave the way for introducing a new BIM-based model to measure the extent of constructability application of a design solution. The development and validation of such a model is discussed, and its impacts on improving constructability are demonstrated. It will aid in minimising encountered issues due to design shortcomings and thus smooth the workflow of the construction process.

1.2. Evolution of constructability concept

Constructability practices have been evolving in recent decades, and various studies have addressed the subject from different perspectives, revealing several contrasting themes:

1. A number of studies have begun to explore difficulties arising during the construction process that causes the widespread and typical failure to meet construction projects' objectives (e.g. finishing on time and on budget). Furthermore, they worked on investigating the common reasons and factors that lead to these issues and identifying their root causes (Odeh and Battaineh, 2002, Assaf and Al-Hejji, 2006, Sambasivan and Soon, 2007).

2. Researchers worked on these factors and how they could be addressed earlier to avoid construction issues and problems. They were investigating how to input downstream knowledge, such as construction competence, to upstream activities, such as design. This witnessed the introduction of the constructability concept, based on construction knowledge and experience (Arditi, 1985, Mohamed, 1996, Park et al., 2005, Hiyassat et al., 2016).

3. Recognising the importance of design stage and its implications on construction has led to directing focus on this critical stage. Studies started investigating how to integrate the design process with construction. As a result, constructability guidelines are now provided for designers. This includes design-to-build approaches, employing construction management techniques and early involvement of

contractors (Fischer and B. Tatum, 1997, Lam et al., 2006, Trigunarsyah, 2007).

4. With the advancement of technologies and design tools that employ digital modelling approaches, efforts were directed to make use of them in implementing the concept. Subsequently, knowledge-based adviser systems were introduced to assist in automating the process (Fischer, 1991, Yang et al., 2013, Jiang and Leicht, 2014, O'Brien et al., 2012).

That said, the present study attempts to address the subject of the last theme of studies. Its main focus is investigating how to quantify design constructability with the employment of BIM technologies to inform decision-making.

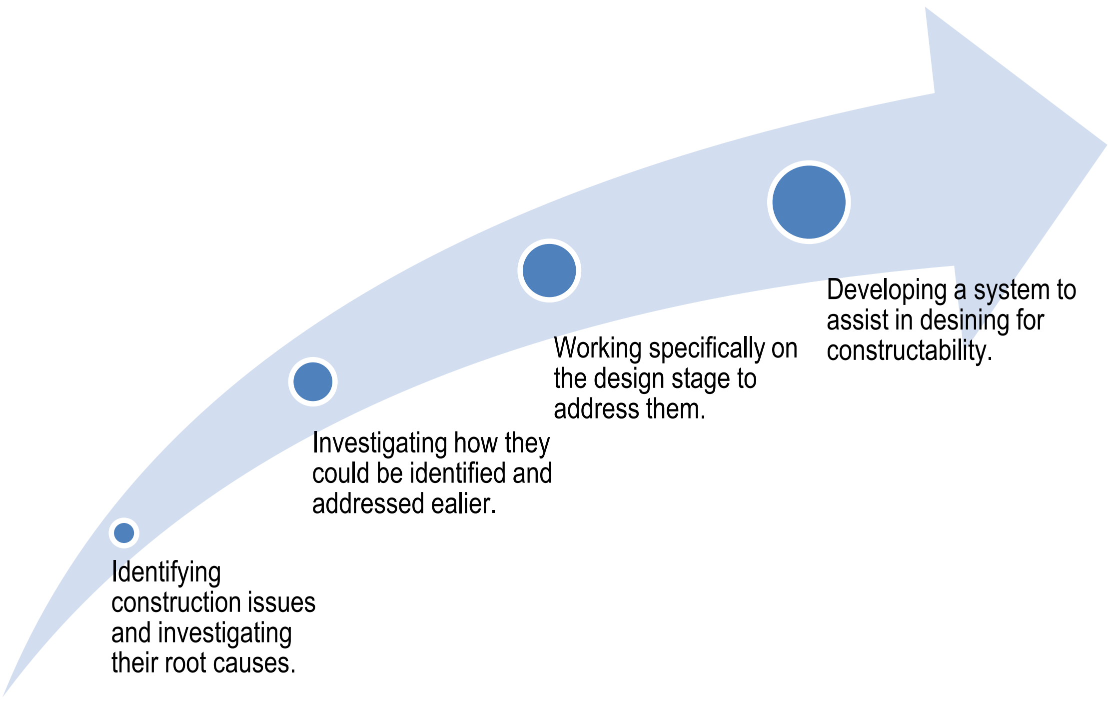

Figure 1-1: Evolution of constructability concept in the AEC industry

1.3. Research motivation

BIM technologies can play a vital role in improving design constructability through a collaborative process with early input into the design stage. It facilitates the integration of the design and construction processes, leading to improved product quality (e.g. buildings), with savings in project cost and time taken (Eastman et al., 2008). Object-oriented models have real potential in quantifying constructability application, enabling designers to draw out related constructability factors using a fast, simple, and precise tool. In addition, BIM has the ability to electronically model and manage the rich information encapsulated in the building model, from its initiation to demolition. Such information can be employed in estimation, scheduling, detailing, advanced bill estimation, automated shop drawing, and site planning for all project stakeholders, working collaboratively due to the BIM system and database.

Furthermore, the integration of time into the design solution to build 4D BIM models could significantly aid visual analyses of constructability status. Design teams can now simulate the entire construction process virtually, enabling early and advanced troubleshooting of potential problems for any stakeholder, and to prepare for potential mishaps during the construction process. Crucial constructability aspects such as materials and labour accessibility, construction sequences, and activities interdependency can be qualitatively analysed and assessed, empowering constructors to optimise the construction schedule (Hijazi et al., 2009).

Another motive for conducting this study is to benefit from gained experience in construction sectors and lessons learnt. These are formulated and published by previous studies as guidelines to be adopted by design teams and consultants. They seek to implement constructability by integrating the design process and construction planning. However, they are invariably too general to be utilised effectively in design solutions (e.g. designed for simple layout rather than technical functionality). The challenge has always been to operate these guidelines into rules and constraints that can be validated to streamline and improve constructability practice (Fischer, 1991). Therefore, this research aims to develop a technology-based tool that utilises such knowledge during the design process, to facilitate knowledge collection and formulation, and to enable its application in the designed product. BIM tools provide the ideal environment to support such a process.

1.4. Research problem

Despite the recognition of constructability benefits and its potential to facilitate the construction process and meet set objectives, its implementation in a method or tool still stands as a challenge. In modern practice, evaluating design constructability paradigms is a complex process and demands more efforts, resources, and time than can usually be devoted to it in real construction projects. The design team has limited technical support to oversee and assess the possible consequences of decisions taken at various stages with respect to constructability, during the design stage. Many constructability aspects are left out of considerations for a later stage, when it is too late to improve the design constructability performance. There is a much greater need to enhance and support the process using specialised tools during the conceptual design stage, where critical decisions are made, rather than during the later detailing stages, where changes are more complex and costly (Aouad et al., 2006).

No current tools provide the necessary construction knowledge to inform design decisions based on constructability considerations. To-date, research has tended to focus on formulating guidelines and measures for designers to follow rather than developing a mechanism or tool to support their application during the design process. The lack of a decision-support tool that quantifies design constructability is identified as the major cause of poor constructability performance in most projects (Fischer, 1991).

BIM technologies have emerged as potential platforms for facilitating the design process of buildings. However, the potential use of their capabilities to design for constructability has not been fully realised (Hijazi et al., 2009). Therefore, this research attempts to address the question of *how to map and model design constructability with the employment of knowledge-based systems and data modelling techniques to inform design decisions*.

1.5. Aim and objectives

The overall aim of this research is to investigate how to use BIM to assess the design constructability of buildings design to inform design decisions. The following objectives were set to realise the aim of this study:

- Investigate existing approaches for measuring design constructability and their underlying theories, and ascertain the observed challenges associated with such process.
- Identify requirements for modelling constructability implications of alternative design solutions of the building product.
- Develop a modelling framework to inform design performance from a constructability perspective.
- Implement the framework in a technology-based tool to be integrated with typical design environment.
- Validate the framework by using the prototype in assessing the constructability of typical designs, and through interviews and a focus group with the industry practitioners.
- Evaluate the effectiveness of the prototype and the framework in improving constructability assessment of design solutions.

1.6. Research Strategy

In order to answer the research question, a research strategy is essential. The strategy should outline how to undertake the research activities and assess the found information (Malhotra, 2017). Four research strategies are commonly used to reason with knowledge: inductive, deductive, retroductive and abductive logics of inquiry (Thapa and Omland, 2018). They provide different tactics for answering research questions, each with a starting point, series of steps, and a finishing point. While the decision of selecting a strategy is reliant on investigated research question (i.e. ‘what’, ‘why’, and ‘how’), it is typical to use more than one reasoning approach (Blaikie and Priest, 2019).

ACAPS (2016) suggests that the four reasoning processes do not exist in isolation. Instead, they make sense together when employed in a certain order.

As such, this research has adopted a mixture of research strategies to address the research question. It employs an inductive and abductive reasoning at the stage of literature review and hypothesis formulation to develop the targeted constructability assessment framework. This is followed up with deductive reasoning at the validation stage to approve or invalidate the developed framework. Such process of choosing which hypotheses are worth further deductive probation and inductive exploration are best defined to be a retroductive research strategy (Brandon, 2018). The following sections explain further how research strategies were employed within the course of this study:

1.6.1. Abductive research strategy:

Abductive reasoning is an exploratory process; it normally commences with a partial set of observations and progresses to the most likely explanation of the set (Blaikie and Priest, 2019). It is commonly used to generate a hypothesis or theory rather than to generalize from a sample to a population (ACAPS, 2016), which is typically carried out through inductive reasoning (Trochim, 2020).

This research, therefore, started with abductive thoughts to establish associated issues with the process of modelling constructability. Through the exploration of current assessment systems, the study came to identify their shortcomings and generate an understanding of the assessment process. Consequently, it paved the way to retroductively produce explanatory reasoning for their existence, which is discussed in section 3.4, and inductively formulate the thesis hypothesis, stated in section 1.8.

1.6.2. Inductive research strategy:

The inductive reasoning is an approach to research where general principle or conclusions would be inferred via observing specific cases (Zalaghi and Khazaei, 2016). The process starts with specific observations, moving to detect patterns and regularities, and eventually to come up with a theory or conclusion (Trochim, 2020), as depicted in Figure 1-2.

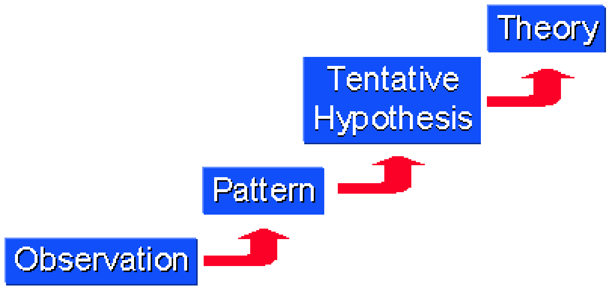

Figure 1-2: Inductive research approach

(Trochim, 2020)

As mentioned, abductive logic produces understanding of shortcomings of current constructability assessment systems. Such premise sets the stage for identifying constructability requirements, remarking the move from data to conclusions. This is represented in having a generic, scalable, flexible, comprehensive, simple, accurate and effective assessment systems to model constructability, as derived in section 2.9.1. The combination between abductive and inductive strategies served as an avenue from the exploration of current constructability assessment systems towards future deductive, theory-testing system requirements to model design constructability.

1.6.3. Deductive research strategy:

Contrary to the inductive approach, deductive reasoning moves from the more general to the more specific (Trochim, 2020). It starts with established theories and hypothesis for testing with specific data (e.g. produced from a case study), to substantiate or refute the analyst's hypothesis (ACAPS, 2016), as Figure 1-3 illustrates.

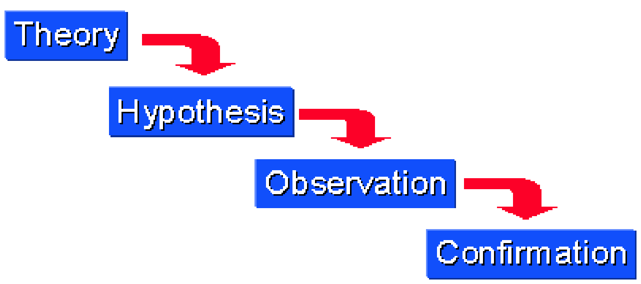

Figure 1-3: Deductive research approach

(Trochim, 2020)

Since the research has developed theories and formulated hypothesis that are used to establish the sought constructability assessment framework. Therefore, a deductive reasoning is required to validate their integrity. The inductively developed theories, represented in the requirements to model constructability, present a criterion for measuring success of any proposed constructability assessment system. The developed framework is employed in a typical case study that is designed for the testing purpose. By interrogating the achieved results, it enabled the observation of the implemented prototype's behaviour and the extent of its satisfaction of established requirements.

1.6.4. Retroduction research strategy:

The retroductive approach is the act of uncovering causal mechanisms that describe the main reasons certain events occur (Jagosh, 2019). Retroduction is an iterative process at the stage of data collection and analysis, enabling researchers to formulate a basic understanding of how to carry out the transformation (Thapa and Omland, 2018).

As discussed in section 1.6.1, the research used retroductive reasoning to formulate tentative hypothesis that can be tested. The iterative process used a combination of abductive and inductive approaches. It aimed at searching for different explanation and observing regularities for possible conclusions to generate the hypothesis.

1.7. Research methodology

A combination of research methods are employed in the scope of this study to accomplish the defined objectives, including quantitative and qualitative approaches, case studies, and model development strategies. The methodologies used are presented with respect to each objective. The objectives can be mainly divided into primary investigation, identification, development, implementation, validation, and evaluation. The process is schematically depicted in Figure 1-4:

- *Objective 1: Investigate existing approaches for measuring design constructability and their underlying theories, and ascertain the observed challenges associated with such process.*

This objective focuses on exploring and evaluating current design practice in assessing design constructability. The main goal is to understand the state-of-the-art design process in employing information modelling and to identify research gaps. To achieve this objective, a literature review has been carried out on previous and current research using textbooks, journals, internet resources, conference papers, and research theses.

- *Objective 2: Identify requirements for modelling constructability implications of alternative design solutions of the building product.*

This objective intends to distinguish constructability features and requirements to model their implications in alternative design solutions. To attain this goal, review work concentrates on previous and currently completed research works on the application of constructability principles on building designs. The most important constructability aspects will be defined, and the question of how they are quantified will be examined based on the available level of detail (LOD) throughout the design stages.

- *Objective 3: Develop a modelling framework to inform design performance from a constructability perspective.*

This objective aims to develop a modelling framework based on identified influential constructability factors and the requirements for modelling building constructability. To accomplish this objective, the research investigates how to quantify the identified constructability factors and to relate them to each other using information gathered from the literature and key related work.

- *Objective 4: Implement the framework in a technology-based tool to be integrated with typical design environment.*

To accomplish this objective, the suitable technologies required to configure the system prototype are identified (i.e. BIM software and modelling tools). Based on the selected modelling techniques and how they are integrated, the prototype is developed.

- *Objective 5: Validate the framework by using the prototype in assessing the constructability of typical designs, and through interviews and a focus group with the industry practitioners.*

A typical design environment for a structure is targeted as a test-case, while also attempting to maintain the possibility of applicability to other building types. The validation process is carried out by applying the model in typical scenarios of considered design solutions. The validation is augmented through courses of discussion with experts to assess its behaviour and practicality.

- *Objective 6: Evaluate the effectiveness of the prototype and the framework in improving constructability assessment of design solutions.*

The intrinsic evaluation will include self-evaluation through testing for any errors during the work progress, and extrinsic evaluation will include carefully selected peer reviewers and a random sample of relevant organizational reviewers during the advanced stages of the work.

1.8. Research hypotheses

The research hypothesises the following:

- Separation of the constructability model (i.e. construction knowledge-based database) from the assessment model (i.e. reasoning the knowledge on design features) enables creation of bespoke knowledgebase instances to accommodate various requirements.
- Extraction of construction relevant knowledge and experience from users directly allows us to formulate a user-based knowledge that can represent their subjective requirements and construction capabilities.
- Constructability related information can be captured using information modelling tools such as BIM to provide access to their authored models, in order to inform the decision-making.
- The use of a BIM-based tool brings the perspective of object-based modelled features to assist in the formulation of object-oriented constructability knowledgebase interactively on the platform, which will retrospectively facilitate the reasoning with such knowledge on various design models.

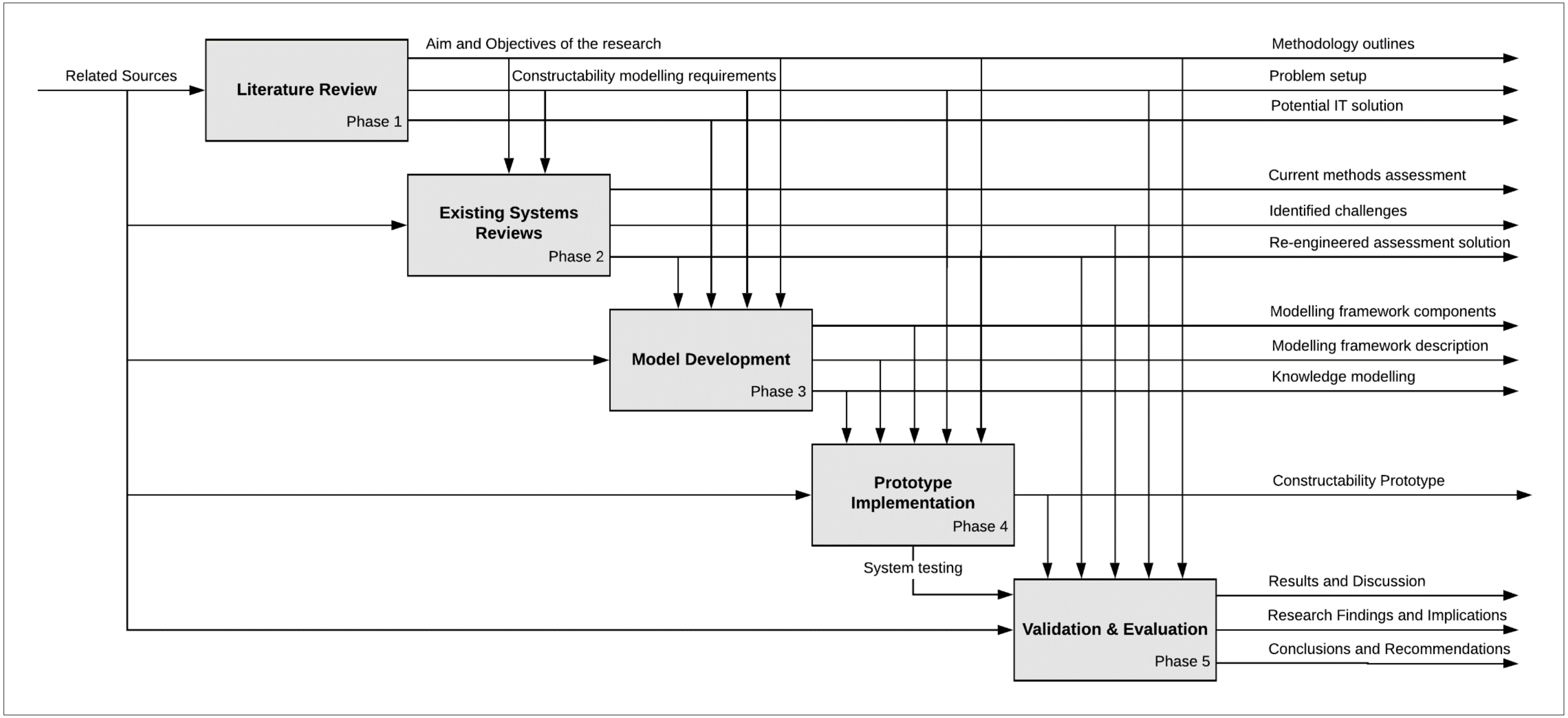

Figure 1-4: The research overview and its phases

1.9. Research scope

This research works in the area of assessing design constructability through combining various methods, techniques and tools. This includes the employment of information technology, construction knowledge-based systems, and decision-making techniques, which are individually quite broad. Therefore, there is a necessity to reduce the domain of this research with respect to the following aspects.

1.9.1. The scope of assessed aspects based on constructability considerations

The proposed framework seeks to assess designs solution from a constructability point of view, without taking into consideration other aspects (e.g. structural performance). This might lead to favouring one design over other options from a constructability perspective, even though it might not perform well in other aspects. In such cases, the design team is not only required to observe their solutions from different perspectives, but also to establish a decision-making criterion to balance between such various design aspects. This would be facilitated by appropriate design tools to inform design decisions, like the one proposed here for constructability.

However, constructability is an abstract concept that covers many broad aspects of construction projects, and it is impossible to address all of them within the scope of a single study. Therefore, the proposed assessment system is not able to provide a comprehensive list of all aspects that affect constructability and the factors to be considered. Instead, it seeks to establish a generic solution that enables its use by different users with various needs. This includes providing them with a room of flexibility to add, amend, or delete from these lists as they see fit. Other studies aiming to develop such a comprehensive list for constructability factors and attributes could be of assistance for users who lack the experience at this point. The ultimate purpose is to apply the proposed method in utilising such knowledge to appraise design constructability.

1.9.2. The scope of the proposed assessment framework functionality

The implemented prototype is a decision-support tool that assists users to assess design constructability rather than a decision-making tool *per se*. Consequently, it depends on input from users to comprehend the constructability status of assessed designs. However, such input requires a fair knowledge of construction practice and expertise gained from previous projects. The tool's main function is to determine how to design for constructability by breaking down the observed problem into small pieces, which can be addressed with BIM support whenever possible (e.g. using visualisation and semantic information).

1.9.3. The scope of the framework implementation

The reader should bear in mind that the proposed assessment framework is implemented as a small-scale prototype. It is intended only to prove the feasibility of the concept and its potential impacts on quantifying design constructability; the presented prototype in this study is an incomplete assessment tool for end-user purposes. Although this limitation has an impact in presenting all its features that would demonstrate the satisfaction of implementation requirements (e.g. in terms of being generic and flexible), there is a scope to extend this framework in future work to a larger scale.

1.10. Thesis layout

- *Chapter 1: Introduction*

This chapter introduces the research, including its background and motivation, the research problem, the research aim and objectives, and the research methodology. It also defines the research scope of work that enables the realisation of its objectives.

- *Chapter 2: Constructability Review*

This chapter reviews the existing state of knowledge regarding this research area. It explores the latest research concerning the implementation of constructability concept and recent efforts of employing BIM to achieve constructible designs. It also reviews currently employed approaches for assessing design constructability and evaluates their effectiveness, highlighting the current bottlenecks and inefficiencies in the process. It then identifies the gaps in knowledge and future work required to address these gaps, to which this study contributes.

- *Chapter 3: Designing for Constructability*

This chapter presents further analysis of the constructability concept and its underlying theories to identify current limitations and issues within its implementation. It then investigates how to address the identified gap in the potential constructability assessment framework with the help of BIM technologies. A high-level structure of such a framework is introduced and the rationale behind them, paving the way for a full description of its components.

- *Chapter 4: A Proposed BIM Constructability Assessment Framework*

This chapter presents a framework that can be employed for assessing building design constructability utilising BIM and knowledge-based systems. It seeks to devise an assessment system that enables implementation of the constructability concept. A description of the proposed constructability modelling framework, its components, and its interaction with the users is provided in this chapter. In addition, the mechanism for calculating Constructability scores of buildings design is explained using the introduced AM.

- *Chapter 5: Implementation of the Constructability Assessment Prototype*

This chapter describes the implementation of the proposed prototype through a plug-in tool built into the Revit software platform. The implementation environment and its components are discussed representing key features of the prototype development. Aspects of the prototype operation are also covered, implementing a combination of classes and event handlers to deliver the desired functionality.

- *Chapter 6: A Case Study Using the Proposed Prototype*

This chapter demonstrates the use of the implemented prototype in a case study, to validate its effectiveness in capturing design constructability. Various design options are tested to understand their sensitivity to the constructability assessment, as well as the prototype behaviour in capturing such responses. Aspects related to the case study goal, its implementations, and obtained outcomes are also analysed and discussed.

- *Chapter 7: Validation*

This chapter validates the implemented BIM-based constructability assessment model. This is carried out through different approaches, including interviews with experienced practitioners and a focus group comprising experts from industry and academia. The validation objectives, procedures, and results are presented and discussed within this section.

- *Chapter 8: Evaluation*

This chapter evaluates the proposed system for assessing design constructability in conjunction with BIM. It examines the implemented prototype in accommodating the abstract concept based on its performance on the applied case study. The evaluation methodology is explained, and obtained results are presented and discussed. Aspects of discussion include the prototype concept, implementation, operation, and delivered assessment outcomes. Suggestions for features addition are also recommended for further improvements.

- *Chapter 9: Conclusion and Recommendations*

This chapter summarises the research objectives and highlights how they are realised within the scope of this study. It also recapitulates the key research findings and its contribution to the current body of knowledge. Furthermore, recommendations for future work are presented.

2. Constructability Review

2.1. Introduction

The literature review explores the latest research concerning construction industry practice in designing for constructability. It gives an overview of constructability and buildability concepts, their evolution, and the growing interest in their adoption. It also highlights the current status of constructability implementations around the globe, the latest developed tools and techniques to support such processes, and the capabilities of current information modelling technologies such as BIM in improving constructability performance.

Furthermore, it reviews currently employed approaches for assessing design constructability and evaluates their effectiveness, demonstrating the current limitations in designing for constructability and highlighting the inefficiencies within such processes. Subsequently, it defines the gaps in knowledge and future work required to address these gaps, to which this study contributes.

2.2. Definitions of constructability and buildability

The separation of design and construction during the 1960s precipitated the necessity for the concept of constructability. However, due to its inherently abstract nature, different theories exist in the literature describing how to implement the concept (Egan and Williams, 1998).

Table 2-1 reveals the emergence of contrasting themes when approaching constructability concept. As for constructability, the most cited operational definition is that developed by the Construction Industry Institute (CII) in the USA: "*The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives*" (CII, 1986).

Table 2-1: Interpretations of constructability

Quotations of constructability	Reference
Constructability is a project management technique for reviewing the whole construction process. Before project implementation, it will reduce or prevent mistakes, delays and overflow costs, through identifying the obstacles'	(Jadidoleslami et al., 2018b)
Constructability is a holistic methodological approach to project management, primarily up to project delivery, with dynamic individual characteristics and various developed tools.	(Kifokeris and Xenidis, 2017)
Constructability programs aimed at integrating engineering, construction, and operation knowledge and experience to better achieve project objectives.	(Arditi et al., 2002)
The feasibility (or complexity) of a considered project to be performed by a specific technology based on the construction knowledge learned from past projects.	(Skibniewski, 1999)
The optimum use of construction knowledge and experience by the owner, engineer, contractor and construction manager in the conceptual planning, detailed engineering, procurement and field operations phases to achieve the overall project objectives.	(Nima et al., 1999)
The stretch version was a planning process that requires customer input in every phase of the capital project planning: front-end engineering, detailed design, procurement, contracting, construction, check-out, start-up, operation, maintenance, business management and communication among all project participants.	(Geile, 1996)
The integration of construction knowledge in the project delivery process and balancing the various project and environmental constraints to achieve the project goals and building performance at an optimum level.	(Australia), 1996)
Constructability of a design refers to the ease with which the raw materials of the construction process (labour, production equipment and tools, and materials and installed equipment) can be brought together by a builder to complete the project in a timely and economic manner.	(Glavinich, 1995)
Constructability involves integrating construction knowledge, resources, technology, and experience into the engineering and design of a project.	(Gupta, 1995)
Constructability programs are the application of a disciplined, systematic optimization of the procurement, construction, test, and start-up phases by knowledgeable, experienced construction personnel who are part of a project team.	(Russell et al., 1994)
Constructability involving construction-oriented input into the planning, design and field operations of a construction project.	(Pepper, 1994)
The process of doing everything possible to make construction easy, to improve quality, safety, and productivity, to shorten construction schedules and to reduce rejection and rework.	(Kerridge, 1993)
The application of a disciplined and systematic optimization of construction-related knowledge during the planning, design, procurement and construction stages by knowledgeable, experienced construction personnel who were part of a project team.	(Sheehan, 1992)
Constructability was defined as a measure of the ease or expediency with which a facility can be constructed.	(Hugo et al., 1990)
The optimum use of construction knowledge and experience in conceptual planning/ planning, design/ engineering/ detail engineering, procurement, and field operations/ operations phases to achieve overall project objectives.	(CII, 1986)

Similar to constructability, the term buildability is used in the literature to reflect the impact that designers may have on the construction process (McGeorge et al., 1992). As for constructability, buildability was approached differently across various studies, but in general they referred to the impact building design has in facilitating construction with the achievement of targeted objectives (Johnson and Jardine, 1995). Table 2-2 illustrates the common definitions of buildability across different studies.

Table 2-2: Interpretations of buildability

Quotations of constructability	Reference
Buildability is strongly related to the materials' early-age structural build up, which is paramount aspect to increase the production rates in 3DCP-based manufacturing of vertical elements, e.g. columns.	(Di Nicolantonio et al., 2019)
Buildability is related to all aspects of a project which enable the optimum utilisation of construction resources. It ensures that there is continuity of work by managing labour, plant and equipment in such a manner that the flow of materials, components and sub-assemblies into the growing building is maintained and optimised to achieve efficient and economic production. It is concerned with activities on site and specifically with the logical sequence of operations and construction methods.	(Pheng and Abeyegoonasekera, 2001)
Buildable designs will lead to improvements in quality… due to the relative ease of construction and the need for fewer skilled tradesmen… The 3S principles of Standardisation, Simplicity and Single Integrated elements can achieve a buildable design.	(BCA, 2005)
The end-result when designs and plans are translated on-site into a building with minimum difficulty to give the best possible results.	(Building, 1993)
The extent to which decisions are made during the whole building procurement process, in response to factors influencing the project and other project goals, ultimately facilitating the ease of construction and the quality of the completed project.	(McGeorge et al., 1992)
The ability to construct a building efficiently, economically and to agreed levels from its constituent materials, components and sub-assemblies.	(Ferguson, 1989)
Practical buildability requires a compromise between consciously making the design more buildable and accommodating the many factors impacting the influence upon design, including quality, aesthetics, time and cost.	(Griffith, 1987)
The extent to which the design of a building facilitates ease of construction, subject to the overall requirements of the completed building.	(Johnson and Jardine, 1995)

Table 2-3 and Table 2-4 summarise the commonalities in the attributes of constructability and buildability concepts among the different interpolations explained above. It can be seen that all of them implicitly or explicitly aim to improve building quality, accomplish design requirements and ease construction within the early design process (Wong et al., 2007b).

Table 2-3: Common attributes among various constructability interpretations

Reference	*Int*	*App*	*Fac*	*Ach*	*Opt*
(Jadidoleslami et al., 2018b)	N	Y	Y	Y	Y
(Kifokeris and Xenidis, 2017)	N	Y	Y	N	N
(Arditi et al., 2002)	Y	Y	N	Y	N
(Skibniewski, 1999)	Y	N	N	N	Y
(Nima et al., 1999)	Y	Y	N	Y	Y
(Geile, 1996)	Y	Y	N	N	N
(Australia), 1996)	Y	Y	N	Y	Y
(Glavinich, 1995)	N	N	N	Y	Y
(Gupta, 1995)	Y	Y	N	N	N
(Russell et al., 1994)	Y	Y	N	N	Y
(Pepper, 1994)	Y	Y	N	N	N
(Kerridge, 1993)	N	N	Y	Y	Y
(Sheehan, 1992)	Y	Y	N	N	Y
(Hugo et al., 1990)	N	N	Y	N	N
(CII, 1986)	Y	Y	N	Y	Y

Table 2-4: Common attributes among various buildability interpretations

Reference	*Fac*	*Ach*	*Opt*
(Di Nicolantonio et al., 2019)	N	N	Y
(BCA, 2005)	Y	Y	N
(Pheng and Abeyegoonasekera, 2001)	Y	N	Y
(Johnson and Jardine, 1995)	Y	Y	N
(Building, 1993)	Y	Y	N
(McGeorge et al., 1992)	Y	Y	N
(Ferguson, 1989)	Y	Y	Y
(Griffith, 1987)	N	Y	Y

Key
Int: Integration of construction knowledge and experience with design
App: Application of constructability concept at various project stages
Fac: Facilitation of ease of construction process
Ach: Achievement of overall project objective/goals
Opt: Optimisation of resource use to achieve results

2.2.1. Establishing the boundaries of buildability and constructability

While some previous studies used constructability and buildability interchangeably, others were careful to differentiate them, as explained in Table 2-5.

Table 2-5: Differences between constructability and buildability terms

Aspect	Constructability	Buildability	Reference
Location of Adoption	Constructability has been widely adopted in the USA and Australia as a means of increasing cost efficiency.	Similar to the UK Buildability Initiative, it placed emphasis on the development of a management system rather than techniques and site productivity detail by design rationalization.	(Cheetham and Lewis, 2001, Amade, 2016)
Concept	Constructability encompasses wider scope and it embraces management functions/systems.	Buildability concerns more on design features.	(Ding et al., 2019)
	Constructability, having a broader scope, encompasses the aspect of buildability as a design-phase related constructability subsystem.	The buildability concept considered only design decisions as the key issues affecting the successful completion of a project.	(Kifokeris and Xenidis, 2017)
	Constructability is concerned with the whole process of project development to enhance construction efficiency.	Buildability deals with the design facilitating ease of construction.	(Hei, 2007)
	Constructability emphasises integration of construction knowledge and experience at various project stages; optimisation of different project requirements to achieve overall goals; and ease of construction.	Buildability is mainly concerned with design, quality of built products, ease of construction and efficient and economic construction projects.	(Wong et al., 2007a)
	The Constructability score measures the level of adoption of labour-efficient construction methods and construction processes, such as system formwork and climbable scaffolding. Higher Constructability scores translate to savings in manpower costs and shorter construction times.	The buildability score computes the extent of standardisation, simplicity and integrated elements applied to projects at the design stage. It measures the potential impact of a building's design on labour usage.	(BCA, 2005)

Aspect	Constructability	Buildability	Reference
	Constructability differs markedly from buildability in terms of its much wider boundaries and holistic perspective, focusing on the consideration of all stages in the total building process.	Buildability, as seen through research studies and practical applications as a concept focused predominantly on the influence that the designer may exert on the ease of construction on site.	(Griffith and Sidwell, 1997)
Synonymous	Practitioners used the two terms interchangeably during different research areas.		(Hijazi et al., 2009, Saghatforoush et al., 2010, Kannan and Santhi, 2018)

2.2.2. Adopted constructability definition within the scope of the study

By reviewing the evolutionary concepts of constructability and buildability, based on the boundaries established earlier, it can be concluded that constructability has a much wider perspective than buildability. Therefore, this research adopts the term "constructability" to cover all building stages, including those considered under the "buildability" concept.

Further to this, and according to Kifokeris and Xenidis (2017), the early definition of constructability introduced by CII was yet viewed as the most holistic one among the others. While researchers continued to re-define constructability, they frequently drew its aspects from other managerial methodologies and approaches (Kifokeris and Xenidis, 2017). However, recent conducted studies in knowledge management systems (Kanapeckiene et al., 2010, Rezgui et al., 2010) enabled the distinction between constructability as a comprehensive concept and its employment as a managerial tool. Certainly constructability incorporates procedural and decision-making aspects of knowledge management (Rezgui et al., 2010), cost analysis (Jin et al., 2017), total quality management (Haider, 2009), value engineering (Russell et al., 1994), time management (Smadi and Tran, 2019, JadidolEslami et al., 2018a), thermal performance (Low et al., 2008a), acoustic analysis (Low et al., 2008b), indoor quality and visual performance (Pheng et al., 2008), and productivity performance evaluation (Jarkas, 2012). However, the ultimate goal of the constructability concept is to accomplish the project objectives, to which these tools and techniques are employed, and not vice versa (Kifokeris and Xenidis, 2017).

Therefore, this research has adopted the CII definition for constructability as "*The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives*". Further analysis of the concept and adopted definition to establish the basis of the new constructability assessment framework is undertaken in section 3.3.

2.3. Demand for constructability assessment

The evolution of the constructability term goes back to the late 1970s, when there were major conflicts between building contractors and designers regarding responsibility for construction problems (Construction Industry Research and Information Association [CIRIA], 1983). Contractors believe it is the fault of designers if design goals are not achieved relative to clients' resources and pre-set objectives. Conversely, architects assert that contractors are not sufficiently qualified to execute their designs effectively, and current industry practice in general is notoriously inefficient and wasteful in material terms; consequently, numerous directions have been pursued to find approaches that can improve the vaguely defined term (Cheetham and Lewis, 2001).

Furthermore, a lack of construction knowledge in terms of its procedures and processes, management strategies, standard procedures and practices often initiates problematic projects that are launched with clashes, discrepancies and design elements that are hardly constructible. This consequently leads to cost overruns, delays and poor quality of such projects, as Figure 2-1 demonstrates. It displays that construction projects have an estimated 80% overrun in their capital expenditure on average, and usually experience 20 months delay beyond original schedules (Agarwal et al., 2016). These are terrifying figures, given the modern global construction industry's knowledge and experience in design and construction, as well as the availability of advanced computing tools in recent decades.

Therefore, there is an obvious necessity to find a way of addressing such concerns from the outset (i.e. from the beginning of the design process) by providing careful consideration of aspects such as fabrication, erection of facilities and other functional necessities (Ugwu et al., 2004).

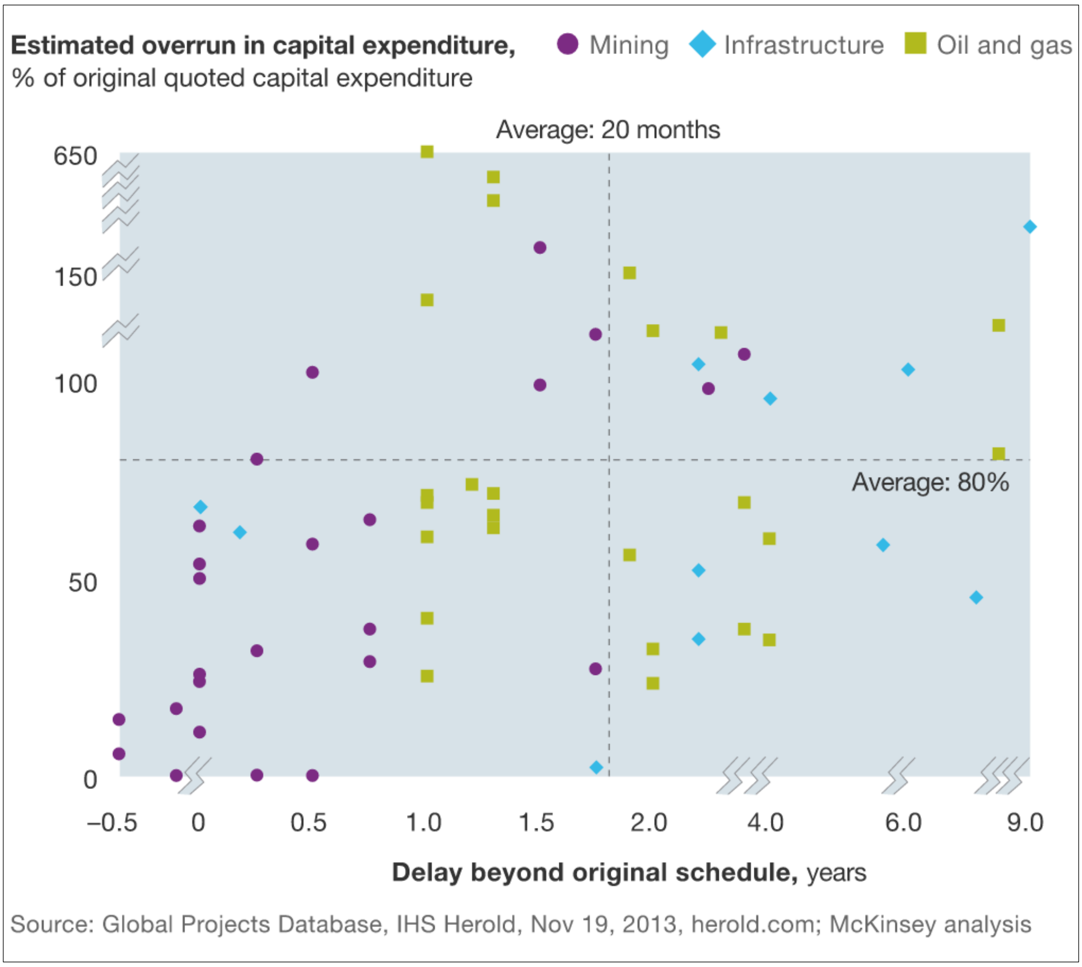

Figure 2-1: Cost and schedule overruns in the construction sector (Agarwal et al., 2016)

2.4. Benefits of improved constructability

The introduction of constructability principles in the construction industry has well-recognised benefits for owners, contractors and designers (McGeorge et al., 1992, CII, 1986). While some of these benefits are tangible and can be manifest in terms of cost, time, quality and safety etc., others are more subjective in their nature and are observed in the sense of their physiological and psychological rewards for the project stakeholders, including client satisfaction (Griffith and Sidwell, 1997). Table 2-6 summarises aspects of identified benefits by previous studies in realisation of the concept implementation.

Table 2-6: Benefits of improved constructability

Domain	Impact	References
Cost	Save 1-14% of capital cost	(Gray, 1983b, Stamatiadis et al., 2017)
	Saving total project cost	(Jergeas and Put, 2001, Elgohary et al., 2003, Trigunarsyah, 2004b, Jarkas, 2012, Smadi and Tran, 2019, Ding et al., 2019)
	Lower cost of bidding	(Gibson Jr et al., 1996)
	Reduced site labour	(Lam, 2002, Shrivastava et al., 2017, Mahamid et al., 2018)
	Increased cost effectiveness	(Pheng and Abeyegoonasekera, 2001)
	Better resources utilisation	(Eldin, 1999, Othman and Seoud, 2016, Ismail et al., 2017)
Time	Early competition	(Griffith and Sidwell, 1997, Eldin, 1999, Pheng and Abeyegoonasekera, 2001, Elgohary et al., 2003, Trigunarsyah, 2004b, Gambatese et al., 2007b, Smadi and Tran, 2019, Jadidoleslami et al., 2018b)
	Increased productivity	(Poh and Chen, 1998, Pheng and Abeyegoonasekera, 2001, Gambatese et al., 2007b, Jarkas, 2012, Putu et al., 2019)
	Reduced outage duration	(Eldin, 1999, Mahamid et al., 2018)
Quality	Higher quality of built products	(Eldin, 1999, Pheng and Abeyegoonasekera, 2001, Pheng Low, 2001, Elgohary et al., 2003, Ding et al., 2019)
Safety	Safer environment on site	(Francis et al., 1999, Eldin, 1999, Trigunarsyah, 2004a, Gambatese et al., 2007b)
Other	Reduction in unforeseen problems	(Francis et al., 1999, Pheng and Abeyegoonasekera, 2001, Cadenazzi, 2019)
	Less re-work of construction put in place	(Gambatese et al., 2007b)
	Improvements in industrial relations, teamwork, communication and client satisfaction	(Francis et al., 1999, Eldin, 1999, Geile, 1996, Jadidoleslami et al., 2018b)

However, those benefits may be extended further to cover the entire building process, including aspects such as: improving planning perception, materials acquisition, design solutions, construction approaches, site management, teamwork, job satisfaction, project performance, and stakeholder involvement and satisfaction (Griffith and Sidwell, 1997).

2.5. Importance of early assessment of design constructability

While project success is reliant on each constituent segment of its entire lifecycle, the design stage is the most crucial part (Fadoul and Tizani, 2017).

Some studies suggest that 75% of problems encountered during construction can be traced back to the design phase (Mendelsohn, 1997), and most influential decisions are typically made during the earliest design stage, in cooperation with the client (Schlueter and Thesseling, 2009). This includes decisions concerned with determining design parameters that affect constructability performance. It is therefore more effective to enforce the concept principles at this stage, when there is a room for significant improvements. In contrast, clients and designers would be reluctant to revise their design for better constructability when they advance on the process, given the potential cost of change it may introduce (Lam et al., 2012), as the cost influence curve displayed in Figure 2-2 illustrates.

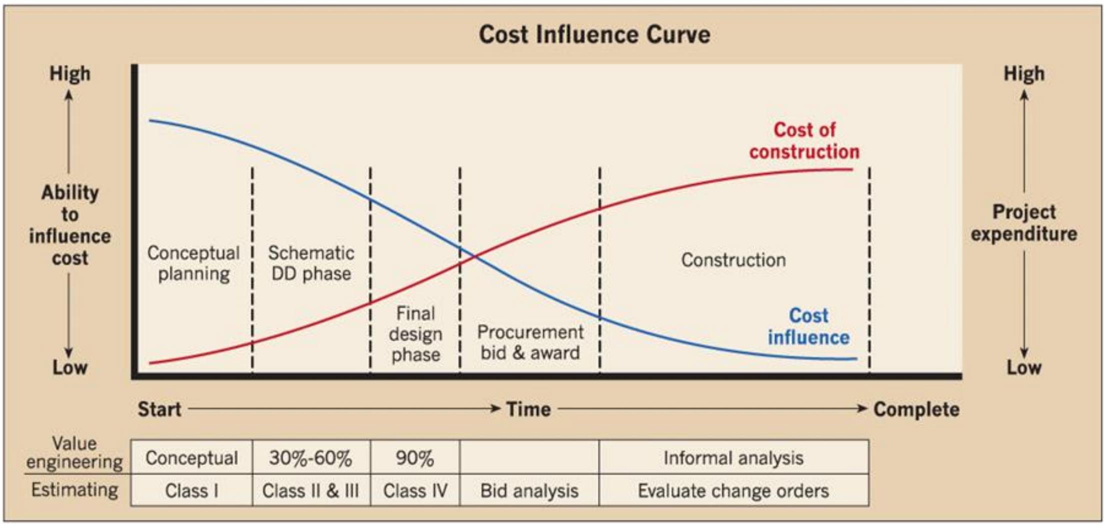

Figure 2-2: Influence of design decisions on the project cost throughout its phases

(Parikh et al., 2010)

Therefore, evaluation of the constructability aspect should be undertaken at the early design stage to proactively detect and address possible routes of problems that may arise in the construction phase to mitigate or minimise their effects. This will lead to effective utilisation of resources while achieving project goals in a safer construction working atmosphere (Ugwu et al., 2004).

2.5.1. Stages of constructability implementation

In general, there is no consensus on how to approach constructability, and at which stages its principles should be applied (Lam et al., 2012); thus different researchers adopted various techniques and methods. Many studies work with the concept at the design stage (Pheng Low, 2001, Fox and Hietanen, 2007, Lam and Wong, 2009, David Arditi, 2002), while others applied their constructability measures comprehensively overall project phases, including conceptual planning, developed design, procurement practice, and construction etc. (Wong et al., 2007a).

A study conducted by (David Arditi, 2002) to assess the extent of constructability application by design firms and the favoured time for its implementation found that 87% of constructability reviews are carried out within the developed design stage. Figure 2-3 shows that 25% of the participants assess design constructability continuously throughout the entire design process (conceptual planning, preliminary design, developed design stages, and after finishing the design), which gives a good indication that it is considered to be part of the overall project improvement, as suggested by (O'Connor and Miller, 1994).

The RIBA Plan of Work (2020) came to emphasise key tasks that contribute to asserting constructability of construction projects (Figure 2-4). This commences from Stage (0) - (*Strategic Definition*), encouraging the project team to review feedback from previous projects to ensure that lessons are learned. At Stage (1) – *(Preparations and Briefing*), preparation of the project brief covers tasks such as understanding spatial requirements, sourcing site info and developing project execution plan, which shall all contribute to accommodating requirements of the construction stage. Moving forward to Stage (1) – (*Concept Design),* the plan includes aspects such as reviewing design product with client and project stakeholder to eliminate any potential issues that may arise. At *Spatial Coordination Stage,* design checks against buildings regulations, shall be carried out to ensure a smooth construction streamline. Also, working collaboratively with other design disciplines results in a spatially coordinated design. In the *Technical Design stage*, a construction phase plan is to be considered, setting out necessary arrangements to ensure health and safety during *construction stage*.

This workflow was featured in a proposed model aimed to integrate knowledge management (KM) systems and BIM layered with RIBA plan of work, to exploit the benefits of such integration (Bhatija et al., 2017).

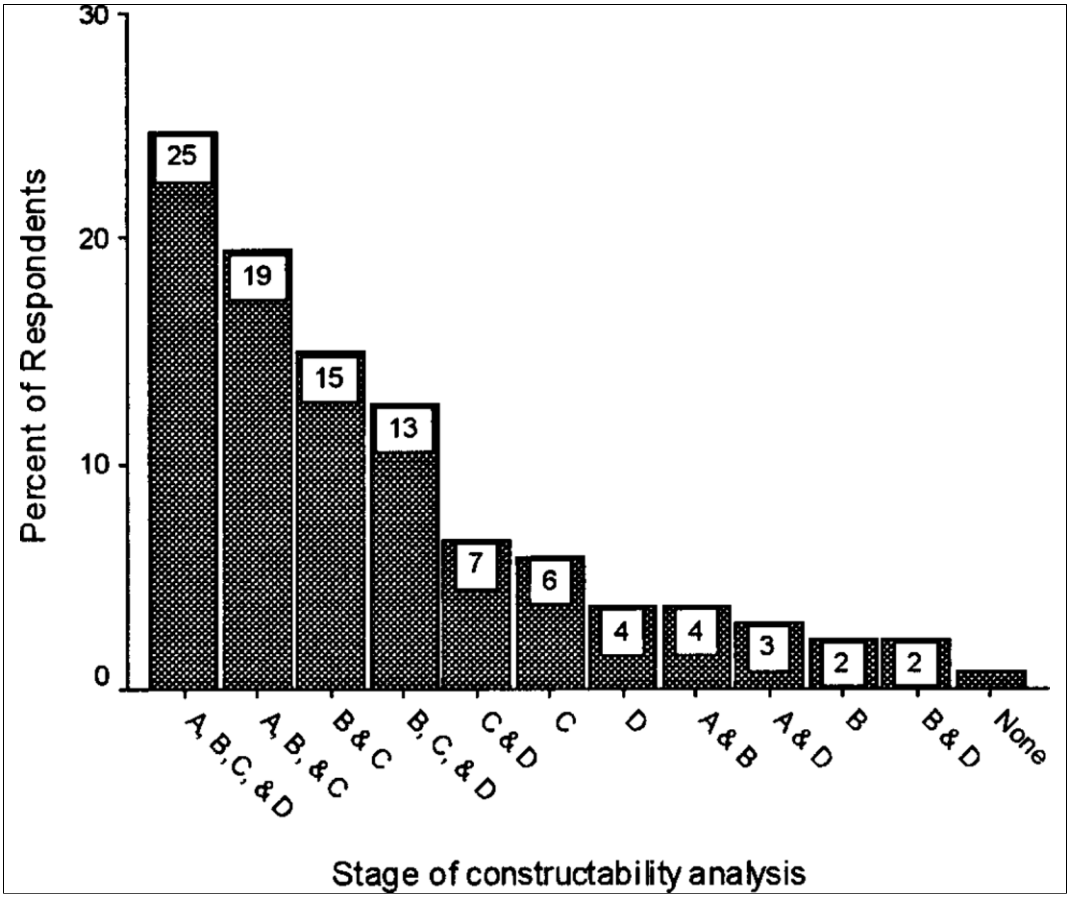

Figure 2-3: Timing of constructability reviews

A: conceptual planning stage; B: preliminary design stage; C: developed design stage; D: after finishing the design

(David Arditi, 2002)

RIBA Plan of Work 2020

The RIBA Plan of Work organises the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages. It is a framework for all disciplines on construction projects and should be used solely as guidance for the preparation of detailed professional services and building contracts.

Stage Boundaries:

Stages 0-4 will generally be undertaken one after the other.

Stages 4 and 5 will overlap in the **Project Programme** for most projects.

Stage 5 commences when the contractor takes possession of the site and finishes at **Practical Completion**.

Stage 6 starts with the handover of the building to the client immediately after **Practical Completion** and finishes at the end of the **Defects Liability Period**.

Stage 7 starts concurrently with Stage 6 and lasts for the life of the building.

Planning Note:

Planning Applications are generally submitted at the end of Stage 3 and should only be submitted earlier when the threshold of information required has been met. If a **Planning Application** is made during Stage 3, a mid-stage gateway should be determined and it should be clear to the project team which tasks and deliverables will be required.
See *Overview* guidance.

Procurement:

The RIBA Plan of Work is procurement neutral – See *Overview* guidance for a detailed description of how each stage might be adjusted to accommodate the requirements of the **Procurement Strategy**.

ER Employer's Requirements

CP Contractor's Proposals

	0 Strategic Definition	1 Preparation and Briefing	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing and Construction	6 Handover	7 Use
		Projects span from Stage 1 to Stage 6; the outcome of Stage 0 may be the decision to initiate a project and Stage 7 covers the ongoing use of the building.						
Stage Outcome at the end of the stage	The best means of achieving the **Client Requirements** confirmed If the outcome determines that a building is the best means of achieving the **Client Requirements**, the client proceeds to Stage 1	**Project Brief** approved by the client and confirmed that it can be accommodated on the site	**Architectural Concept** approved by the client and aligned to the **Project Brief** The brief remains "live" during Stage 2 and is derogated in response to the **Architectural Concept**	Architectural and engineering information **Spatially Coordinated**	All design information required to manufacture and construct the project completed Stage 4 will overlap with Stage 5 on most projects	Manufacturing, construction and **Commissioning** completed There is no design work in Stage 5 other than responding to **Site Queries**	Building handed over, **Aftercare** initiated and **Building Contract** concluded	Building used, operated and maintained efficiently Stage 7 starts concurrently with Stage 6 and lasts for the life of the building
Core Tasks during the stage **Project Strategies** might include: – **Conservation** (if applicable) – **Cost** – **Fire Safety** – **Health and Safety** – **Inclusive Design** – **Planning** – **Plan for Use** – **Procurement** – **Sustainability** See *RIBA Plan of Work 2020 Overview* for detailed guidance on **Project Strategies**	Prepare **Client Requirements** Develop **Business Case** for feasible options including review of **Project Risks** and **Project Budget** Ratify option that best delivers **Client Requirements** Review **Feedback** from previous projects Undertake **Site Appraisals** No design team required for Stages 0 and 1. Client advisers may be appointed to the client team to provide strategic advice and design thinking before Stage 2 commences.	Prepare **Project Brief** including **Project Outcomes** and **Sustainability Outcomes**, **Quality Aspirations** and **Spatial Requirements** Undertake **Feasibility Studies** Agree **Project Budget** Source **Site Information** including **Site Surveys** Prepare **Project Programme** Prepare **Project Execution Plan**	Prepare **Architectural Concept** incorporating **Strategic Engineering** requirements and aligned to **Cost Plan**, **Project Strategies** and **Outline Specification** Agree **Project Brief Derogations** Undertake **Design Reviews** with client and **Project Stakeholders** Prepare stage **Design Programme**	Undertake **Design Studies**, **Engineering Analysis** and **Cost Exercises** to test **Architectural Concept** resulting in **Spatially Coordinated** design aligned to updated **Cost Plan**, **Project Strategies** and **Outline Specification** Initiate **Change Control Procedures** Prepare stage **Design Programme**	Develop architectural and engineering technical design Prepare and coordinate design team **Building Systems** information Prepare and integrate specialist subcontractor **Building Systems** information Prepare stage **Design Programme** Specialist subcontractor designs are prepared and reviewed during Stage 4	Finalise **Site Logistics** Manufacture **Building Systems** and construct building Monitor progress against **Construction Programme** Inspect **Construction Quality** Resolve **Site Queries** as required Undertake **Commissioning** of building Prepare **Building Manual** Building handover tasks bridge Stages 5 and 6 as set out in the **Plan for Use Strategy**	Hand over building in line with **Plan for Use Strategy** Undertake review of **Project Performance** Undertake seasonal **Commissioning** Rectify defects Complete initial **Aftercare** tasks including light touch **Post Occupancy Evaluation**	Implement **Facilities Management** and **Asset Management** Undertake **Post Occupancy Evaluation** of building performance in use Verify **Project Outcomes** including **Sustainability Outcomes** Adaptation of a building (at the end of its useful life) triggers a new Stage 0
Core Statutory Processes during the stage: Planning Building Regulations Health and Safety (CDM)	Strategic appraisal of **Planning** considerations	Source pre-application **Planning Advice** Initiate collation of health and safety **Pre-construction Information**	Obtain pre-application **Planning Advice** Agree route to **Building Regulations** compliance Option: submit outline **Planning Application**	Review design against **Building Regulations** Prepare and submit **Planning Application** See ***Planning Note*** for guidance on submitting a **Planning Application** earlier than at end of Stage 3	Submit **Building Regulations Application** Discharge pre-commencement **Planning Conditions** Prepare **Construction Phase Plan** Submit form F10 to HSE if applicable	Carry out **Construction Phase Plan** Comply with **Planning Conditions** related to construction	Comply with **Planning Conditions** as required	Comply with **Planning Conditions** as required
Procurement Route Traditional Design & Build 1 Stage Design & Build 2 Stage Management Contract Construction Management Contractor-led	Appoint client team	Appoint design team	ER Appoint contractor ER	ER Pre-contract services agreement Preferred bidder	Tender — Appoint contractor ER CP — Appoint contractor CP — Appoint contractor CP — Appoint contractor			Appoint **Facilities Management** and **Asset Management** teams, and strategic advisers as needed
Information Exchanges at the end of the stage	**Client Requirements** **Business Case**	**Project Brief** **Feasibility Studies** **Site Information** **Project Budget** **Project Programme** **Procurement Strategy** **Responsibility Matrix** **Information Requirements**	**Project Brief Derogations** Signed off **Stage Report** **Project Strategies** **Outline Specification** **Cost Plan**	Signed off **Stage Report** **Project Strategies** Updated **Outline Specification** Updated **Cost Plan** **Planning Application**	**Manufacturing Information** **Construction Information** **Final Specifications** Residual **Project Strategies** **Building Regulations Application**	**Building Manual** including **Health and Safety File** and **Fire Safety Information** **Practical Completion** certificate including **Defects List** **Asset Information** If **Verified Construction Information** is required, verification tasks must be defined	**Feedback** on **Project Performance** **Final Certificate** **Feedback** from light touch **Post Occupancy Evaluation**	**Feedback** from **Post Occupancy Evaluation** Updated **Building Manual** including **Health and Safety File** and **Fire Safety Information** as necessary

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Core RIBA Plan of Work terms are defined in the *RIBA Plan of Work 2020 Overview* glossary and set in **Bold Type**.

Further guidance and detailed stage descriptions are included in the *RIBA Plan of Work 2020 Overview*.

Figure 2-4: RIBA Plan of Work 2020

(RIBA, 2020)

2.5.2. Level of detail (LOD) considerations

Enabling BIM functionalities necessitates a certain level of modelling accuracy, information richness, and the practicality of the underlying data (Leite et al., 2011). This is frequently referred to as the level of detail/ development (LOD), specifying the basic level of information that a BIM model should contain throughout the project phases. The importance of the concept for constructability perspective stems from the fact that accurate assessment of design constructability requires as much model details as possible; therefore, the encouraged early assessment process will mainly depend on the available LOD for the model, and hence should be considered in the development of any assessment tool.

2.6. Global status of constructability

The significance of designing for constructability is revealed by many studies, and the demand to devise a mechanism for implementing its principles is evidenced by the growing research efforts in this field in both industry and academia. Tremendous efforts have explored the implementations of various techniques and approaches to enable constructability improvement. At the industrial level, some countries have set up measures for benchmarking design constructability and requirements to be accomplished in each project (Ugwu et al., 2004). This section provides an overview of constructability and buildability development across different countries and their current status.

2.6.1. Evolution of buildability concept in the UK

Studies on buildability in the UK emerged contemporaneously with the concept itself during the 1960s. The Construction Industry Research and Information Association (CIRIA) supported many studies investigating the concept and its principles for further development. This resulted in publishing the definitive report Buildability: An Assessment (CIRIA, 1983), which has posited numerous buildability principles pertaining to aspects such as: design satisfaction for site requirements; practicality of operation sequence and early enclosure; design for simplicity of assembling and reasonable trade sequencing; design for maximum repetition and standardisation; design for attainable flexibility; and specifying appropriate design materials.

Following this, major studies were conducted in the UK to widen the perspective of buildability (Gray, 1983a, Griffith, 1984) (Ferguson, 1989), but it took many years to standardise the concept and bring it into practice (Egan and Williams, 1998, Love et al., 2000), with greater emphasis on the buildability of designs (CIRC, 2001).

2.6.2. Constructability status in the US

Constructability emerged in the US during the 1980s, when it was promoted as the magic key to facilitate the construction process by embracing both design and management roles (Wong et al., 2007b). Subsequently, the Construction Industry Institute (CII) based in Austin, Texas, played a seminal role in improving the concept and providing the necessarily guidelines that can help in implementing the concept at different project phases (CII, 1986, CII, 1987a, CII, 1987b, CII, 1993).

2.6.3. The buildable design appraisal system developed in Singapore

Singapore pioneered the quantification of design buildability through the introduction of its assessment system known as the Buildable Design Appraisal System (BDAS), which adopts three main principles: standardisation, simplicity, and single integrated elements. It was developed in 1999 as incentive for designers to accomplish a buildable design, but it became a perquisite for granting design approval in 2001. Since then, the mandatory design requirements had been progressively increased over years, and new guidelines were introduced by Building and Construction Authority (BCA, 2017). The buildability score under BDAS is calculated based on the performance of four design elements: structural system, walls system, other buildable design features, and bonus points for single integrated components, as illustrated in Figure 2-5.

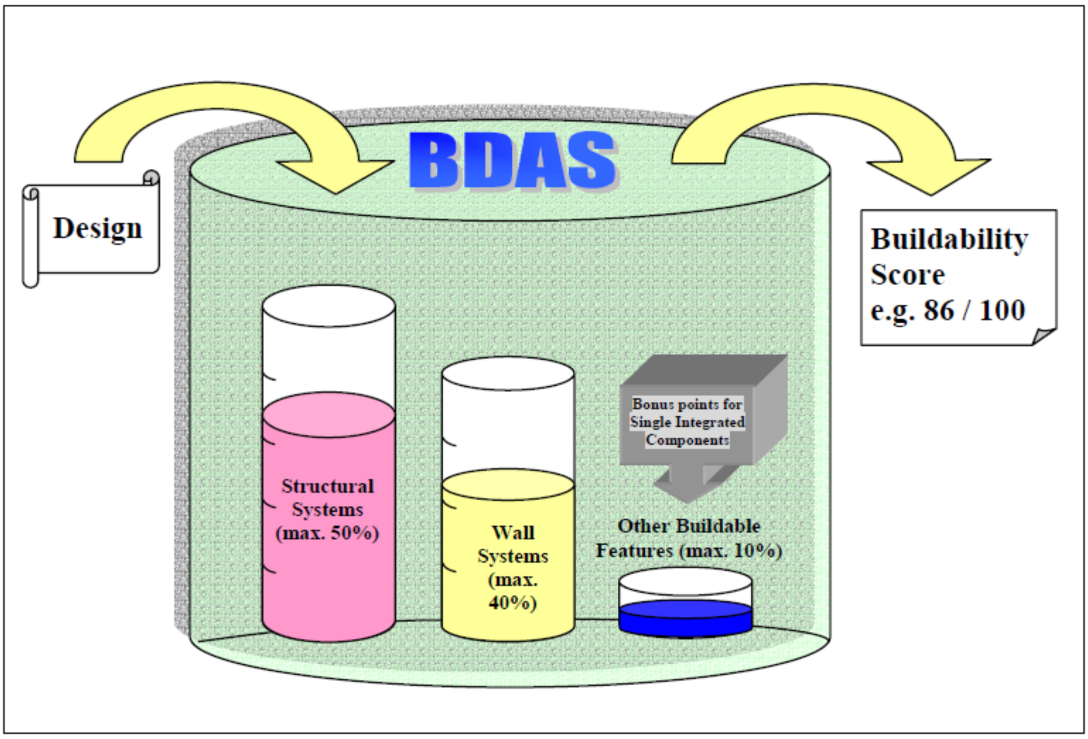


Figure 2-5: Components of BDAS assessed in the examined design (Hei, 2007)

2.6.4. Buildability status in Hong Kong

The Construction Industry Review Committee in Hong Kong produced a report indicating that the buildability of design in the region needs enhancement (CIRC, 2001). Therefore, many researches were undertaken to develop an assessment framework for benchmarking the buildability of design solutions. As a result, the Buildability Assessment Model (BAM) was proposed to measure design buildability based on a complete design (Lam and Wong, 2008). The system adapted the same concept of the Buildable Design Appraisal System of Singapore, adding more design aspects, as illustrated in Figure 2-6.

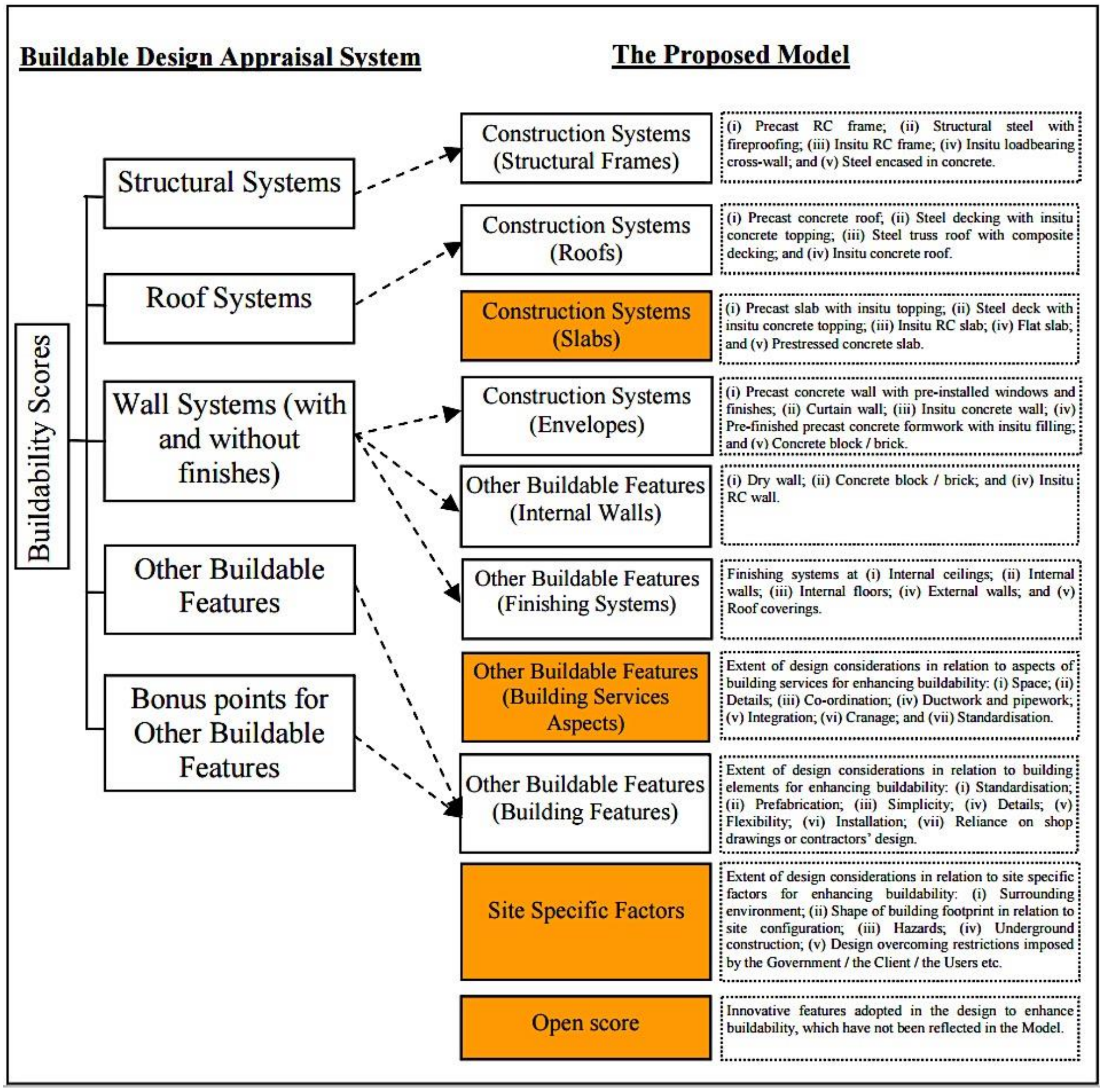


Figure 2-6: Added components to BDAS in the new proposed system BAM (Lam and Wong, 2008)

The model has shown great success in quantifying design buildability, however feedback from industry users requested a rationalised model able to assess the design buildability at the schematic design phase (i.e. when about 35 % of the product has been accomplished). Hence, the scheme design buildability assessment model (SDBAM) was established based on the outcomes of a series of interviews and a questionnaire survey targeting practitioners, to describe buildable and non-buildable design features (Lam et al., 2012). Table 2-7 demonstrates the rationale of the SDBAM. Its main concepts stem from the previous BAM assessment system, but it can be utilised at an early design stage, to provide useful feedback that can assist in improving design buildability.

Table 2-7: Metrics and measurement of the SDBAM

(Lam et al., 2012)

Assessment section	*Metrics involved (brackets indicate units)*	*Measurement needed for assessment*
Core construction systems	Importance weightings (%) BI (0-1) Proportion of specific system within the design (%)	Given (through survey) Given (through AHP) Estimated by designers with approximate quantities
Buildable and non-buildable features	Importance weightings (%) Normalised relative weighting (%) Buildable or non-buildable rating (-3 to +3) Matching coefficient (0 or 1)	Given (through survey) Given (through RIM) Given (through interviews) Assessor assigns "1" if matched, "0" otherwise
Innovative or obstructive elements (not covered above)	Adjustment due to design considerations incorporated with the effect of improving or lowering buildability (%)	A range of value from +10 to -10 is assigned by assessor with justifications
Total score	Conversion of numerical score to a final grade (E - to AA +)	Refer to conversion table or automated by spreadsheet

SDBAM assesses project buildability by its constituent elements (structural system, wall system etc.) with respect to their buildability indicators (BI) derived from deployed questionnaires and surveys. Besides this, buildable and non-buildable features within the examined design will be identified and assessed based on obtained practitioners' recommendations. The relative weightings for the model components are assigned using the analytical hierarchy process (AHP), which considers a set of construction systems and ranks them as to their importance from a buildability perspective (Saaty, 2008).

2.6.5. Constructability status in Australia

Australia has also contributed to constructability research by investigating the impacts of its implementation within a project management environment (Hon et al., 1988, Hon, 1989). Further research was conducted to broaden the constructability scope to accommodate the entire project life cycle (McGeorge et al., 1992). CII Australia introduced its *Constructability Manual* that provides guidelines for implementing constructability concept featured in 12 constructability principles and strategies (Australia), 1996). However, no apparent efforts have been put to build on the concept further since that time (Hei, 2007).

2.6.6. Constructability considerations in Canada

A study was conducted in Alberta (Canada) to ascertain the emerging gaps between the potential benefits of introducing constructability principles to the industry construction projects, and the realised benefits in practice based on practitioners' experiences. It attempted to identify main barriers that contribute in realisations of such benefits (John Van der and George, 2001).

Hijazi et al. (2009) introduced a new method to measure the extent of constructability application on building designs, pioneering the use of BIM and 4D technologies for the concept quantification. Aspects and attributes that affect the constructability of buildings are defined based on a study on constructability characteristics. Multi-attribute decision analysis and AHP were adopted to evaluate constructability performance. This framework was further developed by Zhang et al. (2016) in an assessment system to quantitatively evaluate design constructability. The proposed system is presented in Figure 2-7, describing its constituent modules and operational phases to obtain assessment results. Applying the proposed method using a construction project in Montreal proved the benefits of BIM integration with constructability Assessment.

2.6.7. Constructability status in Finland

In Finland constructability is not a popular subject for designers, contractors, and managers, and there is an obvious need for research in this area. Tauriainen et al. (2014) pioneered the investigation of the subject in the country, establishing an experimental constructability assessment method (ECM) to facilitate a constructability score of building design based on the information content of structural BIM. However, the proposed method is limited to assess the constructability performance of structural frames and elements.

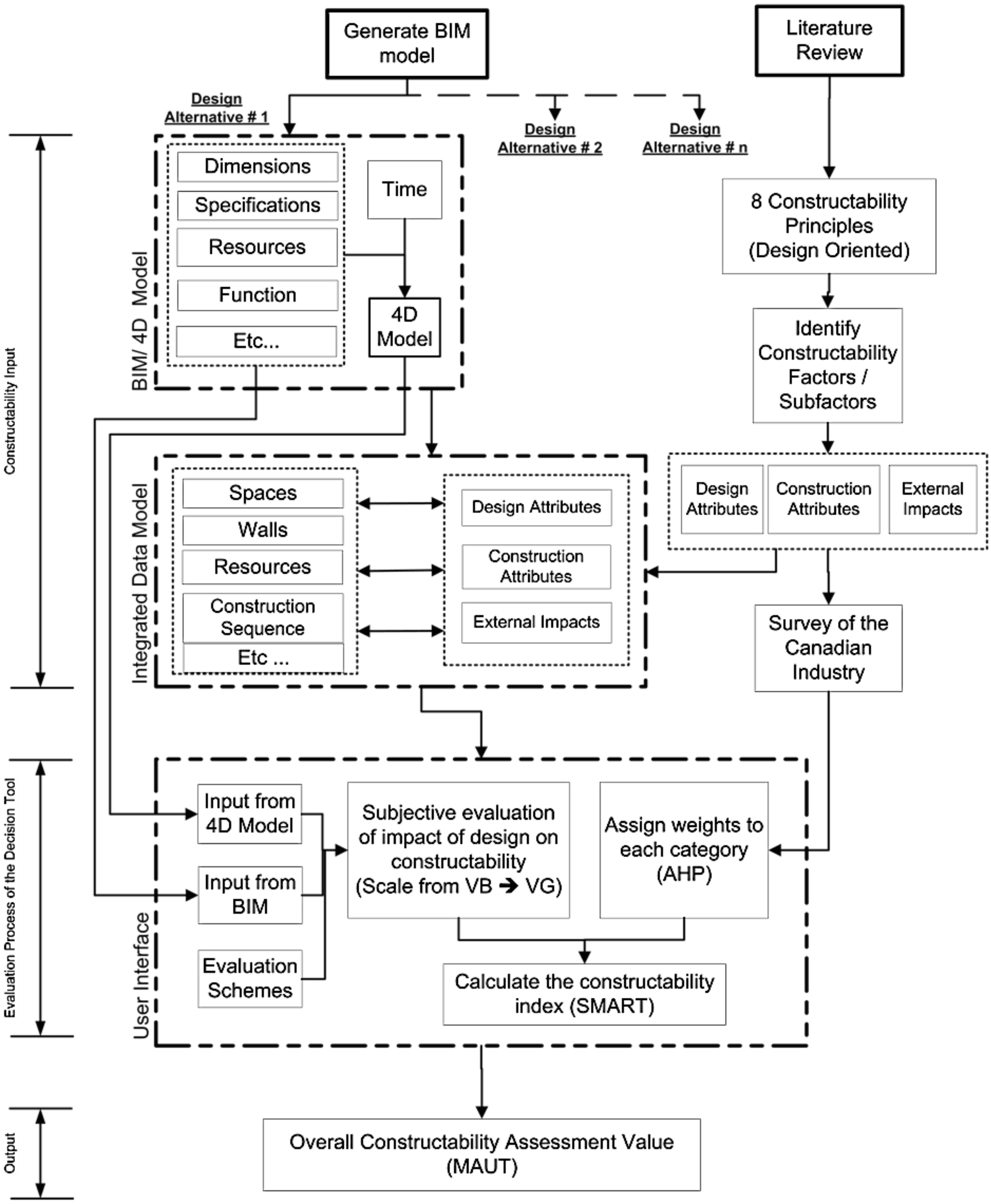


Figure 2-7: The proposed methodology for an integrated constructability assessment system in design environment

(Zhang et al., 2016)

2.7. Information technology for improving design constructability

As an emerging technology, Information Modelling (IM) has become a powerful tool for designers and engineers to validate and communicate their designs. It enables end users to easily interact with their design and understand its function (Carvajal, 2005, Mobach, 2008). In addition, the design can be rapidly created, explored and examined for the building performance to spark innovations (Davies, 2004).

In a report produced by McKinsey Global Institute (USA), five innovative trends were proposed that would transform the construction industry through to the early 2020s, chiefly related to digitalising the sector, as shown in Figure 2-8. None of these ideas is futuristic or even implausible; rather they are all applicable to current practice and are designed to work together to affect a significant improvement in construction practices (Agarwal et al., 2016).

Figure 2-8: Five trends that will shape the construction digital future (Agarwal et al., 2016)

BIM-enabled information management systems are shifting traditional practice in buildings design. Recently, exploiting BIM capabilities to reshape the conventional process is broadly embraced in both academia and industry (Chi et al., 2014). The following sections demonstrate the capabilities of BIM technologies in the AEC domain.

2.7.1. BIM integrations in designing buildings

Nowadays, BIM is approaching its tipping point worldwide to revolutionise the entire workflow for AEC industry (NBIMS, 2007, Lyer, 2010). Among companies attempting to implement BIM and its associated management techniques, the majority of construction practices are using these technologies throughout the project phases, including the dominant design phase, as Figure 2-9 presents.

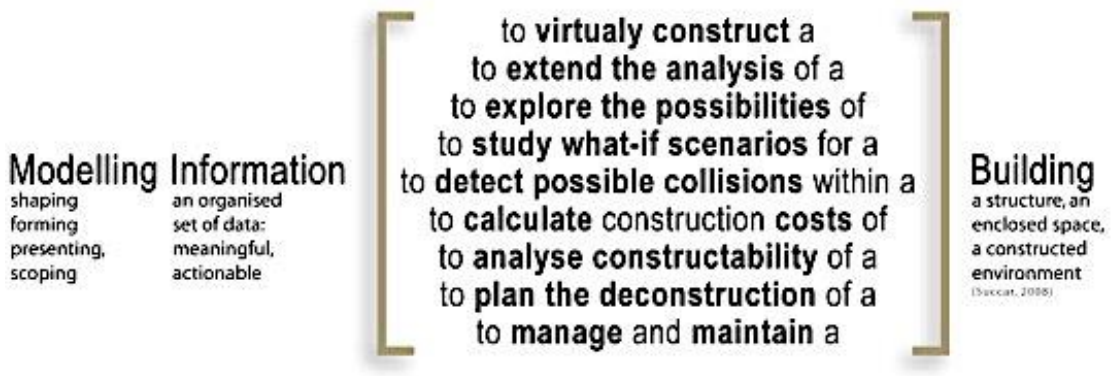


Figure 2-9: Connotations of various BIM terms

(Succar, 2009)

BIM technologies are widely considered to be an advanced platform to design structures due to its efficient modelling processes, intuitive visualisation environments, and data exchange facilities (Gerold et al., 2012). Figure 2-10 features the benefits of BIM-enabled tools in four major building design aspects: parameterised database modelling, visualisation and intuitiveness, collaboration and information exchange, and constructability assessment and code conformance.

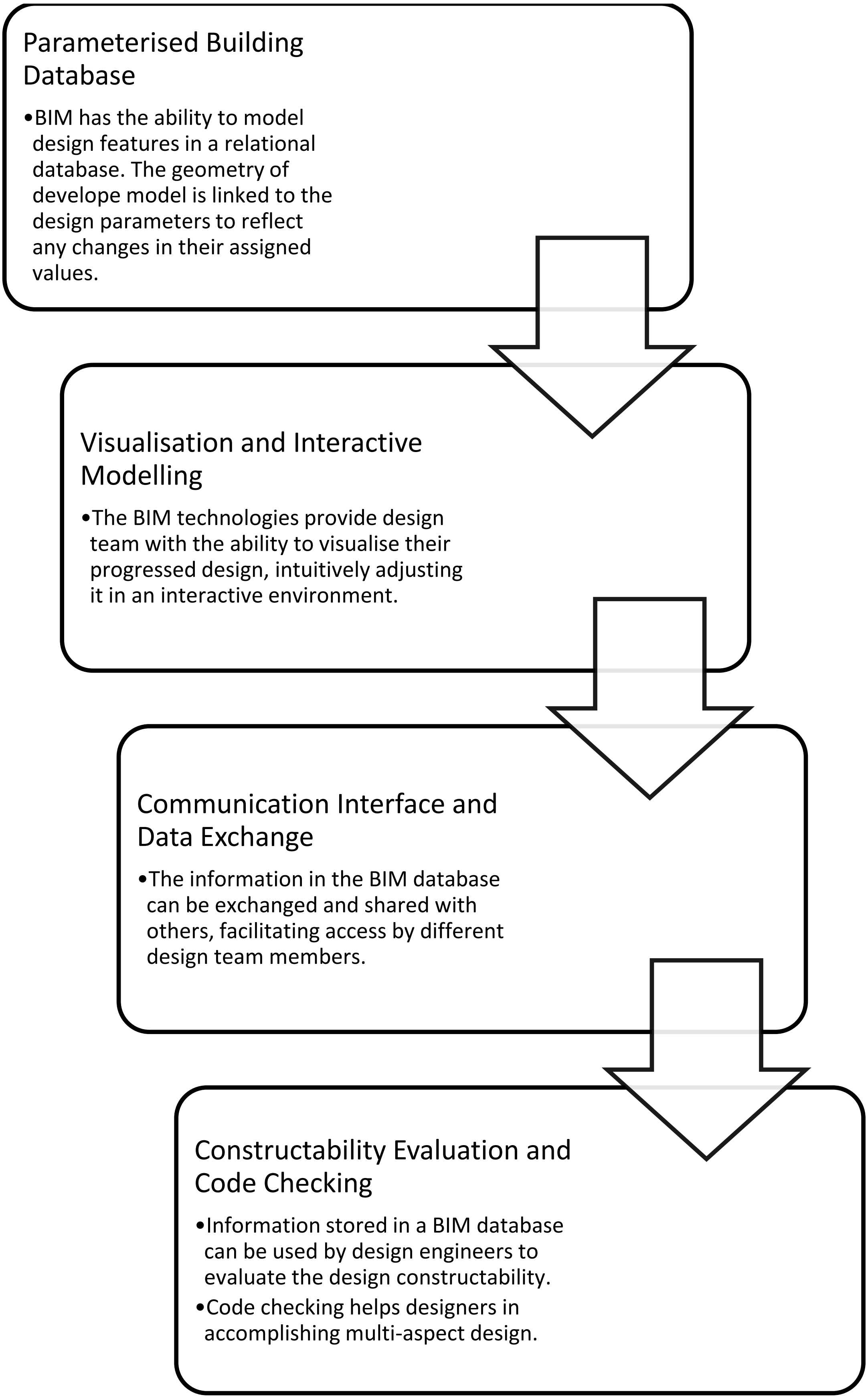


Figure 2-10: Capabilities of BIM in designing buildings (Gerold et al., 2012)

2.7.2. BIM potential for design review and constructability improvement

BIM presents a substantial opportunity to improve design constructability using its rich information repository. It enhances the integration between the design and construction processes, enabling improved quality with savings in project cost and time (Eastman et al., 2008). Object-oriented models are capable to quantify constructability, whereby designers can observe the effects of design decisions (Hijazi et al., 2009).

In addition, BIM-enabled tools can electronically model and manage the vast amount of a building's information throughout its entire lifecycle. Such information can be used to estimate, schedule, detail, automate fabrication drawing, and plan construction activities. Furthermore, incorporating the time dimension in the model allows different design and execution plans to be explored and tested for better design constructability (Zhang et al., 2016).

Figure 2-11 identifies specific BIM features that can facilitate the process of constructability assessment through their implementation in a design decision-support tool (Jiang, 2016).

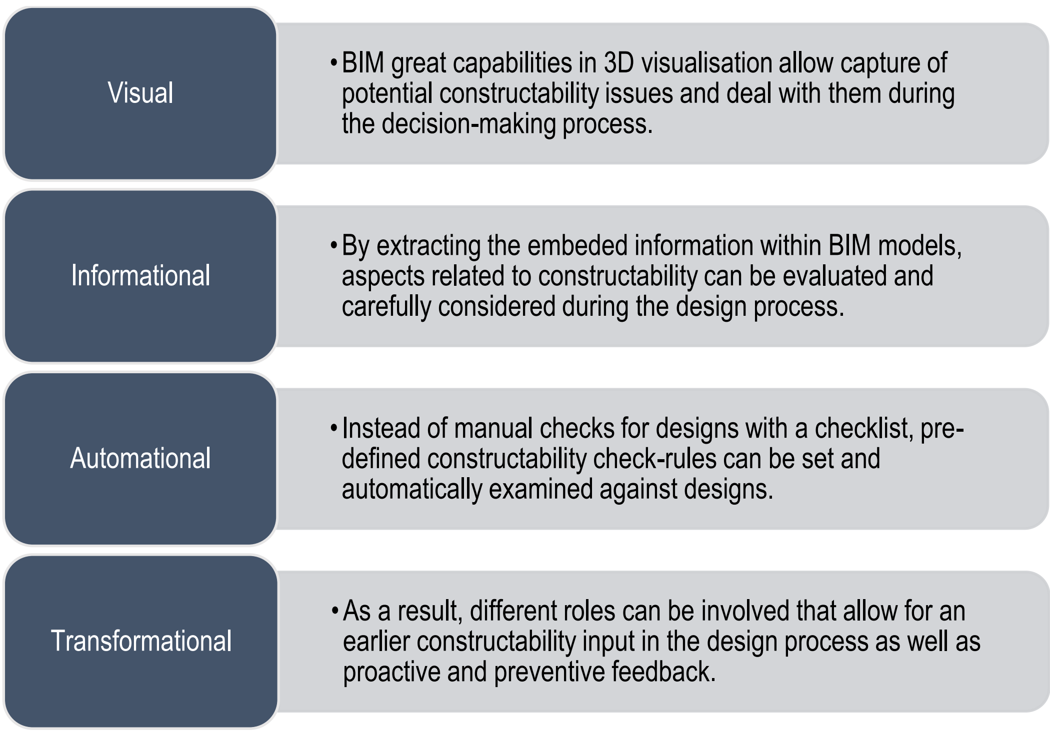


Figure 2-11: BIM capabilities in constructability review

(Jiang, 2016)

2.7.3. Preliminary BIM applications to improve design constructability

Realising the benefits of BIM-enabled constructability assessment, many studies explored the subject for the full adoption in the construction industry. In 2007, the ASCE Constructability and Construction Research Council stated in one of its special journals that "*The potential of new technology-based tools such as 4D CAD or BIM have not been fully realized. This area could also include validation of new constructability software tools*" (Gambatese et al., 2007a).

Therefore, Hijazi et al. (2009) proposed a method to assess the level of constructability application in building designs that integrates the object-oriented BIM and the 4D CAD simulation model, as shown in Figure 2-12. The method shows the preliminary move towards BIM implementation on constructability assessment, although it targeted the late design stage, but still in the pre-construction phase where design can be improved (Jiang, 2016).

The proposed method was validated using different design scenarios, and its application has shown great benefits for designers. It demonstrates that integrating BIM with 4D CAD simulation can contribute largely in evaluating different designs and facilitating this process to be effectively and accurately accomplished (Hijazi et al., 2009).

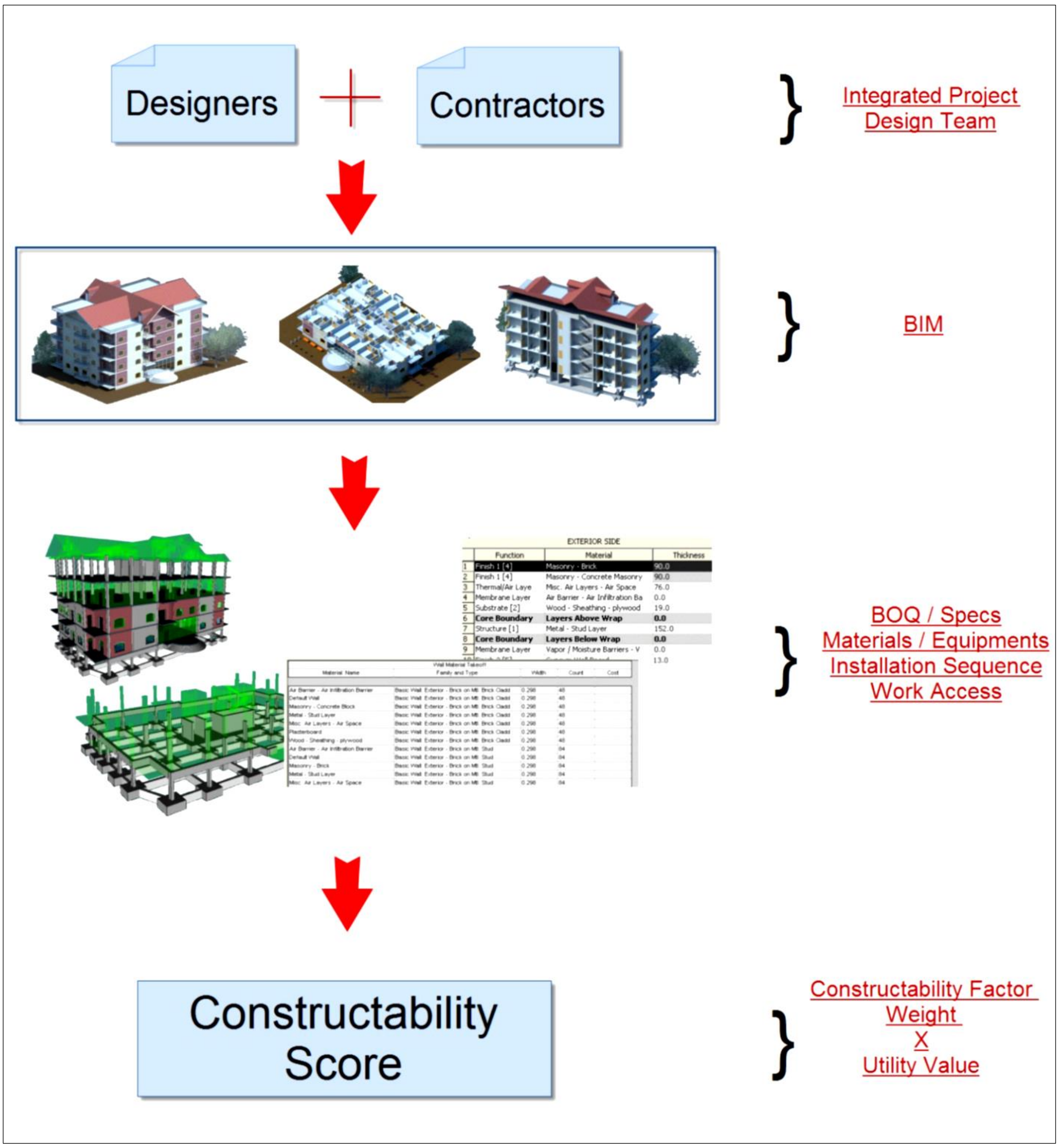


Figure 2-12: Proposed methodology for constructability assessment (Hijazi et al., 2009)

Due to the manifest benefits of BIM in enabling design and delivery integration, many studies started to adopt rule-based approaches to perform automated checking of design models. Here, the rules will be defined by experts, transferred to machine-readable script, and then stored within a model-checking engine that dynamically checks the compliance of BIM contents against such rules. As Figure 2-13 illustrates, the application of rule-based system for constructability checking has four phases, namely: rule definition, design model preparation, rule execution, and constructability assessment outcomes (Eastman et al., 2009).

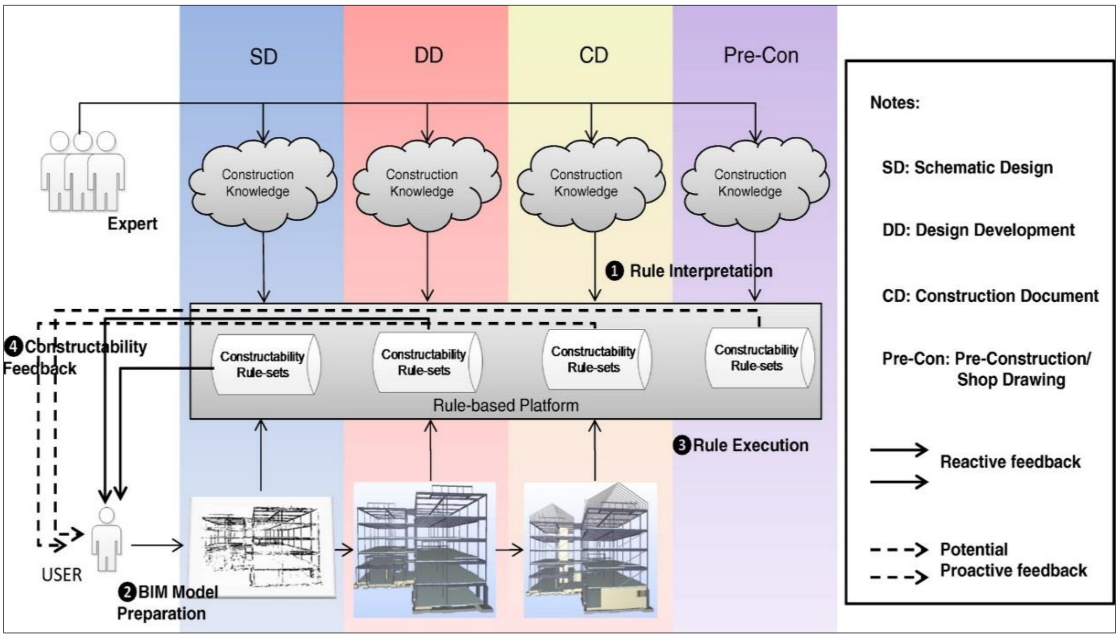


Figure 2-13: Rule-based checking of constructability

(Nexsen, 2012)

The approach has been used for model geometry checking to satisfy any imposed constraints (Hjelseth and Nisbet, 2010). Furthermore, the recent advancement of Industry Foundation Class (IFC) enabled design-checking tools that can advise on design clashes and code compliance using the building model schema, including the Solibri Model Checker, Jotne EDMmodelChecker, FORNAX, and SMART codes (Eastman et al., 2009).

In addition, automatic rule checking has been applied for a safety checking system furnished with fall protection rules from OSHA (Zhang et al., 2013). Also, a new procedure was developed for optimal cast-in-place concrete formwork selection, by defining rulesets that check formwork constructability issues with given BIM content (Jiang and Leicht, 2014).

Following this, many other studies investigated the possibility of exploiting BIM capabilities for constructability assessment. Tauriainen (2014) visually analysed BIM elements to calculate Constructability score based on his experimental constructability assessment method (ECM). This is done after filtering the required element in views and reporting them using the reporting function of the BIM-authoring tools.

Also, Zhang (2016) employed 4D model simulation to interpret design constructability using visual analysis. This can be in a video form, where designers can see the sequence of construction process and adjust it accordingly to meet the design requirements or using snapshots from the model for more detailed analysis. The NavisWorks© tool can be used to develop the 4D simulation.

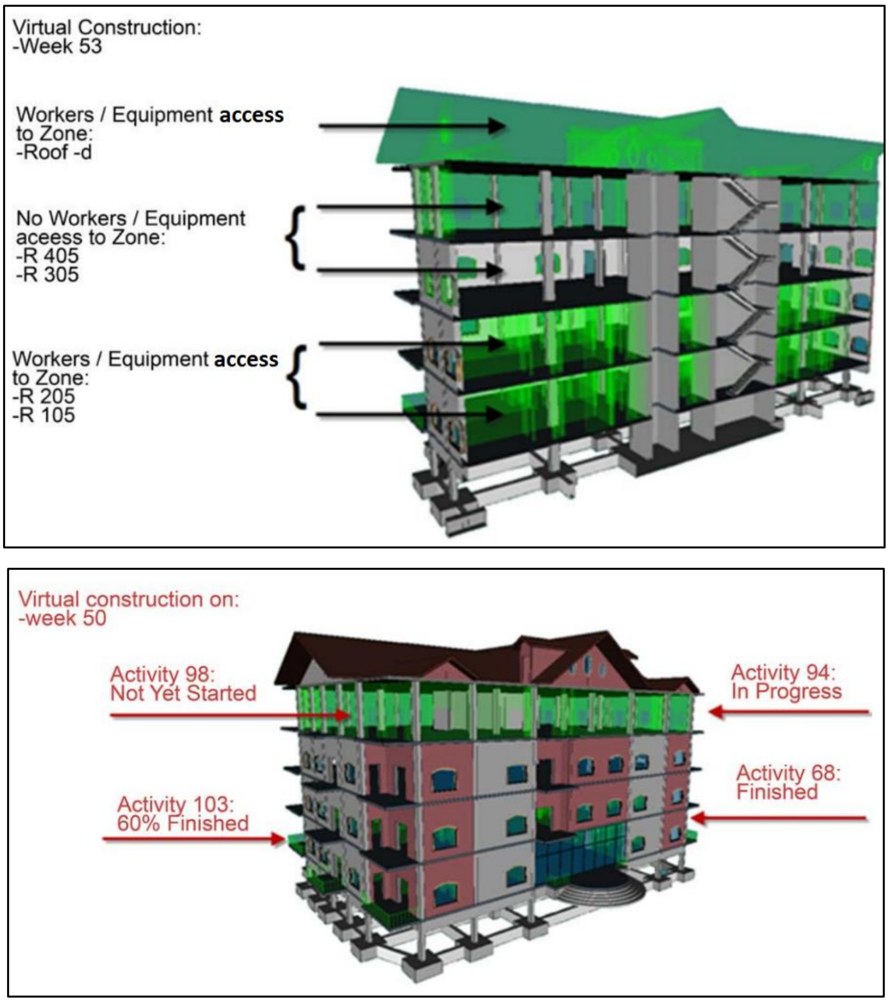


Figure 2-14: Examples of a 4D visual interpretation

(Zhang et al., 2016)

Recently, *(Kannan and Santhi, 2018)* presented an implementation of BIM for constructability assessment of concrete formwork systems. It targets the pre-construction visualization and decision-making phase of a project, depicted in Figure 2-15.

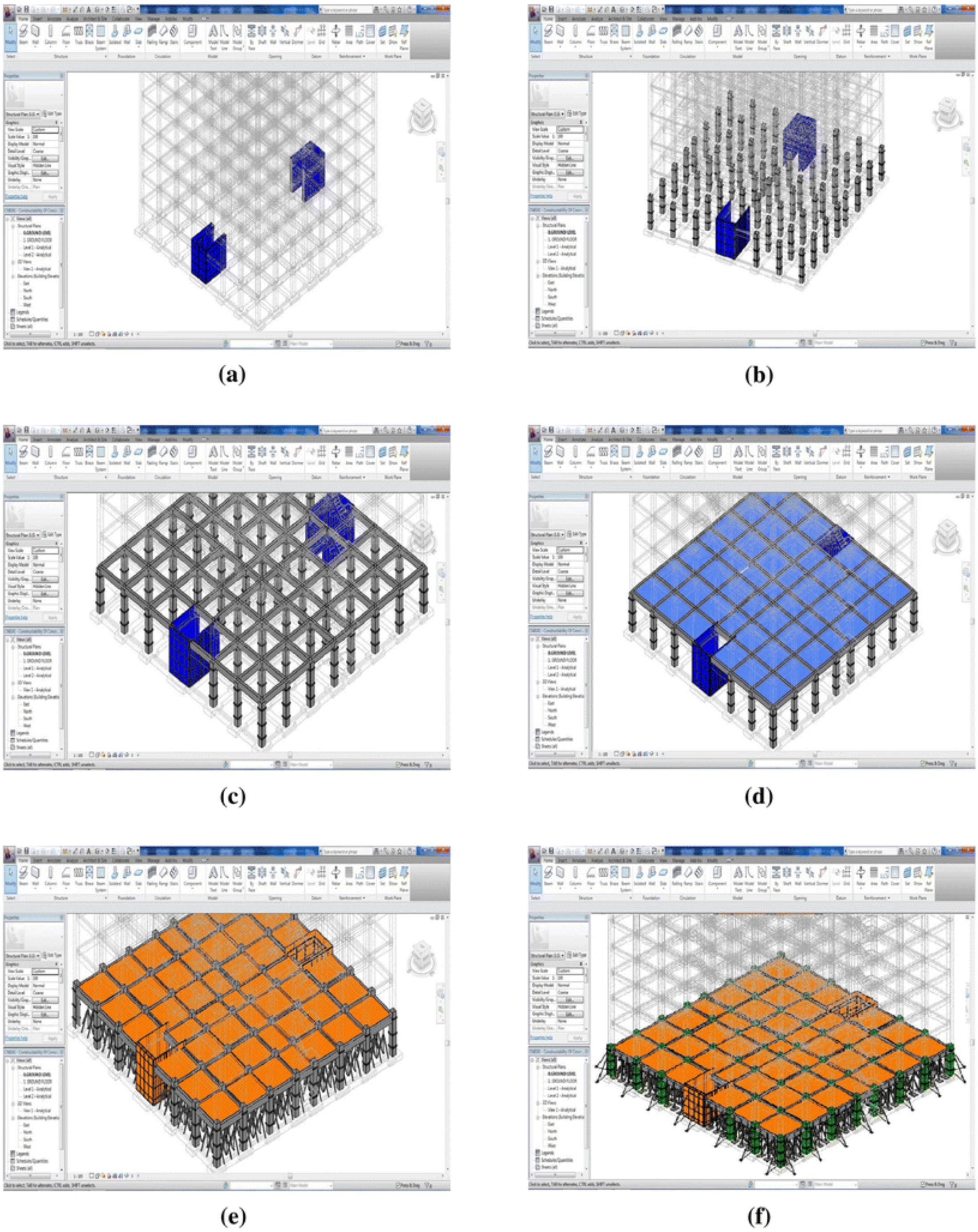


Figure 2-15: Integration of 3D BIM formwork family with 3D BIM structural model (Kannan and Santhi, 2018)

2.8. Adopted approaches for improving constructability

In recognition of the strategic importance of considering constructability and the upside effects that it has on construction performance, studies investigated various approaches to enable the improvement of design constructability. The most commonly employed approaches are numerical assessment of design constructability, constructability review, and implementing constructability programmes (Poh and Chen, 1998, Pheng Low, 2001, Lam, 2002). The following section explains these approaches and how they are employed in different studies, evaluating their advantages and disadvantages.

2.8.1. Numerical assessment of design constructability

The method facilitates an objective evaluation of constructability attributes for a given design and delivers a numerical score or rate indicating how constructible it is, as shown in Figure 2-16. It analyses and evaluates the major design components, such as structural systems, materials and installation techniques, based on developed rating systems, ranking their contributions towards constructability performance. The system was adopted in the Singaporean BDAS (explained previously), which sets a minimum constructability score to be accomplished in each design seeking approval for construction (Lam, 2002). Other studies adopted this system, including the Constructability Appraisal System in Malaysia (Zin et al., 2004), the BAM in Hong Kong (Lam and Wong, 2008), and the *Quantitative Assessment of Building Constructability Using BIM and 4D Simulation* (Zhang et al., 2016).

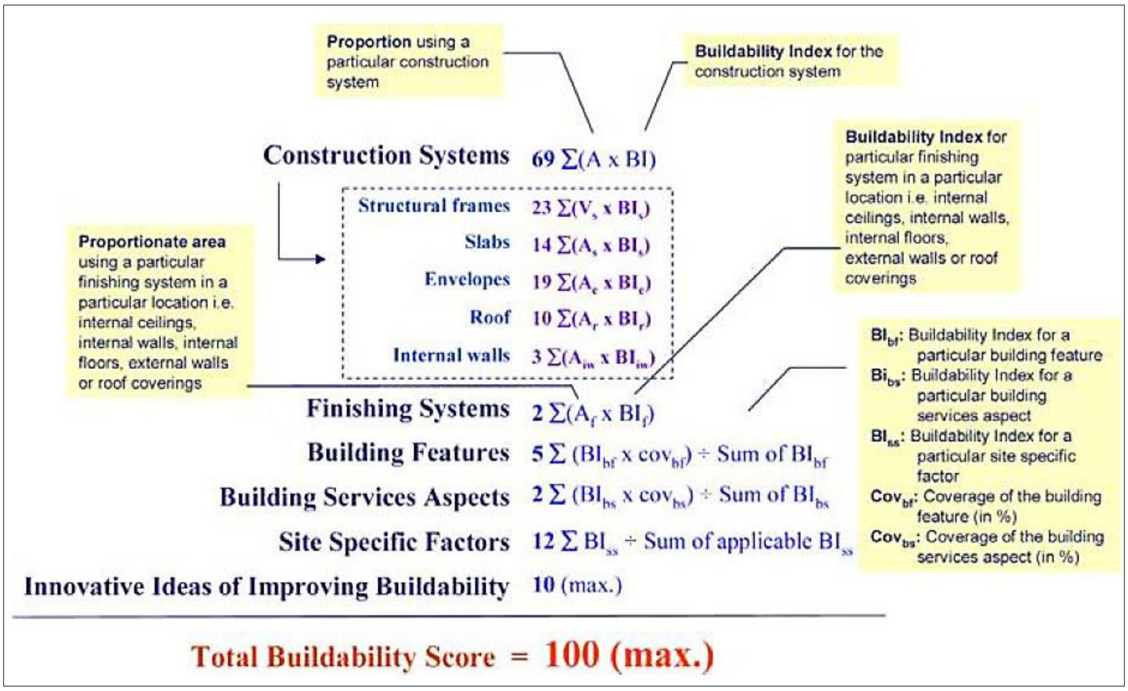


Figure 2-16: Buildability assessment model

(Lam and Wong, 2008)

2.8.2. Constructability review

This is another common method to evaluate the design considerations for constructability issues. It is usually carried out by employing a checklist or lessons-learned scheme to validate the design compliance at a pre-defined milestone (Hancher and Goodrum, 2007). Figure 2-17 shows a typical example of this process.

BIM enables the implementation of rule-based systems; thus, many studies adopted the technique in reviewing design constructability, taking advantage of an automated checking process. Typical checking systems encrypt the pre-defined rules (or checklist) to a readable machine language for verifying their compliance against stored digital information (Eastman et al., 2009).

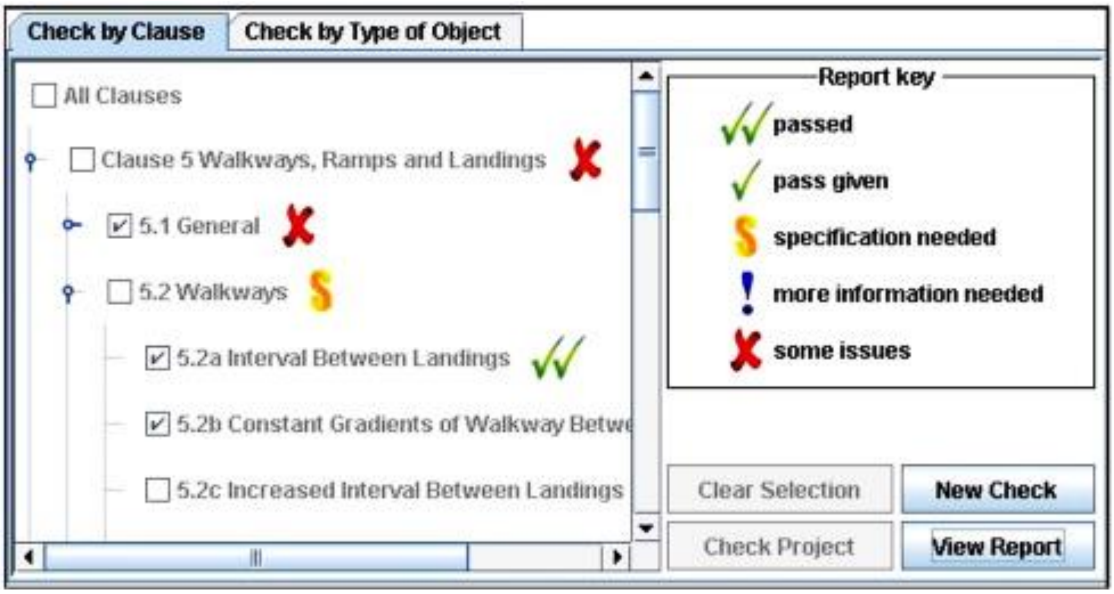


Figure 2-17: Graphical display of the checked results

(Ding et al., 2006)

2.8.3. Implementing constructability programmes

This approach provides a pre-described package for implementation in different construction scenarios to tackle constructability issues. It introduces a set of rules and guidelines throughout the management process (Kog et al., 1999). However, the approach is not recommended as it is an ad-hoc solution, rather than a proactive technique to avoid problems from their inception.

2.8.4. Review of adopted approaches for constructability improvement

While the three mentioned approaches are commonly employed to improve constructability, each has advantages and disadvantages associated with the process. Table 2-8 presents a summary of these observations to be considered and addressed in future studies.

Table 2-8: Pros and cons of common approaches for improving constructability

(Hei, 2007)

Adopted approach	Pros	Cons
Numerical assessment of design constructability	More practical in directing the assessment focus at the design product instead of the design process	Difficult to comprehend all substantial factors influencing constructability in a systematic 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 prior to the commencement of construction process.	Incurs additional time and resource costs. There might be resistance from some design stakeholders regarding the subjective review.
Implementing buildability programmes	Embodies all factors affecting buildability, including interactions between stakeholders	The subjectivity and complexity of the assessment process, especially with the involvement of any programme for a set of factors to be considered. Tracking the entire design progress is not feasible, whereas snapshots captured at specific stages of the process may not be representative.

The numerical assessment of design constructability has shown more practicality among other approaches, and users find it easy to understand and hence improve constructability performance (Wong et al., 2007b). Consequently, many studies employed the concept in benchmarking the design constructability.

As this research aims to develop a novel methodology in assessing the design constructability, a combination between the quantified assessment and the constructability review methods is adopted in the designed constructability assessment system. Each of these approaches offers certain capabilities when observing constructability aspects, and the ultimate objective here is to optimally quantify the design constructability in its multidimensional aspects, so required improvements are well understood and addressed. More explanation of this is provided in the following chapters.

2.9. Evaluation for current studies in quantifying design constructability

Although the quantified approach was previously identified as the most practical method to assess design constructability, different studies working within this framework applied numerous principles and covered various assessment scopes. This section identifies previous assessment tools and evaluates their advantages and disadvantages. As a result, requirements for modelling design constructability are identified that are lacking in current assessment systems, paving the way to design an effective assessment system that accommodates such requirements.

Table 2-9 presents a review of the current assessment models and compares their adopted concepts. Aspects of the comparison included the content of model, scope of application, assessment principles, assessment aspects, and if surveys/interviews were used when developing their knowledge content. It can be clearly seen that the interview approach is the most common way to acquire constructability knowledge from design and construction experts (Jiang, 2016).

Table 2-9: Summary of current constructability systems

Constructability system, study, country	Content	Scope of application	Assessed aspects	Surveys	Interview approach
The BIM-OfA assessment system, Offsite construction: Developing a BIM-Based optimizer for assembly, (Gbadamosi et al., 2019), UK	It proposes a design assessment and optimisation system to assist designers in the selection of alternative building design elements and materials in a building information model.	Used for assessment and optimal selection of building envelop during the early stages of design conception.	The proposed framework resulted in indices which allowed appraisal of design options in relation to: (i) ease of assembly; (ii) ease of handling; (iii) waste greeted from the assembly; and (iv) Speed of assembly.	Yes	No
Evaluation method based on constructability principles, An early-design stage assessment method based on constructability for building performance evaluation, (Contrada et al., 2019), France	It proposes a new assessment method based on the concept of constructability.	Used to support early-design stage decision between two façade components. However, the method can be used for whole-building design evaluation.	The evaluation is based on seven criteria: the simplicity of the solution, the verifiability, project skills availability, the simplicity to manage, the compliance with user-centric requirements, sustainability, and cost efficiency.	Yes	No
A building design assessment system, A BIM Based Approach for Optimization of Construction and Assembly through Material Selection, (Gbadamosi et al., 2018), UK	To develop BIM-based assessment metrics for material selection at early stage design.	Used to aid selection of alternative building design elements and materials in a digital prototype before they are actually constructed.	The assessment system relies on an index derived from production knowledge or data related to ease of assembly, speed of assembly and the waste associated with the assembly or construction of a building element or material.	Yes	No
A CIM-based constructability analysis approach, Applications of Civil Information Modelling (CIM) for Constructability Review in Railway Construction Projects, (Lin et al., 2017),Taiwan	It proposes a CIM-based constructability analysis approach for general contractors during the construction phase.	Utilizes Civil Information Modelling (CIM) technology to work the constructability analysis for the general contractor during the construction.	The frameworks of CIM application for constructability review includes visualized communication, quantity take off, interface coordination, clash detection, mock up, and process simulation.	No	Yes

Table 2-9: Summary of current constructability systems

Constructability system, study, country	**Content**	**Scope of application**	**Assessed aspects**	**Surveys**	**Interview approach**
CONSTaFORM, Automated constructability rating framework for concrete formwork systems using building information modelling, (Kannan and Santhi, 2018), India	To develop an automated constructability rating framework for different concrete formwork systems that are commonly used for the construction of reinforced concrete residential buildings.	Used to rate concrete formwork systems for determining optimal constructability score for simpler constructions.	The template used for the survey assessed aspects such as: Forming cost, forming time, forming quality, forming safety, environmental sustainability, total number of stories, total height of structure, to compute constructability score of each concrete formwork systems.	Yes	No
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 underground, building envelope, weather effect, safety, material access, personnel access, equipment access) Site impacts (adjacent structures)	Yes	No
The Empirical Assessment Model, The Assessment of Constructability: BIM Cases (Tauriainen et al., 2014), Finland	It introduces an experimental constructability assessment method (ECM) 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

Table 2-9: Summary of current constructability systems

Constructability system, study, country	**Content**	**Scope of application**	**Assessed aspects**	**Surveys**	**Interview approach**
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 et al., 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 2-9: Summary of current constructability systems

Constructability system, study, country	**Content**	**Scope of application**	**Assessed aspects**	**Surveys**	**Interview approach**
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

Based on the findings presented in Table 2-9,Table 2-10 focuses on the recently developed constructability assessment systems, and evaluates their effectiveness in improving design constructability.

Table 2-10: Pros and cons of recent developed constructability assessment systems

Adopted approach	Pros	Cons
Offsite construction: Developing a BIM-Based optimizer for assembly (Gbadamosi et al., 2019)	Integration with BIM enabled use of associated data such weight of components, number of on-site workers and number of parts, for buildability assessment. Employed the principles of Design for Manufacture and Assembly (DFMA) and Lean Construction to inform design decision-making.	Aspects of assessment are static, and users are not able to amend. Developed scales and weights are based on a voting matrix not elicited from the user. Assessment system is limited to building envelops and cannot be applied to other building elements.
An early-design stage assessment method based on constructability for building performance evaluation (Contrada et al., 2019)	Provided multi-criteria evaluation and decision-making support in early-design stage. Reported project weakness, enabling constructability enhancement. Enabled exploration of envelope alternatives to inform design decision-making.	Presents a high-level assessment tool for further development. Lacks integration with current design tools. Not based on users' input and requirements Scope of application limited to early-design stage decision between two façade components.
A BIM Based Approach for Optimization of Construction and Assembly through Material Selection (Gbadamosi et al., 2018)	Utilise BIM data to perform the assessment. Three methods of data development are used to develop the evaluation scale Easy to apply.	Assessment factors and their weights are not based on user input. Assessment calculations are performed outside the design environment (Excel) after importing BIM data from assessed model.
Applications of Civil Information Modelling (CIM) for Constructability Review in Railway Construction Projects (Lin et al., 2017)	Used Civil information modeling (CIM) to analyses design constructability in a 3D environment. Identify tangible constructability issues that can be rectified by users.	Relies only on design data to review constructability (perform qualitative assessment to identify issues such as clash detection). Not implementing constructability principles and attributes.
Automated constructability rating framework for concrete formwork systems using building information modelling (Kannan and Santhi, 2018)	Fully integrated with BIM to extract its data, perform the assessment, and report on the platform. Comprehensive in assessed constructability aspects of design formwork. Visualisation of assessment results.	Formulated knowledge is not captured from users' perspective. Assessed constructability aspects are fixed with no allowance for users to amend. Implementation scope is limited to assess design formwork only.

Adopted approach	Pros	Cons
Quantitative Assessment of Building Constructability Using BIM and 4D Simulation (Zhang et al., 2016)	The designer has an input in rating the design components. Utilises BIM in assessing the constructability. Includes the time dimension in the assessment process using the 4D CAD capabilities.	Based on secondary experiences, might not fit the examined case. Limited to a specific location. Not fully integrated with BIM. Assessment method unhelpful to improve design constructability.
The Empirical Assessment of Constructability (Tauriainen et al., 2014)	Very specific and detailed. Outputs accurately reflect constructability assessment in Finland.	Limited to a specific place. Very complicated to understand. Not easy to apply. Not fully integrated with BIM.
The Scheme Design Buildability Assessment Model (SDBAM) (Lam, 2012)	Comprehensive and inclusive in evaluation of all constructability aspects. Buildability factors are reflected directly in the design components. Easy to interpret its output and to improve constructability performance. Can be applied at any design stage without limitation to the LOD.	Based on secondary experiences, might not fit the examined case. Limited to a specific location. No use of modern BIM technology. Manual application – output accuracy questionable. No consideration of time dimension in evaluation.
Constructability Assessment Using BIM/4D (Hijazi et al., 2009)	The designer has an input in rating the design components. Utilises BIM in assessing the constructability. Includes the time dimension in the assessment process using the 4D CAD capabilities.	Based on secondary experiences, might not fit the examined case. Limited to a specific location. Not fully integrated with BIM. Assessment method unhelpful to improve design constructability.

2.9.1. Requirements for effective constructability assessment system

The comprehensive review of contemporary literature helps identify the shortcomings of current assessment systems and what needs to be addressed in this area, given the advanced technologies that are available nowadays. Using retroductive reasoning at this stage facilitates the investigation of patterns and regularities among evaluated constructability systems. This is another important step towards generating an in-depth understanding of constructability modelling process. Typically, the research inductively defined a set of qualities required to characterise any assessment system, to facilitate the process of designing for constructability and deliver it in an effective, fast, and accurate way. These requirements are presented in Figure 2-18.

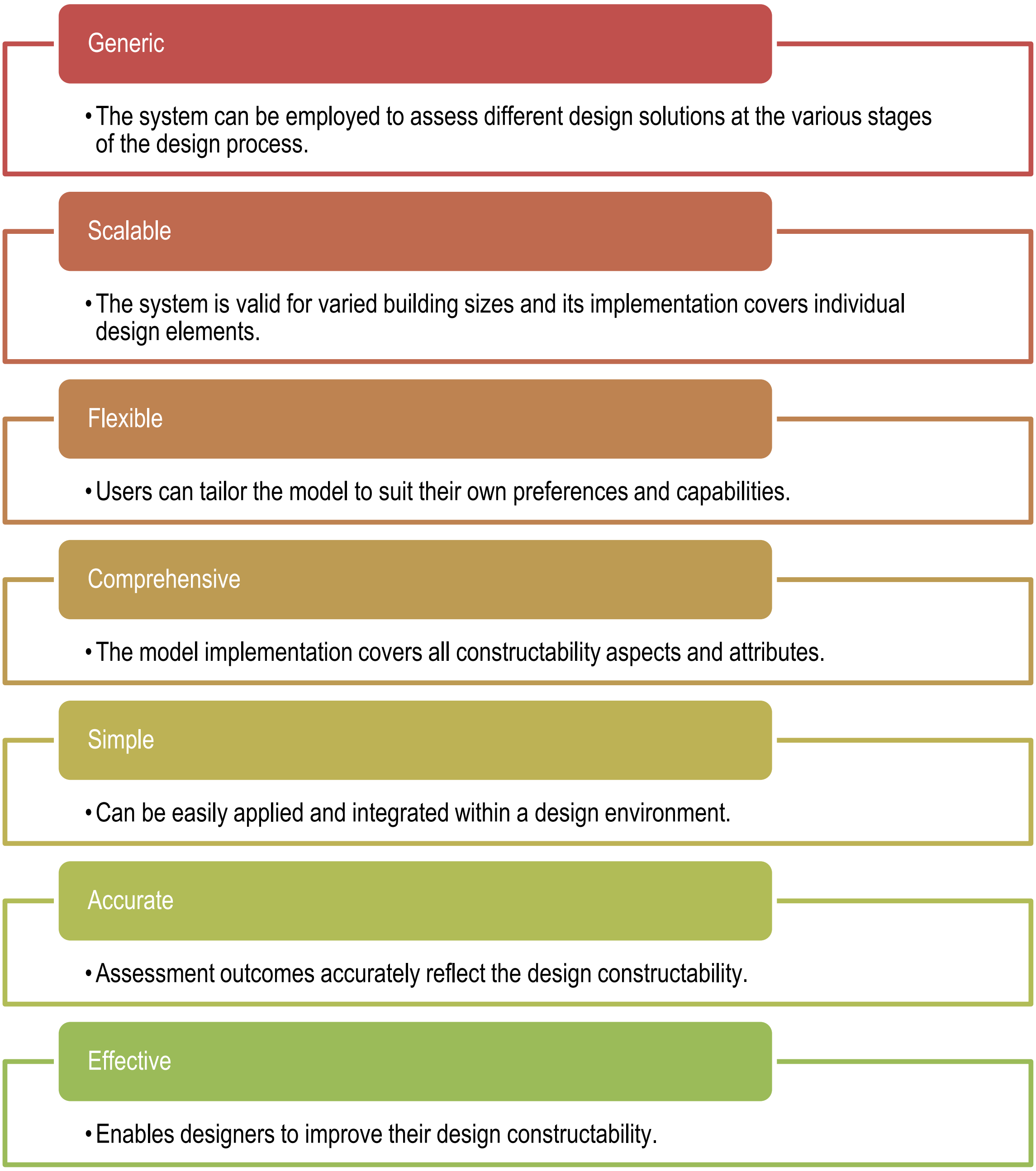


Figure 2-18: Requirements of constructability assessment system

Based on derived requirements for the desired constructability assessment system, Table 2-11 evaluates the extent of their existence in current assessment systems. It clearly indicates the necessity to devise an assessment mechanism that addresses these requirements.

Table 2-11: Evaluation of current constructability assessment systems based on identified requirements

Constructability system	Generic	Scalable	Flexible	Comprehensive	Simple	Accurate	Effective
Offsite construction: Developing a BIM-Based optimizer for assembly (Gbadamosi et al., 2019)	✗	✓	✗	✗	✓	✓	✓
An early-design stage assessment method based on constructability for building performance evaluation (Contrada et al., 2019)	✗	✓	✗	✗	✗	✗	✓
A BIM Based Approach for Optimization of Construction and Assembly through Material Selection (Gbadamosi et al., 2018)	✗	✓	✗	✗	✓	✓	✓
Applications of Civil Information Modelling (CIM) for Constructability Review in Railway Construction Projects (Lin et al., 2017)	✓	✓	✗	✗	✓	✓	✓
Automated constructability rating framework for concrete formwork systems using building information modelling (Kannan and Santhi, 2018)	✗	✓	✗	✗	✓	✓	✓

Constructability system	*Generic*	*Scalable*	*Flexible*	*Comprehensive*	*Simple*	*Accurate*	*Effective*
Assessment of Building Constructability Using BIM and 4D Simulation (Zhang et al., 2016)	✗	✓	✗	✓	✓	✓	✓
The Empirical Assessment of Constructability (Tauriainen, 2015)	✗	✓	✗	✗	✗	✓	✓
The Scheme Design Buildability Assessment Model (SDBAM) (Lam, 2012)	✗	✗	✗	✓	✓	✗	✓
Constructability Assessment Using BIM/4D (Hijazi et al., 2009)	✗	✓	✗	✓	✓	✓	✗
Buildability Assessment Model BAM (Lam and Wong, 2008)	✗	✗	✗	✓	✓	✗	✓
Buildable Design Appraisal System (BDAS) (BCA, 2005)	✗	✗	✗	✗	✓	✗	✓
Buildability Multi-Attribute System (BMAS) (Zin et al., 2004)	✗	✗	✗	✗	✓	✗	✓

2.10. Current limitations and emerging challenges

The concept of constructability aims to facilitate the construction management process through the early involvement of clients and contractors' requirements (Griffith and Sidwell, 1997, Wondimu et al., 2016). However, the focus has been primarily on specific project phases, and hence the integral aspects of constructability were not adequately considered, and its ultimate benefits not fully realised. The majority of projects lack the early input of constructability due to lacking formal, explicit constructability knowledge bases to act as knowledge repositories, to be accessed by relevant project parties to assist with decision-making process, and enforcing constructability principles on design solution being developed (John Van der and George, 2001). Other issues such as designers' lack of incentives and obstacles to use innovative technologies also inhibit the adoption of the concept among construction practitioners (Kalantari et al., 2017).

Clearly, the fragmented nature of construction projects and their involvement of multidisciplinary roles, as well as the use of conventional contracting methods, challenges constructability implementation (McGeorge et al., 1992, Alreshidi et al., 2018). Also, the uniqueness of each project and introduced constraints requires careful considerations for all interactive factors. It is not only challenging to identify these factors and their implications on design products, but also to gauge their criticality from the constructor's perspective (Griffith and Sidwell, 1997).

A tangible improvement in the construction industry through constructability implementation requires devoted commitment from all project stakeholders. Both client support and project team assistance can activate the potential of the concept to enhance the design process, construction techniques, construction management and ultimately product quality and efficiency (Griffith and Sidwell, 1997).

2.11. Gap in knowledge

It can be concluded that current conventional practice on constructability implementation is failing to effectively take advantage of construction knowledge, expertise and experience to enhance project performance. Today, designing for constructability demands serious efforts, resources and time from the design team, discouraging them from considering the concept during the process.

There is an essential need to explore new techniques and methods to employ construction knowledge in producing a constructible design. This entails the use of computing techniques, tools and IT technologies, exploiting the capacity of artificial intelligence (AI), KM, and information and communications technology (ICT) to renovate the design platform. Constructability should enable designers to access a knowledge-based tool to support the decision-making process in a facilitated way, even for inexperienced designers (Jergeas and Put, 2001, Gambatese et al., 2007a).

The main challenge now is to establish a mechanism or assessment system that exploits BIM capabilities, to assess design constructability (Lam et al., 2012), constituting an intrinsic research gap to be addressed by this study. Such a system would have a significant impact on improving constructability at the early design stage, with its principles factored-in from the design concept stage. Clearly more research and work is needed in this area.

2.12. Summary

The chapter reviewed the constructability concept and associated challenges with its implementation. It evaluated different studies on the topic and their adopted approaches to improve the constructability performance of building design. It concludes that the main challenge to design for constructability is lacking a design-support tool assisting practitioners in related tasks. The tool should facilitate the process of acquiring relevant construction knowledge, formulating it in a knowledge-based system and mapping it on design features to influence the decision-making process.

3. Designing for Constructability

3.1. Introduction

This chapter investigates constructability decision tools to exploit the capabilities of BIM technologies in their implementation. Developing such a tool requires a framework that can model constructability of design solutions. To enable this, further analysis of constructability concepts is carried out to understand its principles and underlying theories. This covers how constructability knowledge is acquired from experts, formulated in knowledge base systems, and incorporated into design solutions. Design-relevant construction knowledge is identified based on its influence on designs to improve their constructability. Contributions of BIM technologies are investigated in facilitating knowledge acquisition and its reasoning on design features. Current approaches for quantifying constructability are visited and assessed, to understand the theoretical and practical backdrop of such research, and to re-engineer the assessment mechanisms. This paves the way to introduce the proposed assessment framework and its components. It outlines the necessity of each part of its structure accommodating constructability in its abstract nature.

3.2. Design-relevant constructability knowledge

There are several factors that could make a construction process go wrong, which are frequently reflected in project delays and cost overruns (Le-Hoai et al., 2008). The root causes could be contributed by the client, the consultant, or the contractor (Ren et al., 2008). However, the concept of constructability looks specifically into construction difficulties that were originally caused by design decisions. It seeks to exploit construction knowledge and experience to influence the design process. Such design-construction integration is likely to be more beneficial for project success (Fischer, 1991).

However, the lack of construction knowledge at the design phase is the main reason for ignoring its input at this stage. The practice dealt with the issue by defining some sort of contractual or organisation measures. They seek to input downstream knowledge (such as construction) to upstream activities (e.g. design). This includes design to build, construction management and techniques, early involvement of contractors, employing a friendly contractor, making use of designers' knowledge and experience, carrying out investigation studies, and value engineering (Fischer, 1991).

Though existing measures partially implement the constructability concept, utilising designers' construction knowledge and experience, the ideal solution is to formulate solid knowledge-based systems that effectively implement the constructability concept by acquiring and classifying construction knowledge that potentially has an influence on the design decisions. This includes considerations of critical design variables (e.g. elements' dimensions, layout, sizes, and shapes) that later facilitate the construction process. The built knowledge base should be formulated in a suitable way that eases its reuse by various design and project parties.

3.3. Constructability knowledge life-cycle

Based on the CII (1986) definition of the term constructability, we can derive the main components of the concept and how they are interrelated. The definition states that constructability is "*the ultimate use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives*". Thus, the following constituents are necessary to enable concept implementation (Figure 3-1):

- **Knowledge identification:** This part of the process deals with identifying design-relevant constructability knowledge. It is the type of knowledge that could influence the design, if applied at the appropriate time, to ease the construction process.
- **Knowledge acquisition:** This is the most challenging part, which deals with quantifying a very subjective issue. It seeks to extract the construction knowledge from construction expertise to formulate a knowledge base ready for integration with the design process.
- **Knowledge formulation and representation:** This part deals with formulating acquired construction knowledge expressed in terms of

views, opinions, preferences, and constraints into a knowledge base that could be used in modelling constructability of similar designs when applicable.

- **Knowledge reasoning:** This is the important part, making use of the formulated construction knowledge database to provide assessment, feedback, warnings, and recommendations regarding design constructability status.

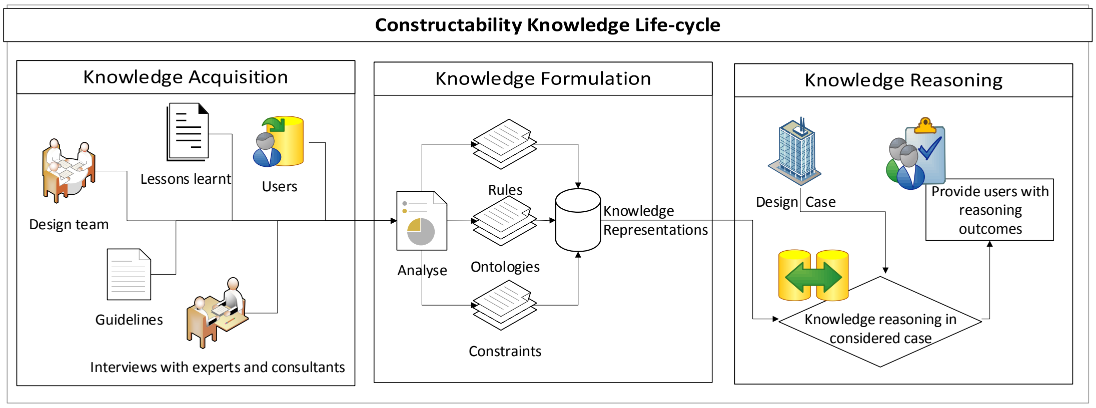


Figure 3-1: Constructability knowledge life-cycle

Associated challenges with building construction knowledge-based systems include the following:

1. Identifying a practical way to extract the human element of construction knowledge and experience for the building the knowledge base. It should target only design-relevant knowledge that may influence design solutions to facilitate construction.
2. Formulating the extracted knowledge in an effective way that enables reuse for similar construction projects.
3. Mapping the formulated knowledge on various design cases while accommodating differences by applying only what is relevant to them.
4. Highlighting areas of weakness to be targeted for constructability improvement.

3.3.1. Constructability knowledge identification and acquisition

The main sources of knowledge acquisition are construction experts and industry practitioners (e.g. contractors, sub-contractors, and consultants etc.), therefore surveys and interviews are the best way to gather their knowledge and experience to build any knowledge-based system (Jiang, 2016). However, it has always been challenging to extract relevant knowledge, as well as managing the subjectivity of participants' views, to formulate a solid knowledge base whose accuracy can be relied upon for future use.

The Analytic Hierarchy Process (AHP) was the common approach used with interviews in previous studies (BCA, 2005, Lam and Wong, 2008, Hijazi et al., 2009, Lam et al., 2012, Zhang et al., 2016). It was used to establish constructability indicators for various construction systems. The technique was developed by Thomas Saaty (1990) for the analysis of complex decisions using mathematics and psychology. It organises a decision problem into a hierarchy of criteria, sub-criteria, and alternatives, to be scored for their priorities in a series of pairwise comparisons.

The rationale behind using AHP for constructability assessment is that it enables the quantification of abstract concepts, involving a set of complex interrelated problems that feed into one another, which requires breaking down into simple chains of reasoning. Through measuring these pieces alongside tangible factors acting as criteria for decisions, it enables decision-makers to reach a decision (Saaty, 1994).

3.3.1.1. AHP for modelling constructability

An example-based approach is used to describe AHP-enabled decision making. It uses BAM case to demonstrate the development of its buildability indices (BIs) (Hei, 2007), according to the standard procedure explained below.

1. Define the problem and the required knowledge and expertise to make the decision.

Example problem description: to decide on the constructability performance of various roof types using the expertise of interviewed construction practitioners.

2. Structure the problem into decision hierarchy that facilitates its observation, starting from the goal on the top, then identified objectives that enable the goal, through criteria to reach the decision, to the available alternatives from which we need to pick one (Figure 3-2).

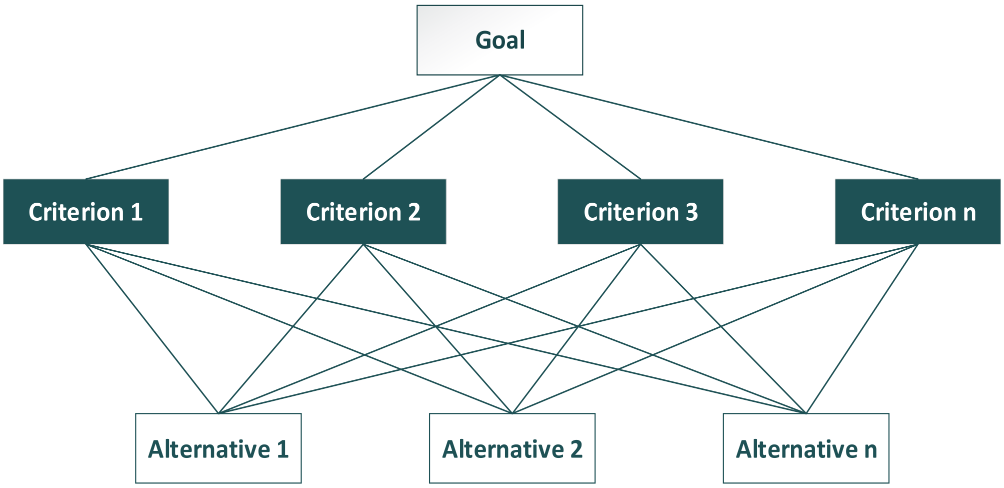


Figure 3-2: AHP decision hierarchy of goal, criteria and alternatives

(Saaty, 2008)

Example problem decomposition: as Figure 3-3 demonstrates, the goal is selecting the most buildable roof type; the decision criteria are a set of buildability factors defined to characterise the ideal solution; and the alternatives are possible alternative for roof construction.

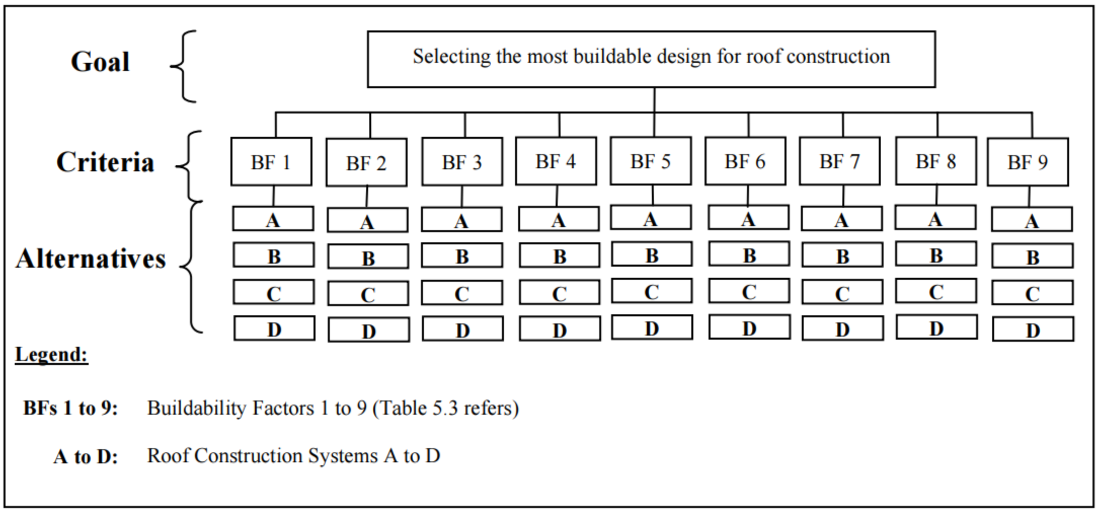


Figure 3-3 Problem decomposition into goal, criteria and alternatives to identify the most constructible roof system

(Hei, 2007)

3. Perform a pairwise comparison between elements. Each set of elements is compared with respect to the immediate upper element (criteria, objectives, and goal) using scales presented in Table 3-1. These scales express the extent to which one element is more or less favoured over another with respect to the criterion against which they are compared.

Table 3-1: Defined scales for pairwise comparisons

(Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal importance	Element a and b contribute equally to the objective
3	Moderate importance of one over another	Slightly favour element a over b
5	Essential importance	Strongly favour element a over b
7	Demonstrated importance	Element a is favoured very strongly over b
9	Absolute importance	The evidence favouring element over *a* over b is of the highest possible order of importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed. For example, 4 can be used for the intermediate value between 3 and 5
1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	These values represent the opposite of the reciprocal whole numbers. For example, if "9" means that x is much more important than y, "1/9" means that x is much less important than y.	

Note: Elements a and b represent considered criteria

Example comparative judgement: Figure 3-4 shows the recorded pairwise comparisons to calculate the priority vectors of defined buildability factors (BFs) using scales in Table 3.1.

	BF 1	BF 2	BF 3	BF 4	BF 5	BF 6	BF 7	BF 8	BF 9	Priority vector
BF 1	1	1/2.5	1/2.0	5.5	1/1.5	1/3.5	6.5	1/1.5	2.0	**0.089**
BF 2	2.5	1	1.5	7.0	3.0	5.0	8.0	2.0	3.5	**0.252**
BF 3	2.0	1/1.5	1	6.5	2.5	4.5	7.5	1.5	3.0	**0.204**
BF 4	1/5.5	1/7.0	1/6.5	1	1/5.0	1/3.0	2.0	1/6.0	1/4.5	**0.025**
BF 5	1.5	1/3.0	1/2.5	5.0	1	3.0	6.0	1/2.0	1/2.5	**0.096**
BF 6	3.5	1/5.0	1/4.5	3.0	1/3.0	1	4.0	1/4.0	1/2.5	**0.061**
BF 7	1/6.5	1/8.0	1/7.5	1/2.0	1/6.0	1/4.0	1	1/7.0	1/5.5	**0.018**
BF 8	1.5	1/2.0	1/1.5	6.0	2.0	4.0	7.0	1	2.5	**0.162**
BF 9	1/2.0	1/3.5	1/3.0	4.5	2.5	2.5	5.5	1/2.5	1	**0.094**
Σ	12.84	3.65	4.91	39.00	12.37	20.87	47.50	6.63	13.20	**1.00**

BFs 1 to 9: Buildability Factors 1 to 9

(Note: the fractions represent reciprocal relationships)

Figure 3-4 Comparative judgement of buildability indices (Hei, 2007)

In a similar way, the alternatives, i.e. Roof types A, B, C and D will be compared with respect to each of defined criteria, i.e. BFs.

Since the integrity of any obtained priorities from the process mainly relies on the accuracy of scored pairwise comparisons, a consistency ratio is generated to inform on the consistency of the scales. It is expressed as an index, with a value of 0 representing perfect, consistent judgement, and values greater than 0.1 indicating poor consistency in judgements (Saaty, 1990).

4. Use generated local priority for each element from the comparison to accord weight to elements in levels, immediately generating their global priorities. Accumulating global priorities for all sets of criteria generates an overall priority for each alternative, ranking their performance to achieve the set goal.

Example hierarchal composition: Figure 3-5 shows developed buildability indices (BIs) of design alternatives clustered under various construction systems for BAM derived by the AHP.

Different parts of a building superstructure	Common construction systems	Priority Ratios (i.e. Buildability Indices)	Totals
Structural Frame	• Precast RC frame *	0.239	1.00
	• Structural steel with fireproofing *	0.210	
	• Insitu RC frame	0.194	
	• Insitu loadbearing cross-wall	0.181	
	• Steel encased in concrete *	0.176	
Slab	• Precast slab with insitu topping *	0.270	1.00
	• Steel deck with insitu concrete topping *	0.253	
	• Insitu RC slab	0.200	
	• Flat slab	0.176	
	• Prestressed concrete slab	0.101	
Envelope	• Precast concrete wall with pre-installed windows and finishes *	0.257	1.00
	• Curtain wall *	0.206	
	• Insitu concrete wall	0.179	
	• Pre-finished precast concrete formwork with insitu filling *	0.179	
	• Concrete block / brick	0.178	
Roof	• Precast concrete roof *	0.271	1.00
	• Steel decking with insitu concrete topping *	0.271	
	• Steel truss roof with composite decking *	0.238	
	• Insitu concrete roof	0.220	
Internal Wall	• Dry wall *	0.434	1.00
	• Concrete block / brick	0.317	
	• Insitu RC wall	0.249	

Figure 3-5 Buildability representations of construction systems alternatives (Hei, 2007)

3.3.2. Classification of constructability knowledge

Various studies came up with different classifications for the acquired knowledge based on how they approach the concept to enable its quantification. Figure 3-6 demonstrates how constructability knowledge was classified in previous constructability systems. A class uses the acquired knowledge to define a rule-based system that sets limitations on the design variables. Such rules are defined based on causes of construction problems or how to avoid them and their impacts. Others classified the knowledge based on its relation to the design or construction processes. Various terms are used to classify this category of knowledge, such as constructability factors, attributes, and principles etc.

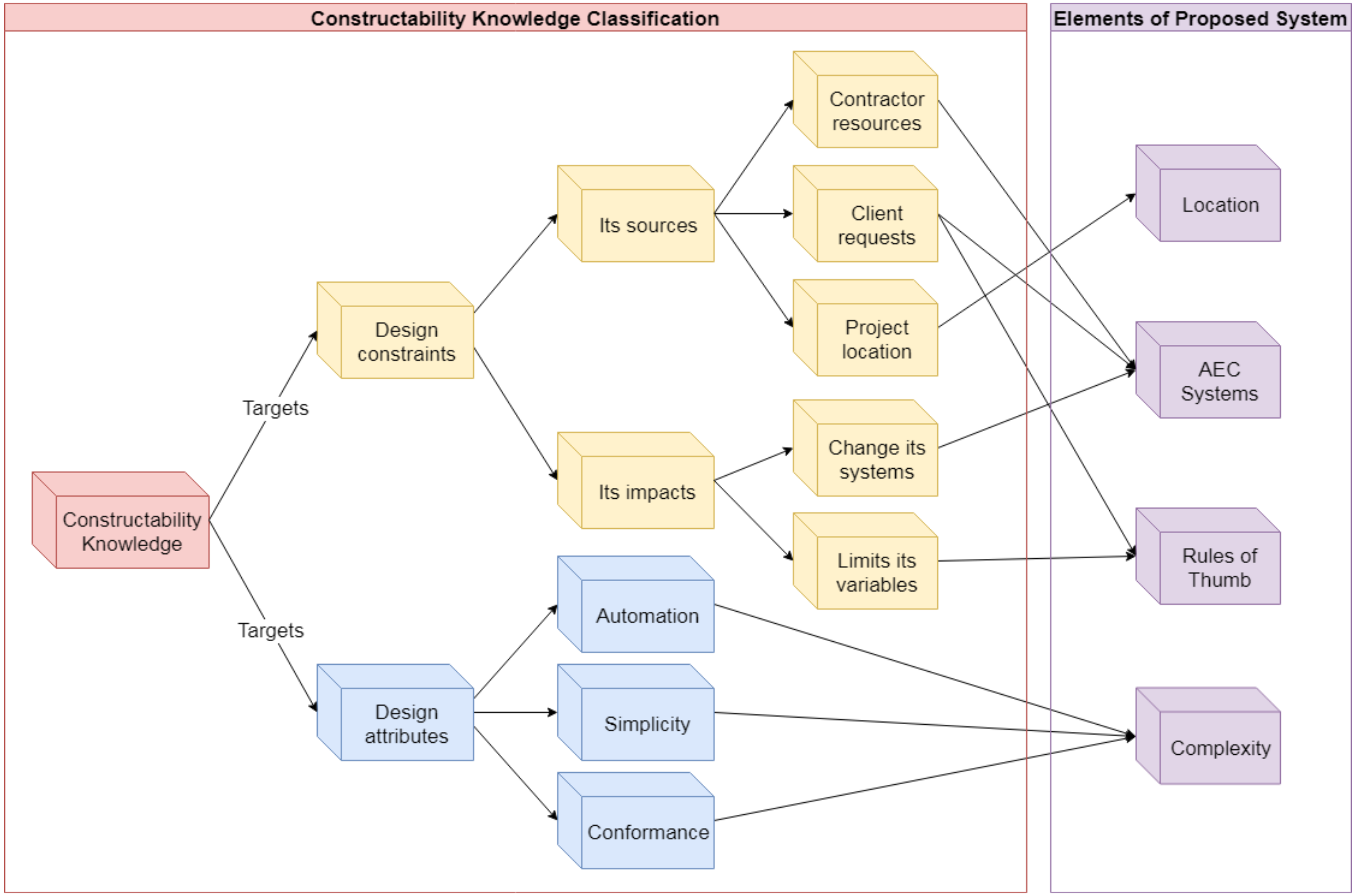


Figure 3-6: Classification of design-relevant constructability knowledge

3.3.3. Constructability knowledge incorporation into design process

The main purpose of knowledge acquisition is to be employed during the design process to inform designers about what can be improved. However, it has always been challenging to incorporate such knowledge into the design environment. Previous constructability tools addressed this by adopting mainly two approaches, demonstrated in Figure 3-7.

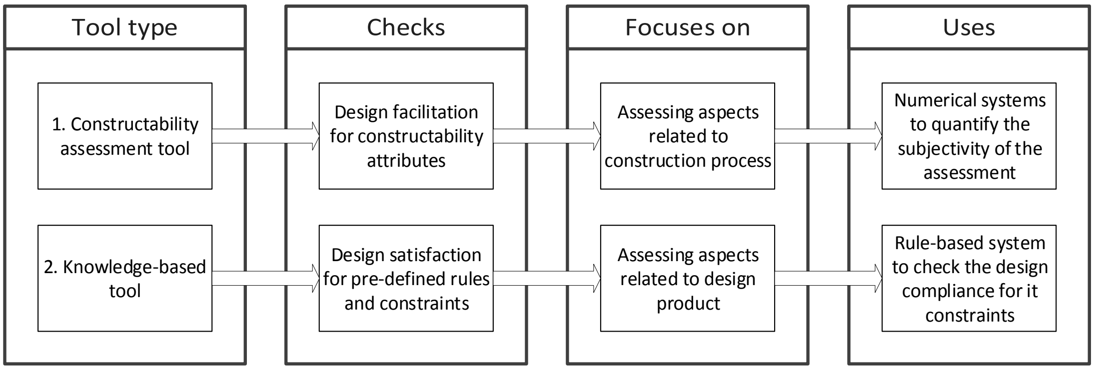


Figure 3-7: Categories of constructability tools

One of the approaches focuses on observing the big picture of considered designs. It investigates how such designs facilitate certain constructability qualities, such as standardisation, replications and automation. This includes examining how selected shape, layout, sizes, dimensions, or materials simplify the construction process. The advantage of this approach is its investigation of the ultimate constructability goal, being able to construct the design product. However, these attributes are always subjective, and are hard to quantify, which may lead to losing focus on the problem. Also, its output recommendations are often too complicated to be reflected in the design's elements, as it does not identify the exact area of weakness.

The other approach implements a rule-based system that imposes constraints on design solutions, which ensures design avoidance of any potential issues that may arise during construction. These issues may be due to resources availability, client requests, or site conditions. While this approach is effective in informing designers directly what elements they need to amend in their designs to meet their targets, it is not capable to quantify all aspects of constructability that are examined in the first approach.

3.4. Necessity to re-engineer constructability assessment mechanism

This part investigates the drawbacks of currently employed approaches to model constructability. It identifies major issues in the process of modelling design constructability, and then draws a strategy for how to address these issues in the new proposed assessment framework. This contributes to meet the requirements of modelling constructability of buildings design, identified in section 2.9, as Figure 3-8 demonstrates.

The identified issue: Previously developed models are limited to a particular place, which can be used for assessing constructability in specific, narrow contexts. This is because their construction knowledge is usually acquired in such places through surveys and interviews with local experts, and hence the model is only valid there. Assessment models should enhance flexibility to be adopted by various users (Das and Kanchanapiboon, 2011).

Proposed solution: To develop a universal Constructability Model (CM) that can be applied anywhere. However, when such a model is provided, its effectiveness in quantifying constructability is doubtful, because each design is unique in its conditions (Lee et al., 2015), and any proposed model, should accommodate potential specialities. The suggestion is to address this issue by presenting a generic model that is amenable to customisation, to factor in any particularities.

The identified issue: One major encountered issue in all previous assessment systems is ignoring users' inputs in the process. Their employed knowledge is based only upon expert views, which might not truly reflect constructors' capabilities. Implementation of constructability should come up with a design solution that suits constructors' capabilities, while considering the construction environment. This requires benchmarking such capabilities first, which can be best obtained from user inputs. Their contribution to the assessment process should validate the effectiveness of developed models and the accuracy of their delivered results (Naaranoja and Vares, 2017).

Proposed solution: To provide a facility for users (design team, consultants, and early involved contractors) to have their inputs in customised constructability models. This should be through a guided process with an intuitive and friendly implemented UI. While such input defines users' preferences and gauges their construction capabilities. It should also direct their attention to hidden parts of their design that require special consideration from a constructability perspective.

The identified issue: Further to this, the current employed process to represent constructability knowledge results in many limitations to reason with the formulated knowledge. These include:

1. **Design-relevant construction knowledge identification**: The knowledge is typically extracted through surveys and interviews with construction experts. As a result, it is normally identified, classified, captured based on the pre-designed surveys and interviews' questionnaires, developed by the model creator. Potential users of the model have no input in structuring such knowledge database to suit their requirements, or to include constructability aspects that only relate to their situations (i.e. considering the weather factor which might not be an issue in some places). Designing generic knowledge-based repositories to be used by anyone, without personalising its content to their construction circumstances, questions the accuracy of obtained assessment results.
2. **Knowledge classification**: Current systems adopt either a numerical system to assess constructability quantitatively, or a rule-based system to assess constructability qualitatively. However, each of the approaches partially addresses constructability concerns, while an ideal solution should consider both of them concurrently to model constructability in its multidimensional aspects.
3. **Knowledge elicitation:** The extracted knowledge itself, through the response to designated surveys and interviews by a third party, might not necessarily represent the views and capabilities of potential design constructors. Part of measuring design

constructability is to measure someone's' ability to construct that design.

4. **Knowledge Formulation**: Current established models are not formulated in the form of object-oriented knowledge bases, and hence they don't support automatic reasoning about constructability when used with object-based BIM modelled features.
5. **Knowledge store**: Current knowledge bases are rarely stored in digital formats. Consequently, this does not facilitate enquiring their contents or investigating their suitability to assess specific design cases.
6. **Knowledge update**: Furthermore, a static represented knowledge that is only extracted once, at the time of its elicitation, cannot be updated to suit various construction situations, or to accommodate new invented construction techniques and methods.
7. **Knowledge reasoning**: The lack of a design tool that can effectively reason the captured knowledge onto assessed design features to inform constructability performance, is a big hurdle in the process of designing for constructability. Current assessment systems demand manual calculations and interpretations. As such, it discourages practitioners from employing them, given the dynamic of design process and the need for ongoing modifications in designed products. Even if they go through the process once, they are unlikely to do it a second time to test design modification capabilities.

Proposed solution: This necessitates to separate between the knowledge formulation and the knowledge reasoning processes. Hence, it enables to establish a user-based constructability knowledge that allows for the sought flexibility.

The identified issue: Some practitioners are reluctant to assess their design constructability because of the tedious efforts required (Lin et al., 2017); furthermore, some of them lack knowledge on how to implement the concept (Fadoul and Tizani, 2017). This is mainly due to the sophistication of constructability concept and associated challenges with its implementation. Even studies that managed to come up with models to assist designers in this task, they demand manual calculations and interpretations. This discourages practitioners from employing them, due to the lack of incentive to try new tools, and the belief that it is not their duty to adopt innovations. Even if they use it once, they are unlikely to use it a second time, to test design modification capabilities (Das and Kanchanapiboon, 2011).

Proposed solution: To design a system that integrates the design process with the implementation of the constructability concept, and making use of currently available technologies that may provide assistance in this aspect. Particularly, integration of the assessment system with parametric design authoring software such as BIM would simplify the process and motivate designers to factor in concepts starting from the design inception (Akinade et al., 2015, BCA, 2016).

The identified issue: Previous assessment tools adopted only one approach between two to incorporate constructability in the design process, either by checking the design compliance with pre-defined constraints, or assessing its satisfaction for identified constructability qualities. However, each of the approaches partially addresses constructability concerns, while an ideal solution should consider multi-objective approach concurrently (Jürisoo and Staaf, 2007, Das and Kanchanapiboon, 2011, Akinade et al., 2015). It is challenging to combine between different approaches, due to the way they impose constructability over design elements, and how they report status to users.

Proposed solution: To develop a system that covers the assessment of constructability in its multidimensional aspects. This should enable the assessment of constructability quantitatively and qualitatively to accommodates any requirements. The next section elaborates on the proposed solution in detail.

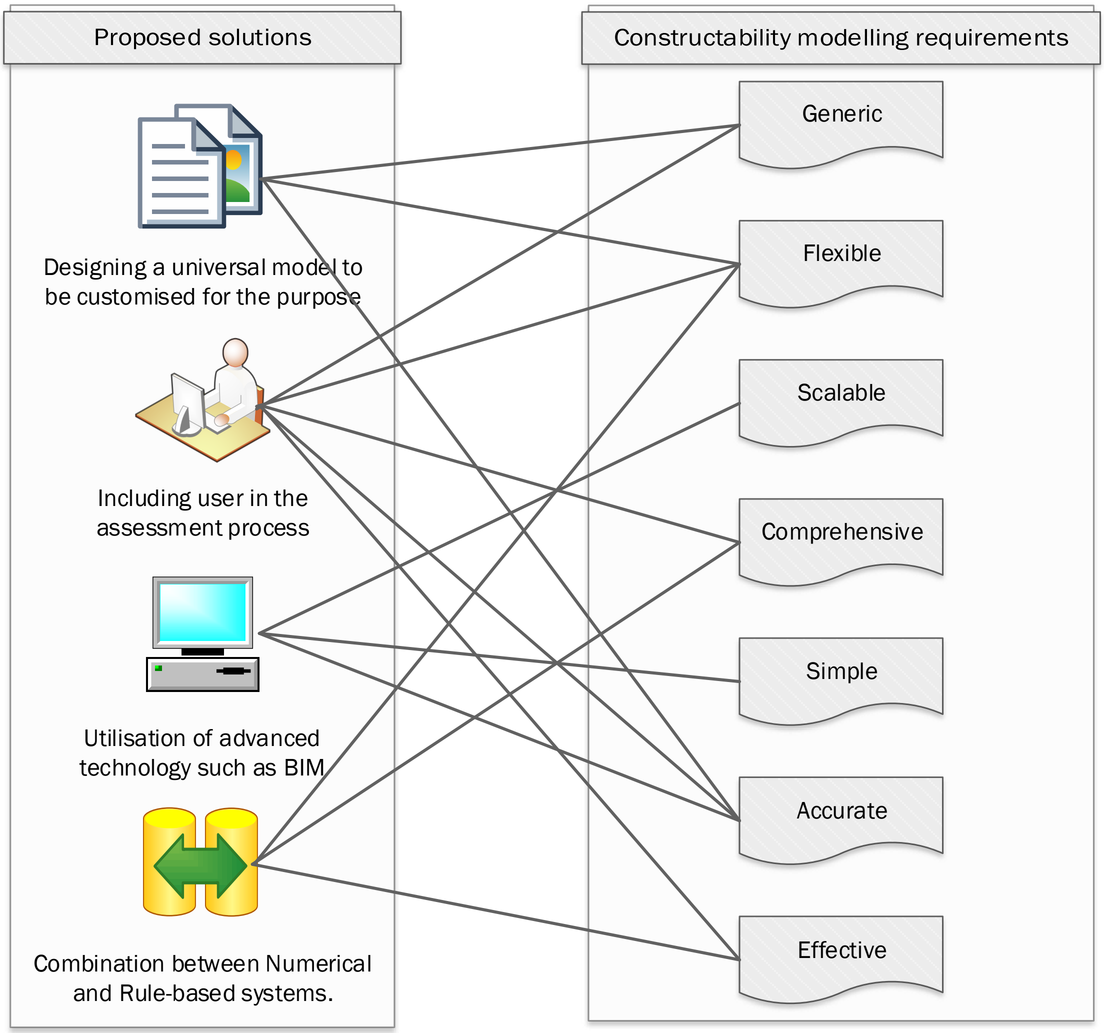


Figure 3-8: Proposed solutions and their contributions to meet the requirements of modelling constructability in buildings

3.5. The conceptual Constructability Model (CM)

3.5.1. Proposed approach to model constructability

As mentioned previously, the proposed assessment system combines two main approaches in quantifying design constructability. It assesses both of design facilitation for constructability attributes as well as its satisfaction for defined constraints (qualitatively and quantitatively). This is done by adopting the numerical method, implicitly encapsulating the assessment of constructability attributes and qualities. It assigns scores to indicate their performance in observed designs as a part of the whole system.

3.5.2. Knowledge identification and acquisition

The system is designed to have two sources for acquiring information to shape targeted CMs: the potential user of the model, and the BIM model which is being assessed. However, the user is considered as the main source of knowledge acquisition, either directly, by providing their input to the system when customising the model, or indirectly, by information associated with the assessed design product using the BIM model. Inputs from the system user determine the following:

- How they would like to observe and assess constructability in their designs. This is typically done by enabling only the needed parts of the CM to be customised, and the variables and knowledge to be acquired accordingly.
- Factors that usually affect constructing their designs based on their own experience. They will be able to select what applies to them from a comprehensive list, derived from empirical literature.
- Their ultimate design objectives and how accomplishing constructible design can benefit them (e.g. finishing on time and on budget, client satisfaction, and attaining a safe construction environment).
- The importance of design construction systems (floors, roofs, walls, structural framing etc.) in contributing toward achieving defined objectives.
- Their constructability preferences for different design elements, communicated through assigned indices, based on their satisfaction with defined criteria (i.e. constructability factors).

3.5.2.1. Role of BIM in the proposed Constructability Model

The BIM model will mainly be used for reasoning purposes when triggering the assessor engine. It shall provide the required information about the design to benchmark its constructability against what is targeted, presented in the customised CM. However, it can also be used during customising the CM for the following purposes:

- It can act as a source of information about construction materials used in the design solution. Extracting names and properties of such materials paves the way to assign them indices that indicate their constructability status.
- Deciding on the importance of construction systems, which can be decided automatically based on considered design and pre-defined objectives. For instance, if the objective of finishing on time is prioritised, then construction systems requiring more time than others will be scored lower. This pushes users to target the right area for improvement to achieve better scores in targeted dimensions.
- Estimation of required construction resources to construct a design based on calculated quantities in the design. This assists in evaluating gaps between what is needed by and what is accessible to design constructors.

As utilised by previous studies, the proposed system employs the AHP technique to acquire construction knowledge from the user side. However, the main difference in such employment is the dynamic use of the technique throughout the assessment process. Previous studies used the technique to process the knowledge collected through surveys and interviews, representing an already structured decision problem. The hierarchy of the problem was already set (i.e. in terms of goal, criteria, and alternatives), and the conducted pairwise comparisons were done only once to develop the model indices to be utilised by all users at the all the time. The use of the technique was static for a pre-defined decision problem, as demonstrated in section 3.3.1.1.

Conversely, the technique is employed here to analyse structured problems that are customised by users dynamically. They can define what criteria and alternatives should be considered, and then the priorities and indices are generated at the running time. For instance, a particular system user can include only available types of internal wall alternatives in their regions, in order to rank their performance based on constructability considerations. This allows for the sought flexibility when structuring the CM to cater to diverse perspectives. The actual implementation of the AHP technique to calculate Constructability scores is examined in chapter 4.

3.5.3. Classification of formulated knowledge

As highlighted earlier, the targeted CM requires structuring for its elements in order to enable the knowledge acquisition from practitioners. The end users will have the facility to form the model hierarchy based on how they want to observe constructability in their design solution. They can decide on how the knowledge is classified, and constructability factors are clustered. Once this is established, they can use AHP to perform the prioritisation to generate the model figures, similar to what was demonstrated in section 3.3.1.1.

3.5.4. Mapping acquired knowledge on design features

Having identified, acquired, and classified targeted knowledge, it is necessary to incorporate it into the design platform. The deployed knowledge, representing constructors' capabilities, preferences, and constraints, is mapped onto design elements (i.e. beam, column, wall, etc.) to determine constructability status. The rationale behind using design elements to model design constructability is to:

- Facilitate the process of assigning Constructability scores through the consideration of each element separately. It is more practical to quantify constructability of an individual physical element rather than the entire design together. Each element has different considerations when it comes to assess its constructability in comparison to other types.
- Formulate an element-based constructability knowledge base that is easy to be mapped onto design features. This is also compatible with the nature of BIM design models, and the way their entities are represented on elements basis.
- Enable improvements in design constructability based on how individual elements perform. Lower performing design elements can be easily identified and modified to achieve better Constructability scores.
- Develop a reusable knowledge base that is separated from assessed designs. By formulating an element-based knowledge base, it enables

its use for assessing designs that have similar elements. Aggregating this to a higher level, the authored CM can be used to assess other design products (i.e. BIM models).

3.5.5. Constructability knowledge incorporation in design process

The formulated knowledge can be applied to influence internal constructability factors in the design solution (e.g. design variables such as design sizes, shapes, or material selections), to control what is out of users control (market conditions, facilities, or applied constraints from surrounding environments) (Figure 3-9).

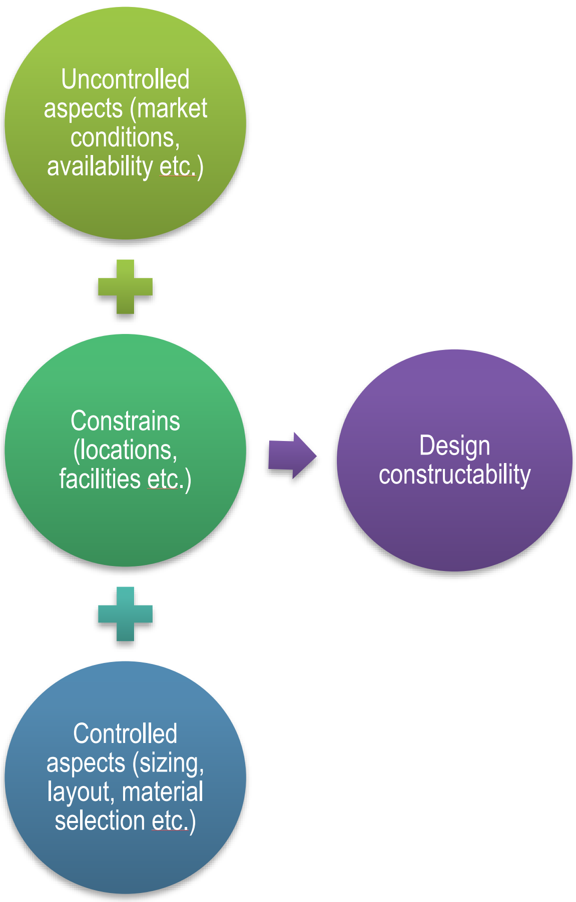


Figure 3-9: Aspects of constructability concept

Therefore, the proposed conceptual model is arranged for different levels of knowledge enforcement to effectively influence constructability, as Figure 3-10 demonstrates. The applied levels of constructability reinforcement seek to cover the assessment of both design product and construction process, aiming to inspect the design product first, ensuring that each of its selected element is constructible on its own and has the resources it requires to be built. It then moves on to the construction process to investigate what can ease its progress. All of these steps include consideration of any applied constraints and limitations.

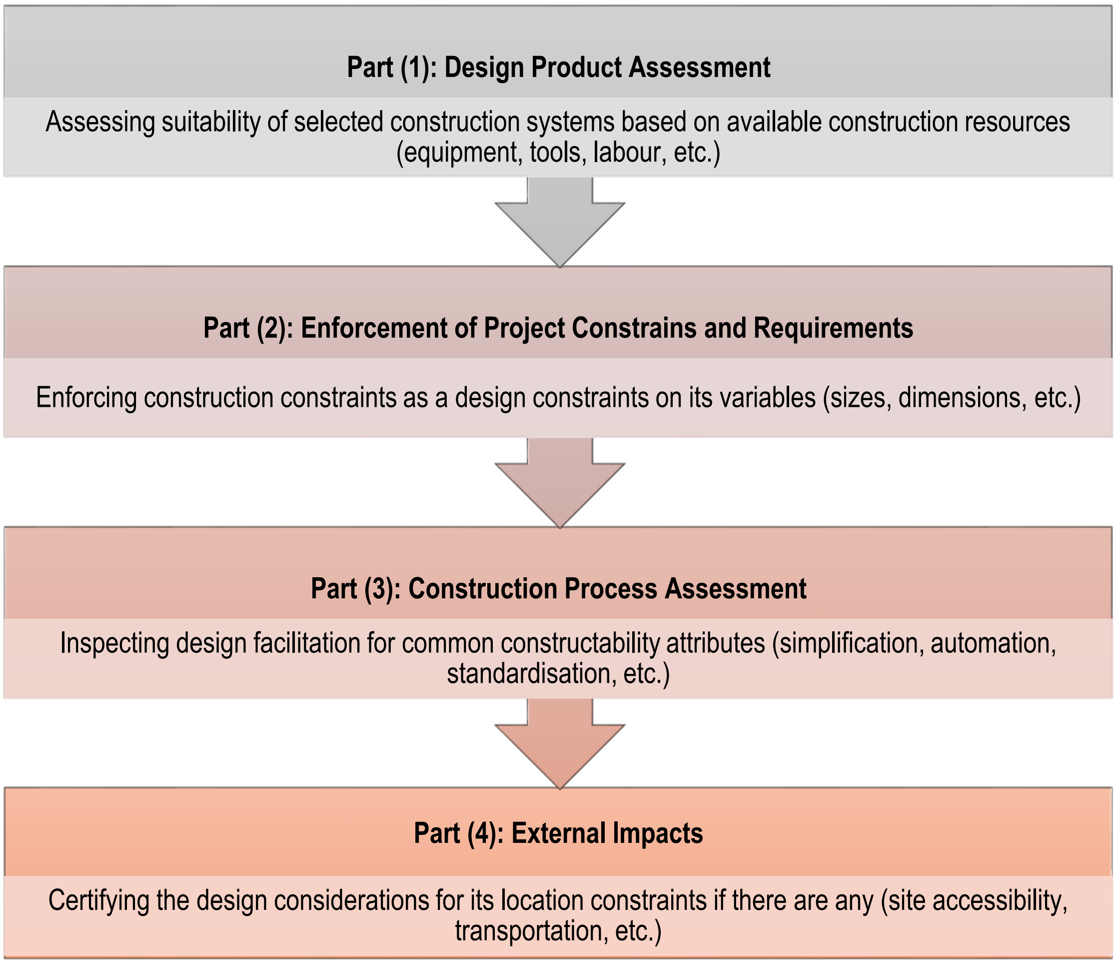


Figure 3-10: Proposed strategy to model constructability in buildings design

Consequently, this reveals the necessity of the following sections in the proposed CM:

- Firstly, inspecting the design product and ensuring the individual constructability of all selected parts. Consequently, this suggests the necessity for examining AEC Systems and matching their decided elements with available resources. [This section is called *AEC Systems* in the proposed model].
- Secondly enforcing the design variables based on construction constraints. Accordingly, this reveals the necessity for a rule-based

system that imposes such limitations on the design variables. [This section is called *Rules of Thumb* in the proposed model].

- All selected elements are checked for their constructability as individual components. The next step is to look at complexities that may arise when they are installed and fabricated together (i.e. during the construction process). Therefore, a section for examining such complexities is required to ensure the design facilitation for construction phase. [This section is called *Complexity* in the proposed model].
- The above sections should provide fair assurance of the design constructability, given that there are no applied limitations due to the project location. However, if there are any, then the design should cater for them to avoid any changes that may arise later. This necessitates a section for certifying design considerations for the location. [This section is called *Location* in the proposed model].

This, therefore, justifies the necessity for the four modules of the proposed CM (i.e. AEC systems, Rules of thumb, Complexity and Location) to model constructability in its multidimensional aspects. While such design of the knowledge repository has implications on how it will be collected and formulated, as discussed in section 3.3.2 and 3.5.3. It however comprehensively enables the assessment of all constructability aspects quantitatively and qualitatively. The designed CM can accommodate all kinds of knowledge that are required to assess all constructability aspects covered by previous assessment systems collectively, presented in Table 2-9.

3.6. Adaptation of the previous assessment concepts in the proposed system

The proposed method is built using lessons learned from previous studies. It seeks to employ their strengths and avoid any weaknesses identified in relevant literature or in the conducted review for related works as a part of this research. Starting from this point, this work aims to improve on current work, and provide alternative approaches for simplification purposes, while making use of available information technologies such as BIM. Specifically, these research efforts provide major input for the development of the constructability concept.

- Classification of design-relevant construction knowledge was inspired by Constructability Information Model (CIM) developed by (Hanlon and Sanvido, 1995), in which key attributes of constructability information is classified, stored and retrieved accurately and efficiently throughout the project (Kannan and Santhi, 2018). It enables capturing all aspects related to constructability (i.e. quantitative and qualitative) to inform decision making as discussed in the previous section. As such, the model is still being adopted by researchers for its comprehensiveness, especially with studies focused on modelling constructability of concrete formwork (Kannan and Santhi, 2018).

  Though the model was originally introduced to classify constructability information for reinforced-concrete structures, its scope enables much broader application, with necessary adjustments. This includes expanding its information model to accommodate different types of buildings, as well as their associated constructability attributes. The study adopted only the hierarchy of the information model, but not the way of conducting assessment, since it was based on CAD drawings, while here BIM is employed. This will enable the formulation of an object-based constructability knowledge that facilitates the reasoning process with BIM objects, as explained in section 3.5.2 and 3.5.4.
- The idea of assessing the design constructability based on its used construction systems was inspired by the scheme design buildability assessment model (SDBAM) (Lam et al., 2012). However, the construction systems here are defined based on BIM classification for design elements. This is to facilitate knowledge acquisition and reasoning, as explained in section 3.5.

3.7. Summary

This chapter analysed the constructability concept and its utilisation for construction knowledge to influence the design stage. It also reviewed knowledge-based systems and associated challenges with their development.

Consequently, it assisted in identifying issues with current constructability assessment approaches. This paves the way to look at these issues separately, and to propose practical solutions to address them. To design for constructability, the basis of the proposed assessment system was introduced, as well as the underlying rationale. A detailed description of the framework and its components is presented in the next chapter.

4. A Proposed BIM-Based Constructability Assessment Framework

4.1. Introduction

This chapter expands on the framework to be employed for assessing building design constructability utilising BIM and knowledge-based systems. It seeks to devise an assessment model that enables implementation of the constructability concept. A description of the proposed constructability modelling framework, its components, and its interaction with building product models with BIM-enabled tools for constructability analysis is elaborated upon in the following sections.

4.2. Demand for a framework

The literature review revealed the challenges associated with designing for constructability, and the observed difficulties when deciding between design alternatives from a constructability perspective. Considering the complexity of current building design processes, there is a necessity to provide a decision support tool enabling the design-constructability assessment, and hence an improvement in their performance accordingly.

4.3. Description of proposed framework and its components

This section introduces the constructability modelling framework and its components. It describes the framework elements and how they contribute to the overall assessment mechanism when modelling design constructability. Figure 4-1 illustrates the proposed framework to assess design constructability using the embedded information within a BIM. It demonstrates the modelling framework in three parts: the conceptual design model, the CM, and the AM enabling the decision-making phase based on constructability considerations.

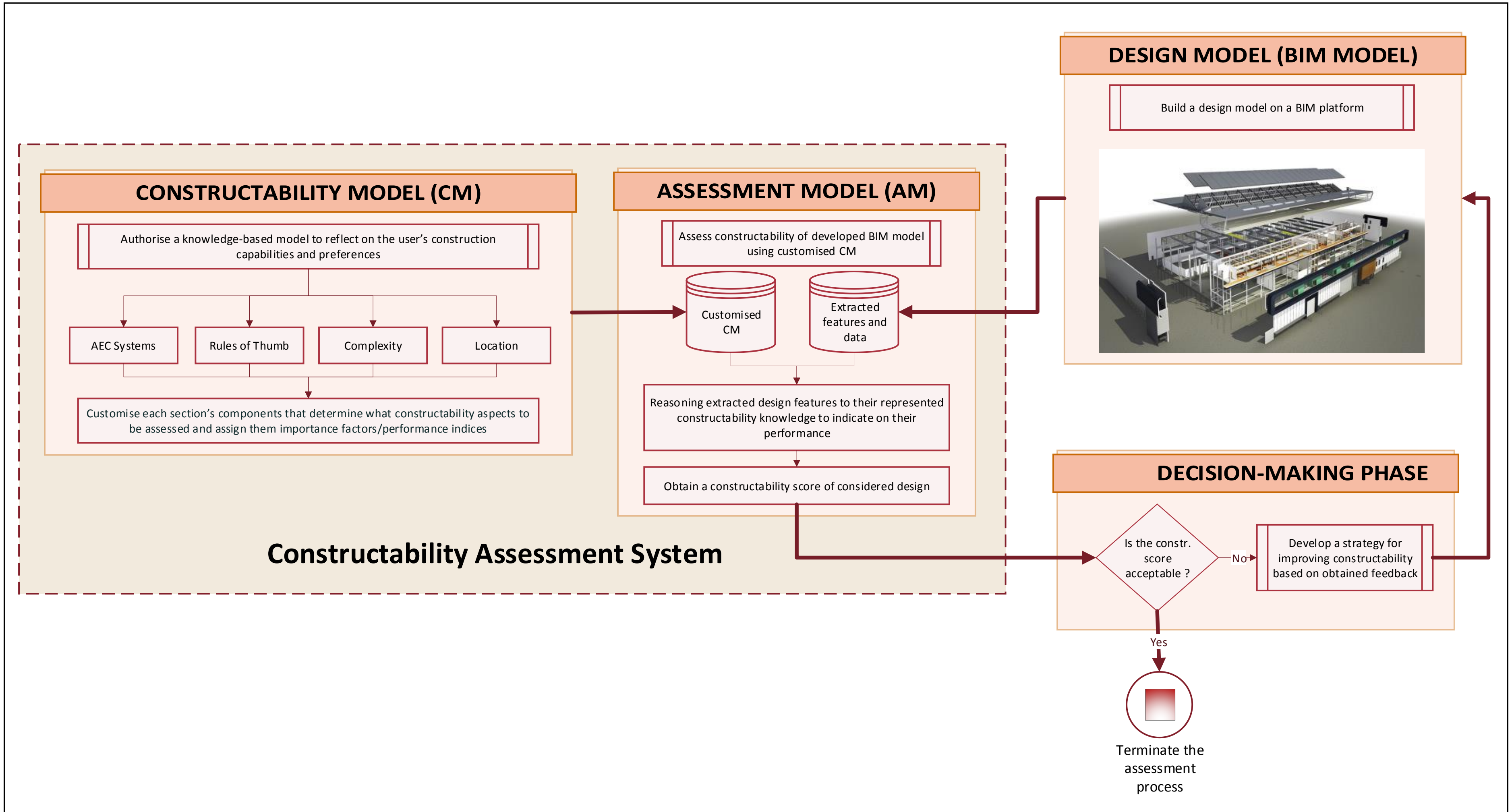


Figure 4-1: Components of the proposed framework

4.4. Conceptual design models: BIM-data representation and required level of detail (LOD)

The conceptual design model refers to the digital building model that needs to be assessed for constructability. At this stage, designers build their conceptual model using BIM authoring tool to a suitable LOD, (Table 4-1). Such information is an essential input for the assessment process, and consequently any delivered outcomes. Therefore, BIM-enabled tools should allow for features extraction from their product models for the purpose of constructability analysis.

The design-relevant constructability knowledge defines what features are required to model design constructability. Consequently, this describes the level of information that should be made available in a BIM model to enable its constructability assessment (Figure 4-2). To articulate this, Table 4-1 specifies the satisfactory LOD of BIM models to function the assessment of various model parts (AEC Systems, Rules of Thumb, Complexity, and Location).

Figure 4-2: BIM LOD 100, 200, 300, 400 & 500 (Oussama, 2018)

Table 4-1: Required LOD of assessed BIM model to enable constructability assessment

Model components	***Necessary information to configure the CM***	***Satisfactory LOD***	***Necessary information to perform the AM***	***Satisfactory LOD***
AEC Systems	Names of used materials within design elements to enable their reasoning when actual models are assessed.	LOD 100 - Concept Design	Elements parameters that enable the calculation of material quantities.	LOD 100 - Concept Design
Rules of Thumb	No inputs from the model at this stage, however, a better understanding of the model and its components suggests required rules to be defined.	LOD 100 - Concept Design	Depending on defined rules, the model should provide values for their parameters such as sizes, dimensions etc.	LOD 200/ 300 - Schematic Design/ Detailed Design
Complexity	No inputs from the model. Users need to decide on which design complexities and constructability qualities are assessed.	LOD 100 - Concept Design	Based on enabled complexities, models should provide values for their equations' parameters.	LOD 200 - Schematic Design
Location	No inputs from the model, only specifications data and legislation requirements are needed (e.g. transporting abnormal loads).	LOD 100 - Concept Design	Based on applied restrictions, models should contain details that enable verifications (e.g. girder dimensions)	LOD 200/ 300 - Schematic Design/ Detailed Design

4.5. CM

As introduced in section 3.5.5, the CM consists of four main components: AEC Systems, Rules of Thumb, Complexity, and Location, as Figure 4-3 illustrates. The model components are designed to accommodate both quantitative and qualitative assessment of the design constructability. They are configured by users to match their construction capabilities. Such configuration includes constructability aspects to be assessed and their weights, constructability indices of considered construction materials to compose various construction systems, and values of any restricted design parameters to be verified in the design under assessment. The importance of these components is balanced using weighting factors assigned based on their contribution towards satisfying the design objectives.

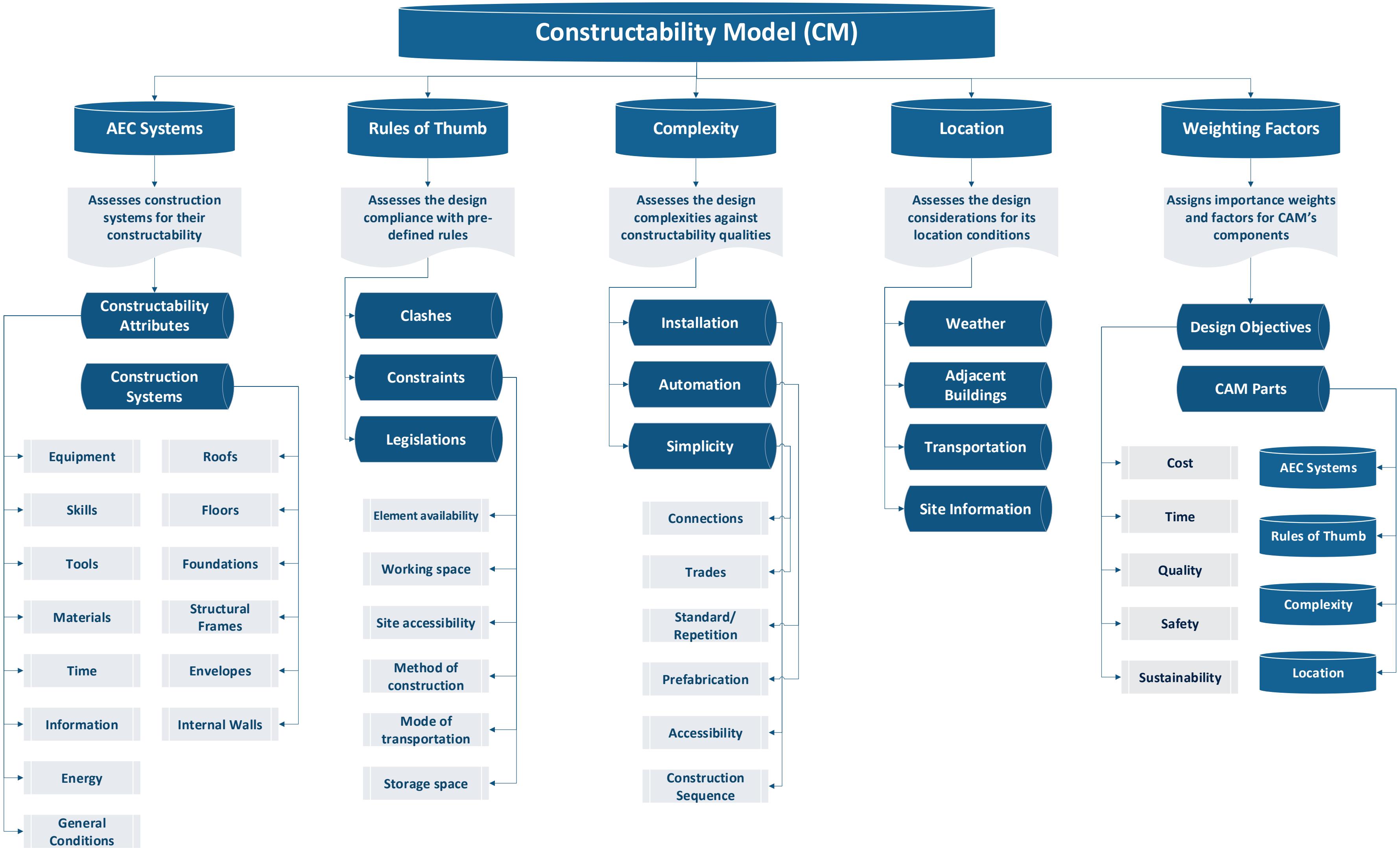


Figure 4-3: Proposed CM hierarchy

The CM is the knowledge-based model used for benchmarking the constructability of design solutions. It is typically customised by the design team to impose their design objectives and meet particular project requirements. It can be seen as container, storing constructors' capabilities in terms of what they can build, and defining their preferences using various construction systems and methods. A specialised CM would typically be authored once for every type of project (e.g. multi-storey office buildings, multi-story car parks, and residential buildings, etc.), and is re-used many times for similar project types.

The CM is designed to cater to diverse perspectives and design products. It seeks to assess different constructability qualities using various methods and techniques of analysis and assessment, as explained further below. The user of the implemented framework is the key player who shapes the CM, selects its components, and scores their importance. Such models objectify the subjective qualities of constructability, represented in numerical scores. These are to be mapped onto design features to formulate an overall unique score that informs on the design constructability, relative to the capabilities and resources of a particular constructor.

4.5.1. CM: AEC Systems

This part of the model seeks to assess the design constructability based on its used construction systems (e.g. slabs, floors, and foundations). It is designed to ascertain the constructability of design elements relative to the availability of construction resources (tools, equipment, and skills etc.). The model adopts a numerical system to score the constructability of different design elements (i.e. beams, columns, etc.), categorised under different construction systems, with respect to a considered constructability factors and attributes (Table 4-2). Table 4-3 demonstrates a sample of such factors that are covered within the scope of this study. Whilst this is not an exhaustive list and is merely extracted from literature (discussed in section 3.6) to demonstrate the conceptual framework. However, the system allows its users to add/delete/amend such lists as required to suit their requirements, as explained in section 3.5.2. It shows the greater flexibility of the system to enable its users to observe constructability from their perspectives and only theirs, which has not been achievable in existing assessment systems as exhibited in section 2.9.

Following the establishment of considered constructability factors and construction alternatives, they are then to be rated for their constructability based on users' input. The system employs AHP to develop the targeted scores, following the procedure described in section 3.3.1.1. Obtained scores rank the constructability of design elements from users' perspectives with accounting for their design preferences and constraints. Thus, it enables the deployment of captured construction knowledge and experience from human to the design platform, enabling designers to quantify what is not quantifiable now, usually requiring manual reading and interpretation. As a result, users can decide between design alternatives based on available resources as well as demonstrated capabilities to build. It also establishes an element-based system to model design constructability rather than assessing vague constructability factors for the entire design.

Table 4-2: Example of AEC Systems content scoring the alternatives of various construction systems

Construction system	Weighting factors	System design alternatives	Constructability Index
Floors System	W floors (%)	Precast slab with *in situ* topping	CI floor [1]
		Steel deck with *in situ* concrete topping	CI floor [2]
		Flat slab	CI floor [3]
		In situ RC slab	CI floor [4]
		Prestressed concrete slab	CI floor [5]
Roofs System	W roofs (%)	Stone-coated metal	CI roof [1]
		Interlocking roof tiles	CI roof [2]
		Metal roofs	CI roof [3]
		Concrete tiles	CI roof [4]
Structural Frames System	W str.fr. (%)	Precast RC frame	CI st.fr [1]
		Steel frame	CI st.fr [2]
		In situ RC frame	CI st.fr [3]
		Steel encased in concrete	CI st.fr [4]
Foundations System	W found (%)	Isolated footings	CI found [1]
		Raft foundation	CI found [2]
		Piles	CI found [3]
Envelopes System	W envel. (%)	Structural glass assemblies	CI envel [1]
		Precast concrete panel cladding / features	CI envel [2]
		Metal composite panel cladding / features	CI envel [3]
		Curtain walling	CI envel [4]
		Concrete block/ brick	CI envel [5]
Walls System	W walls (%)	Brick wall	CI wall [1]
		Concrete block	CI wall [2]
		Masonry wall	CI wall [3]
		Fiberglass mat gypsum panels	CI wall [4]
		Fiberglass reinforced panels	CI wall [5]

Table 4-3: A sample of constructability factors that can be employed to compare between various construction systems

Rational attribute	***Sub-attribute***	***Factors to consider***
Information	Coordination	Required level of information to allow for the necessary coordination with other trades during the system construction.
	Construction	Required level of information to perform the construction process properly and accurately.
	Tolerance	The flexibility of the system for changes due to unforeseen circumstances/ issues.
Skills	Labour	Amount and type of labour required to build the considered construction system.
	Supervisory	Required level of supervision during the construction, given the criticality of the system.
	Craft	If the construction of the considered system demands a high level of skilled craft to perform the task.
Equipment	Type	Consideration for the required specifications of the equipment to build the system and satisfy any standards that may be applied.
	Amount	The quantity of required equipment to perform the task according to a defined construction program.
Tools	Type	Specifications of required tools to build the considered system and if any standards apply.
	Amount	The quantity of required tools to perform the task according to a defined construction program.
Materials	Amount	Consideration for the quantities of materials and how their availability in the current market might affect the construction process.
	Rates	Specify the cost aspect of materials type to differentiate between them.
Time	Lead time	Allowance of the selected system for a lead time during the construction process.
	Coordination	Considerations for the consumed time to coordinate the construction of the system.
Energy	Type	Availability of required energy type to construct the selected construction system.
	Amount	Availability of required energy amount to construct the selected construction system.
General Conditions	Facilities	Suitability of current available facilities to construct considered construction system.
	Services	Suitability of currently available services to facilitate the construction of the system.
	Systems	Allowance of the current system to accommodate the construction process of considered elements.

4.5.2. CM: Rules of Thumb

This feature of the CM allows users to assign a set of rules that need to be satisfied in design solutions. It employs a rule-based system to assess the design constructability based on its embedded information. Such rules are typically applied to impose constraints on the design variables which may affect the construction process later. These include limitations related to design spacing, layout, dimensions, etc.

The rationale behind the introduction of the Rules of Thumb module within the proposed CM is due to many reasons. These include:

1. To enable a comprehensive assessment of constructability, of which parts of its attributes are asserted only through satisfying specific conditions. Meeting requirements of such conditions ensures the avoidance of a problematic matter that will otherwise happen. It includes design constraints that are introduced due to site conditions or logistics limitations. As such, it entails a rule-based system that verifies the observation of such limitations in proposed design solution.
2. To benefit from the established practice of designing for constructability. To date, construction companies and practitioners came to develop their own approaches, to assert design constructability. This includes methods such as checking list analysis or a lessons-learned system at particular stages of design process (30, 60, or 95% design) (Soibelman et al., 2003). These approaches are based on an important element of constructors accumulated experience and can accurately inform constructability on future ventures. Therefore, they should be an essential part of any developed assessment system to maintain the developed practice.
3. To exploit the use of BIM technologies and features modelling techniques in designing for constructability. With the availability of rich repositories of design data and the means to enquire, check and validate their status, a rule-based system can be deployed to automate the process of constructability review.

4. While the AEC System section targets to objectivity the subjectivity of user's tacit knowledge through the production of representatives scores that can accordingly mirror its content, it is sometimes simpler to deal with objectified measures to impose such knowledge. This can be accomplished through processing of such tacit knowledge to produce rules that may represent its content. While the induction and validation of such rules demands extra efforts from knowledge holders. It however, delivers tangible and easy to understand feedback when these rules are executed. Typical outputs of rule-based systems are ones or zeros (i.e. satisfied or non-satisfied), which in constructability can be interpreted constructible or non-constructible. Furthermore, it highlights particular elements that requires attention to address their identified issues, enabling feedback receivers to improve the performance.
5. With the tendency towards design automation utilising techniques and tools such as AI is becoming dominant, aspects such as designing for constructability requires a human-based elicited knowledge intelligent system. However, the implementation of such systems is still an issue due to challenges related to the knowledge formulation processes and adopted approaches. This research, through the implementation of Rules of thumb module, takes an important step towards the digitalisation of human element knowledge. It brings the perspective of linked digital data to assist in the development of the forever sought object-oriented knowledge. It seeks to cluster extracted construction knowledge to design features to facilitate the reasoning process. Implementation aspects of such database architecture are further discussed in section 4.5.5.

The prospect of using a rule-based system to automate design checking and analysis processes is broad and can be extended to cover many aspects. It could lead to deviate from the focus of this study, which is analysing design features from constructability perspective. Thus, the Rules of Thumb part focuses on demonstrating the concept implementation to design for constructability. Aspects that are covered within the scope of this study include:

4.5.2.1. Constructability constraints:

This Rules of Thumb feature seek to integrate downstream project constraints into the design environment to ensure constructability. It deals with setting up a rule-based system that checks design compliance with construction requirements. The latter constrain design variables, such as the section sizing and dimensioning of the structure layout. Therefore, constructability knowledge is used here to interpolate all potential issues into endogenous constructability factors that can be imposed as design rules. For instance, to use available formworks requires constraining beams or columns to specific dimensions.

Constraints can be due either to exogenous or indigenous factors to the project environment (Jiang and Leicht, 2014). Exogenous constraints represent factors that are beyond the control of design team/constructors and will have implications on the selected construction materials/method (e.g. the lack of specific steel tiles that would prevent using a particular type of cladding). On the contrary, indigenous constraints are introduced to cover deficiencies in the contractor construction capabilities (e.g. lacking specific construction equipment).

4.5.2.2. Design clashes:

Successful management of the building design coordination process is critical to the delivery of construction projects (i.e. constructability) (Mehrbod et al., 2019). Existing research estimate that 57% of design coordination errors will directly impact construction costs, with some, estimated the figure of over 26,000 USD per design error (Lee et al., 2012). As constructability seeks to identify potential problems and obstacles at the design stage and work to resolve their causes to reduce or prevent errors, delays, and cost overruns in the construction stage. It, therefore, essential to incorporate this aspect in the scope of the assigned constructability score for a design solution to incite the observation and resolution of design clashes. This became more achievable nowadays with contemporary design tools that can assist in a detailed virtual clashes analysis for enhancing constructability.

4.5.2.3. Legislation and regulation:

There is a fine line between using the Rules of Thumb feature to verify constructability of design elements, and to check the compliance of these elements against specific regulations or code of practice. While rules of the former rely on a users' related construction experience to guide the process, the later employ knowledge formulated by governments and professional bodies to be met in design products.

That said, this study claims that designing in compliance with mandatory legislation constitutes is an important part of designing for constructability, the primary goal of the research. This is because ignorance of these rules has implications on the streamlining of the construction process. This is typically by interrupting the process, re-doing some packages of the work, or not commencing the construction at all.

Some studies have already attempted to address the subject by covering aspects such as automatic regulatory compliance check of construction projects (Zhang and El-Gohary, 2015), representation of building codes using object-based rules and Industry Foundation Classes (IFC)-based design model to verify accessibility regulations (Ding et al., 2006), the Construction and Real Estate Network (CORENET) project of Singapore used FORNAX library (i.e., a C++ library) to represent regulatory rules, e.g., building control regulations, barrier free access, and fire code (Khemlani, 2005). However, this study seeks to feature the aspect of regulatory compliance of design features in the proposed assessment framework. Through the reflection of this element on the delivered constructability score, it acts as an incentive to satisfy regulatory rules to improve constructability status.

4.5.2.4. Lessons Learned:

Lessons learned, or what is termed as "professional experience", comprises key concepts that are evolved throughout the construction practice from past project experience. Typically, it describes a specific problem or situation and a solution to that problem accompanied by suggestions for future problem avoidance (Jiang, 2016).

Lessons learned represent an important element of constructors related experience, and as such, can accurately inform constructability on future ventures. However, they are normally associated with certain challenges in their practical implementations. An overview of these challenges and how are approached by the study, are discussed in the below section.

4.5.2.5. Associated challenges with the implementation of rule-based systems:

Generally, design rules have been commonly employed in AI tools to avoid the subjectivity of constructability quantification, providing designers with more tangible assessment outcomes (Jiang, 2016). However, they face many challenges in their practical implementations. This section provides an overview of such common challenges and explains the study approach in dealing with them in the proposed mechanism.

Typical challenges at the stage of rules representation:

The main challenge has always been how to classify accumulated construction knowledge and experience, define design rules that represent them, and deploy these rules into the design environment to be validated (Jelev et al., 2017, Jokste and Grabis, 2017). This is mainly due to the abstract nature of such instances (Final and Hietanen, 2006), uniqueness of each design project (Lee et al., 2015), and the vast spectrum of potential end-users (Junior et al., 2018). While the practice has adopted different approaches to documenting and reasoning lessons learnt, it is common to rely on human interpretation to carry out such task (Kliegr et al., 2018). This has resulted in ignoring this important element of knowledge, or not utilising it to its maximum benefits during the process.

Although the primary goal of the introduction of Rules of Thumb within the proposed assessment system is to allow constructability assessment in its multidimensional aspects. However, the study brought the prospect of how to address the flagged issues in the system implementation to ensure its practicality. As such, the study established a mechanism that can be adopted to manage the classification of users' knowledge to facilitate the implementation of a rule-based system. The description of such a mechanism is explained within the guidance customising Rules of Thumb CM module, featured in section 4.5.5.

Typical challenges at the stage of rules execution:

One of the main obstacles at this stage is the integration of defined rules with the design environment to be executed (Jelev et al., 2017). Their transformation into a machine-readable language may carry an element of challenge for non-programmer end-users (Sydora and Stroulia, 2019).

The study approach to address this issue is through the implementation of generic design rules packages that can be personalised by end-users. Particularly, with the case that the rules are object-oriented formulated, targeting to validate certain values of design elements parameters (e.g. dimensions, materials properties, etc.), due to various reasons from the user perspective. Hence, the same rules can be re-used for enforcing various requirements. This eliminates the necessity for model users to acquire programming skills in order to add new design rules. While this may accommodate constructability rules that are in common among various users. This might not be practical in some special cases. However, with the industry tendency towards using flexible and powerful design tools, acquiring programming skills to design are becoming an essential requirement. Additionally, using innovative programming means such as visual scripting (e.g. Dynamo, Grasshopper 3D, etc.) are facilitating such remits (Kensek, 2015).

Another major challenge in the proposed CM is the lack of satisfactory LOD to operate defined rules, because an enabled rule essentially relies on the BIM platform to feed the values of parameters (Solihin and Eastman, 2015). This challenges the system on how to proceed if a specific design parameter falls short of targeted LOD. Fischer (1991) advises that the encountered issue could be addressed with supplementary knowledge acquisition to tackle the limitation of these rules. Alternatively, more complex but less brittle reasoning-based mechanism systems can be used, which mimic human reasoning.

This can be tackled through implementing an intuitive system that notifies users of any issues during the rules execution. The proposed CM also seeks to design an effective rule system that accounts for design stages and their LOD, while accommodating the uniqueness of the considered project. These are discussed and explained with the respect to the implemented aspects (i.e. Constructability constraints, Design clashes, Legislation and regulations and Lessons learned), presented in section 4.5.5.

4.5.3. CM: Complexity

This part of the CM investigates how the selected design facilitates its construction. It inspects some design qualities against common constructability attributes. Such attributes are commonly mentioned in the literature as characteristics of constructible designs, or as some provided guidelines for designers to observe in their designs, to facilitate their constructions. However, there are no tangible measures provided to examine the level of their existence in a specific design. Some studies have tried to quantify these attributes on design solutions, adopting questionnaires and interviews with experts to acquire necessary information, but little has been achieved in this regard. This is because the concluded recommendations were too general to offer firm indicators of how well the design responded. For example, standardisation of column dimensions would facilitate their construction, but this does not consider the extent to which such standardisation should be sought. On the contrary, some recommendations were too specific, and could only be applicable to particular cases (Fischer and B. Tatum, 1997). For instance, using precast components of 50kg would restrict their lifting to applications using cranes.

This research seeks to take this further forward by proposing a set of formulas that quantify constructability attributes in observed designs, aiming to describe the behaviour of designs towards defined constructability attributes using their variables. These formulas are derived logically, using engineering common sense. The Complexity section could include various aspects to be assessed, however, this research addresses the following constructability qualities.

4.5.3.1. Simplicity

The simplicity or complexity of a design is an inherently subjective matter, and a very tiny detail could turn a simple design into a complex one, or vice-versa. This section inspects some critical aspects that are commonly flagged up, but which are rarely addressed. Also, any assigned indicators resulting from this assessment would direct users to take the best course of action in improving their designs, no matter how slight their impacts. These aspects include design connections and trades.

- *The simplicity of design connections*

Design connections can be considered as a critical element in determining design constructability. They usually play a crucial role during the construction process, and hence need to be included as a part of any assessment. In addition, the previous sections of the CM (AEC Systems and Rules of Thumb) put focus on individual design components (design products) rather than their compatibility with each other (construction process). Furthermore, the tendency of the construction industry is shifting towards precast/ prefabricated structures, and hence their connectivity should be an important matter of consideration. The customisation of this section and how connections are assessed in the actual design are described in the following sections.

- *The simplicity of trades (host and hosted components)*

Obviously constructing a plain wall without any windows or doors is a much easier construction, since there is no hassle regarding the trades, and the sequence of components. Therefore, this category looks into the simplicity of design features from the perspective of involving many trades. This is represented in design model walls, and how adding different types of windows and doors complicates the task of their construction. The concept could be expanded to cover other similar parts, such as ducts and staircase openings for floors and roofs.

4.5.3.2. Automation

This part examines the design facilitation for construction automation. This includes design standardisation and repetition, as well as using novel construction methods such as prefabrication.

❖ *Design standardisation and repetition*

It has been widely agreed that standardising design solutions and replicating selected elements, sections, shapes, and sizes will massively improve constructability. However, the challenge is how to examine this in any design and to determine its impacts. Since all such information is now available within the design platform, such data could easily be presented to assessors as an incentive to encourage them to standardise their design models.

❖ *Pre-cast/ prefabrication coverage within a design*

Pre-cast components (e.g. concrete elements) and prefabricated structures are increasingly utilised in the construction industry, for obvious reasons, including the following:

- Control of end products' quality to the specifications under factory (rather than site) conditions.
- Reduction of labour congestion at the site and necessary trades coordination.
- Reduction of wastage, such as timber formworks or any temporary site works.
- Less waiting time between activities that contribute to accelerate the construction process.
- More control on the site, with advanced planning for deliveries which improves site cleanness and tidiness.
- Enhanced site safety.

However, there are some drawbacks that need to be accounted for when deciding to use prefabricated components, such as:

- The demand for early planning with a high level of coordination between those involved on site.

- The demand for high attention to joint details, to ensure the integrity of the connection between pre-cast and *in situ* cast components.
- The potentially high cost if specific moulds are to be manufactured for producing unfeasible quantities, which might not compensate for the initial cost.
- Risk of being damaged by other trades during the construction.
- Less flexibility to corrections and modifications that may be required at later stages.

As noted previously, the possibility of accessing such information from BIM models facilitates their inclusion as constructability indicators. However, any connectivity challenges that may arise due to compatibility or lack of coordination should also be accounted for in Constructability scores.

4.5.3.3. Installation

This section accommodates the complexity of the installation process represented by site accessibility and the construction sequence in the proposed CM. Both are categorised here, as they will be assessed using visual aids features available in modern design tools, such as Navisworks.

❖ *Accessibility*

Accessibility of equipment, tools, and workers to working zones is vital in the construction stage. It is now possible to animate the construction sequence and visualise these aspects, identifying any critical issues, therefore it is recommended to make use of such features to decide on design constructability. This enables assessors to better understand designs, identify potential challenges that may arise, and to work to address them before they actually occur.

❖ *Construction sequence*

The construction sequence is a vital input element in any scheduled construction programme. Therefore, critical analysis of the construction program with more focus on any identified critical path would flag up any potential challenges during the design construction. This could be integrated with logistic information, site conditions, and the surrounding environment, to achieve realistic scenarios.

4.5.4. CM: Location

This part of the model assesses 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 the way they are installed. Additionally, site accessibility and proximity to delivery sources play a vital role in choosing construction methods (e.g., precast or *in situ* casting for concrete components). In the proposed CM, 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. Such extracted information includes:

1. The construction schedule linked with weather forecasts to decide on suitable construction methods and appropriate working hours.
2. Selected construction materials and components within the design, delivery requirements, site accessibility, and the availability of storage space. Coordinating for just-in-time deliveries to avoid double lifting.
3. Selecting the foundation system and its suitability for site soil conditions.
4. Compliance of the design with legal requirements for its adjacent buildings (e.g. the Party Wall Act in the UK, which prevents and resolves disputes related to party walls, boundary walls with neighbours, and excavating near buildings).
5. Any other restrictions laid on the design due to its surrounding environment, the availability of utilities, and accessible infrastructure facilities.

4.5.5. CM Customisation

As mentioned in previous sections, users will need a CM to perform the assessment process. This can be selected from previous customised models or any standard models developed by local authorities. However, they need to be appropriate for the purpose of the assessment, given the considered design model for examination as well as its potential constructor. Alternatively, an adjustment can be made to these models if needed. This will be the case if a new dominant material is used that was not initially included on the defined models.

Users can always customise new CM for different types of buildings. A good practice of archiving for these models would facilitate their reusability or recall necessary amendments. For this reason, it is recommended to have key information that helps in recognising the nature of any CM, and what types of designs can be employed for their constructability assessment. Also, the viewing option for any personalised CM can provide more details, assisting in identifying their suitability for a specific case.

Customisation of any CM and the scoring process it includes should be performed by key stakeholders to have their input on what will act as a reference model. Ideally, they should truly reflect their construction capabilities and any expressed preferences between design alternatives. The involvement of potential constructors is very crucial to the process, contributing significantly to the accuracy and correctness of subsequently obtained results. However, it is still possible to have other parties not involved in the project customise the model, to be used by assessors. Such parties could act as regulators or legislators for the construction industry in the region, to improve its productivity. This includes but is not limited to governmental bodies, national and international institutions, construction bodies of knowledge, and any local committees appointed on specific projects, such as consultancy firms. They usually aim to introduce good practice in the construction sector and provide their recommendations based on gathered experience and lessons learned. Table 4-4 demonstrates the possible scenarios that necessitates customising new or using an authored CM.

Table 4-4: Potential scenarios that entail the customisation of a new CM

Party customising model	Purpose of customisation	Parties using model	Purpose of use
Design team and project stakeholders	To review design constructability on an ongoing basis along the design process.	Design team, including clients	Ensuring design alignment with defined project objectives (cost, time etc.)
Consultancy firm or clients' representation	To assess the constructability of a design developed by a third party	Consultancy firm or clients' representation	Checking design compliance with client requirements and objectives
Contractor or sub-contractor	To model constructability capabilities for various designs	Same contractor or sub-contractor	Investigating bidding feasibility for design
Contractor or sub-contractor	To model constructability capabilities for various designs	Same contractor or sub-contractor	Checking ability to construct an assigned design and resources required
Contractor or sub-contractor	To model constructability capabilities for various designs	Project manager and team	Identifying critical parts of any assigned project to avoid any potential challenges that may arise in the construction phase
Governmental or regional institution concerned with construction productivity	To model or regulate the recommended design practice in the region for a better construction performance	Design firms and individual contractors	Checking design compliance with local regulations or seek legislative approval

❖ *Guidance on CM customisation*

This section describes the process of configuring a new CM. It covers the customisation steps of the model to suit the requirements of its potential users. The typical process commences from the scenario shown in Figure 4-4, whereupon the model customiser would be required to:

- Provide basic information describing the new CM. This is mainly to define what it assesses and the suitable types of buildings that the design could be employed for. Such information later facilitates reusability when assessing similar cases. It includes model name, a brief description of the model, the model customiser, project location, and targeted type of building for the assessment. Tagging systems or keywords could be used here if it is thought this may facilitate recognition of recalled CMs.

- Select CM parts that to be customised and hence assessed in design during the assessment process, comprising the four main parts of CM described earlier: AEC Systems, Rules of Thumb, Complexity, and Location.

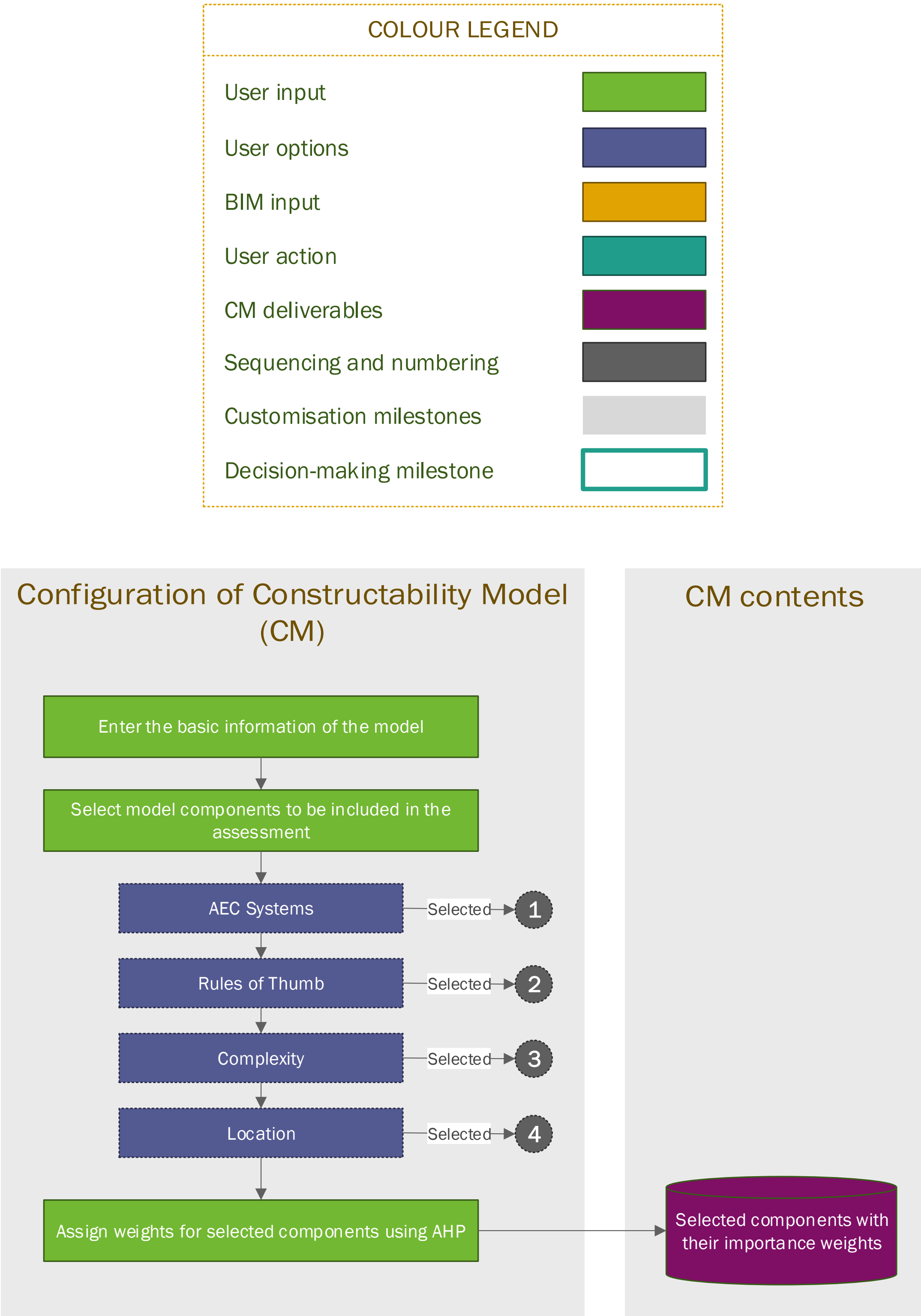


Figure 4-4: Customisation of a new CM

- Assign weights for enabled parts to reflect on their importance towards the overall Constructability score from a user perspective. AHP technique is used to generate these weights. Alternatively, users can opt to assign equal weights if they are equal in importance with respect to constructability performance (i.e. 25% for each part if the four are selected, or 100% if only one component is selected). This will mainly depend on the purpose of CM customisation. For instance, a project manager onsite is more concerned about the potential restrictions of the construction process (Rules of Thumb/ Location) rather than looking into changing the design at this stage represented in the (Complexity) section.
- Customise enabled CM parts accordingly and their components, as described in following sections.

AEC Systems

The main output of this module is a catalogue of construction features and components that are scored for their suitability from a user perspective. They are clustered under various construction systems (floors, slabs, walls etc.) to be used in potential design solutions.

As can be seen from Figure 4-5, the user goes through the illustrated steps to obtain representatives constructability scores. The process starts with the identification of sought design objectives, and scoring their weights using AHP. This varies between users and projects, indicating that the same user may need more than one customised model for various projects. For example, the finishing time of a project may have given priority over other objectives. This will be reflected typically on design construction systems to achieve such objectives. Consequently, it assigns higher importance weights for systems that usually take more project time. This ensures that the user puts more focus on improving the constructability performance of such systems in order to get better scores. An example of this is favouring a precast concrete system over cast *in situ* in a specific project, despite higher upfront financial costs incurred, due to significant savings in time and materials storage.

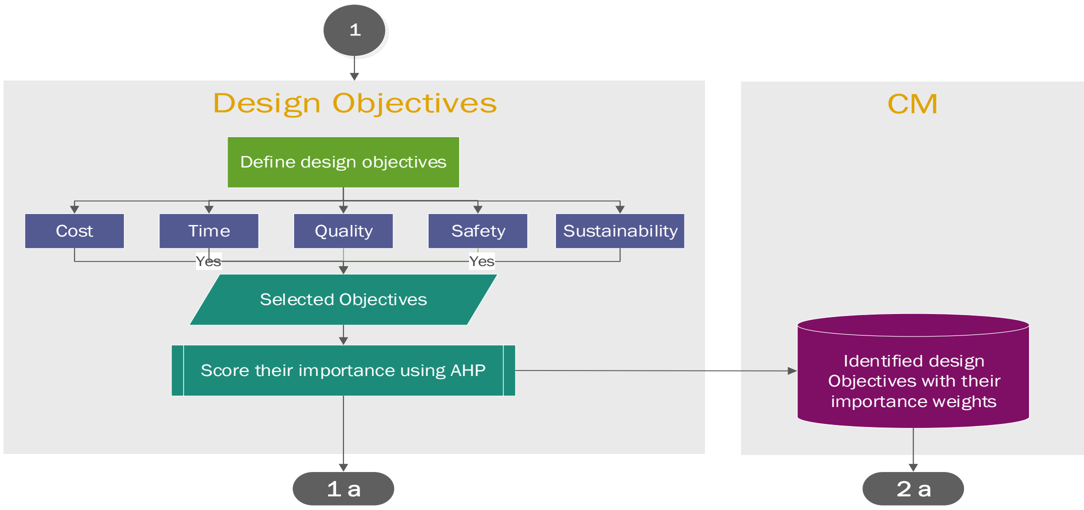


Figure 4-5: Determination of targeted design objectives and their importance

Table 4-5 demonstrates an example of how to balance between selected design objectives and assign them weights, to influence selected construction systems alternatives later.

Table 4-5: Example of scoring the importance of defined design objectives

Design Objective	Cost	Time	Quality	Safety	Pairwise comparisons	Priority vector
Cost	1	3	3	1	$(1 \times 3 \times 3 \times 1)^{1/4} = 1.732$	1.732/4.846 = **0.357**
Time	1/3	1	1/3	1/5	$(1/3 \times 1 \times 1/3 \times 1/5)^{1/4} = 0.386$	0.386/4.846 = **0.080**
Quality	1/3	3	1	1/3	$(1/3 \times 3 \times 1 \times 1/3)^{1/4} = 0.760$	0.76/4.846 = **0.157**
Safety	1	5	3	1	$(1 \times 5 \times 3 \times 1)^{1/4} = 1.968$	1.968/4.846 = **0.406**
Total					4.846	1

Subsequently, the contribution of various construction systems (i.e. floors, roofs, etc.) towards the accomplishment of these objectives can be identified by carrying out a series of pairwise comparisons for the selected construction systems with respect to the objectives. Table 4-6 presents an example of such scoring and how the global weights are attained. The calculations of local priorities are carried out, using the facilitated web-based AHP online calculator as Figure 4-6, Figure 4-7, Figure 4-8, and Figure 4-9 illustrate. While the presented scores in these figures are subjective to the views of their scorers, they demonstrate now users can influence the process to represent their situations. Obtained global weights of construction systems are presented in Figure 4-10.

	A - wrt Cost - or B?		Equal	How much more?
1	(•) Floors	( ) Roofs	( ) 1	(•) 7
2	(•) Floors	( ) Str. Frames	(•) 1	
3	(•) Floors	( ) Found.	( ) 1	(•) 5
4	(•) Floors	( ) Envel.	( ) 1	(•) 7
5	(•) Floors	( ) Walls	( ) 1	(•) 7
6	( ) Roofs	(•) Str. Frames	( ) 1	(•) 5
7	( ) Roofs	(•) Found.	( ) 1	(•) 5
8	( ) Roofs	(•) Envel.	( ) 1	(•) 5
9	( ) Roofs	(•) Walls	(•) 1	
10	(•) Str. Frames	( ) Found.	( ) 1	(•) 3
11	(•) Str. Frames	( ) Envel.	( ) 1	(•) 3
12	(•) Str. Frames	( ) Walls	( ) 1	(•) 5
13	(•) Found.	( ) Envel.	(•) 1	
14	(•) Found.	( ) Walls	( ) 1	(•) 5
15	(•) Envel.	( ) Walls	( ) 1	(•) 3

CR = 5.8% OK

Calculate | Submit

Resulting Priorities

Cat		Priority	Rank
1	Floors	41.1%	1
2	Roofs	3.7%	6
3	Str. Frames	27.9%	2
4	Found.	12.5%	3
5	Envel.	10.9%	4
6	Walls	4.0%	5

Figure 4-6: Weighting factors of construction systems based on contributions towards the satisfaction of cost objective

	A - wrt Time - or B?		Equal	How much more?
1	◉ Floors	○ Roofs	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
2	◉ Floors	○ Str. Frames	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
3	◉ Floors	○ Found.	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
4	◉ Floors	○ Envel.	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
5	◉ Floors	○ Walls	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
6	○ Roofs	◉ Str. Frames	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
7	○ Roofs	◉ Found.	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
8	◉ Roofs	○ Envel.	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
9	○ Roofs	◉ Walls	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
10	◉ Str. Frames	○ Found.	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
11	◉ Str. Frames	○ Envel.	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
12	◉ Str. Frames	○ Walls	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
13	○ Found.	◉ Envel.	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
14	○ Found.	◉ Walls	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
15	◉ Envel.	○ Walls	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
CR = 6.5% OK				
Calculate				Submit

Resulting Priorities

Cat		Priority	Rank
1	Floors	40.4%	1
2	Roofs	4.3%	6
3	Str. Frames	30.5%	2
4	Found.	7.7%	4
5	Envel.	7.0%	5
6	Walls	10.1%	3

Figure 4-7: Weighting factors of construction systems based on contributions towards the satisfaction of time objective

	A - wrt Quality - or B?		Equal	How much more?
1	◉ Floors	○ Roofs	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
2	◉ Floors	○ Str. Frames	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
3	◉ Floors	○ Found.	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
4	○ Floors	◉ Envel.	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
5	○ Floors	◉ Walls	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
6	◉ Roofs	○ Str. Frames	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
7	◉ Roofs	○ Found.	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
8	○ Roofs	◉ Envel.	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
9	○ Roofs	◉ Walls	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
10	◉ Str. Frames	○ Found.	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
11	○ Str. Frames	◉ Envel.	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ◉ 9
12	○ Str. Frames	◉ Walls	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
13	○ Found.	◉ Envel.	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ◉ 9
14	○ Found.	◉ Walls	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ◉ 7 ○ 8 ○ 9
15	◉ Envel.	○ Walls	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
CR = 9.2% OK				
Calculate				Submit

Resulting Priorities

Cat		Priority	Rank
1	Floors	11.3%	3
2	Roofs	10.4%	4
3	Str. Frames	3.6%	5
4	Found.	2.4%	6
5	Envel.	46.7%	1
6	Walls	25.7%	2

Figure 4-8: Weighting factors of construction systems based on contributions towards the satisfaction of quality objective

	A - wrt Safety - or B?		Equal	How much more?
1	◉ Floors	○ Roofs	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
2	◉ Floors	○ Str. Frames	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
3	◉ Floors	○ Found.	○ 1	○2 ○3 ○4 ○5 ○6 ◉7 ○8 ○9
4	◉ Floors	○ Envel.	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
5	◉ Floors	○ Walls	○ 1	○2 ◉3 ○4 ○5 ○6 ○7 ○8 ○9
6	◉ Roofs	○ Str. Frames	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
7	◉ Roofs	○ Found.	○ 1	○2 ○3 ○4 ○5 ○6 ◉7 ○8 ○9
8	◉ Roofs	○ Envel.	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
9	◉ Roofs	○ Walls	○ 1	○2 ◉3 ○4 ○5 ○6 ○7 ○8 ○9
10	◉ Str. Frames	○ Found.	○ 1	○2 ○3 ○4 ○5 ○6 ◉7 ○8 ○9
11	◉ Str. Frames	○ Envel.	◉ 1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
12	◉ Str. Frames	○ Walls	○ 1	○2 ◉3 ○4 ○5 ○6 ○7 ○8 ○9
13	○ Found.	◉ Envel.	○ 1	○2 ○3 ○4 ○5 ○6 ◉7 ○8 ○9
14	○ Found.	◉ Walls	○ 1	○2 ○3 ○4 ◉5 ○6 ○7 ○8 ○9
15	◉ Envel.	○ Walls	○ 1	○2 ◉3 ○4 ○5 ○6 ○7 ○8 ○9
CR = 1.1% OK				
Calculate				Submit

Resulting Priorities

Cat		Priority	Rank
1	Floors	22.1%	1
2	Roofs	22.1%	1
3	Str. Frames	22.1%	1
4	Found.	2.8%	6
5	Envel.	22.1%	1
6	Walls	8.6%	5

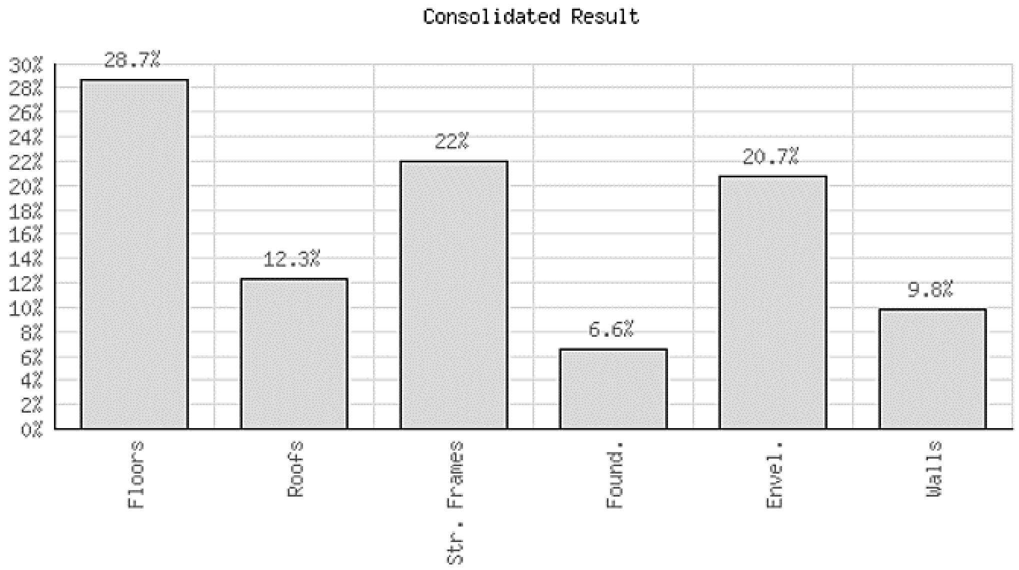
Figure 4-9: Weighting factors of construction systems based on contributions towards the satisfaction of safety objective

Table 4-6: Weights of construction systems with respect to the defined design objectives

Design Objective	Global weight	Const. Systems	Floors	Roofs	Struct. Frame	Found.	Envel.	Walls	Global priority
Cost	35.7%	Floors	1	7	1	5	7	7	41.1%
		Roofs	1/7	1	1/5	1/5	1/5	1	3.7%
		Str. Frames	1	5	1	3	3	5	27.9%
		Foundations	1/5	5	1/3	1	1	5	12.5%
		Envelopes	1/7	5	1/3	1	1	3	10.9%
		Walls	1/7	5	1/5	1/5	1/3	1	4.0%
Time	8.0%	Floors	1	7	1	5	7	7	40.4%
		Roofs	1/7	1	1/7	1/3	1	1/3	4.3%
		Str. Frames	1	7	1	3	3	5	30.5%
		Foundations	1/5	3	1/3	1	1	1/3	7.7%
		Envelopes	1/7	1	1/3	1	1	1	7.0%
		Walls	1/7	3	1/5	3	1	1	10.1%
Quality	15.7%	Floors	1	1	5	7	1/5	1/3	11.3%
		Roofs	1	1	5	7	1/7	1/5	10.4%
		Str. Frames	1/5	1/5	1	3	1/9	1/7	3.6%
		Foundations	1/7	1/7	1/3	1	1/9	1/7	2.4%
		Envelopes	5	7	9	9	1	3	46.7%
		Walls	3	5	7	7	1/3	1	25.7%
Safety	40.6%	Floors	1	1	1	7	1	3	22.1%
		Roofs	1	1	1	7	1	3	22.1%
		Str. Frames	1	1	1	7	1	3	22.1%
		Foundations	1/7	1/7	1/7	1	1/7	1/5	2.8%
		Envelopes	1	1	1	7	1	3	22.1%
		Walls	1/3	1/3	1/3	5	1/3	1	8.6%

In the next step (Figure 4-11), the user identifies constructability factors that usually affect them when constructing their designs, highlighted earlier in Table 4-3. These will act as the basis on which various elements and features are assessed, to reflect constructor capabilities and circumstances. They are usually expressed as restrictions on available construction resources such as equipment, tools, and skilled workers.

Hierarchy with Alternatives										
No	Node	Criterion	Glb Prio.	Compare	Floors	Roofs	Str. Frames	Found.	Envel.	Walls
1.	Design objectives	Cost	35.7%	AHP	0.411	0.037	0.279	0.125	0.109	0.040
2.		Time	8%	AHP	0.404	0.043	0.305	0.077	0.070	0.101
3.		Quality	15.7%	AHP	0.113	0.104	0.036	0.024	0.467	0.257
4.		Safety	40.6%	AHP	0.221	0.221	0.221	0.028	0.221	0.086
				Total weight of alternatives:	**0.287**	**0.123**	**0.22**	**0.066**	**0.207**	**0.098**



Cat		Priority	Rank
1	Floors	28.7%	1
2	Roofs	12.3%	4
3	Str. Frames	22.0%	2
4	Found.	6.6%	6
5	Envel.	20.7%	3
6	Walls	9.8%	5

Figure 4-10: Construction systems global priorities and ranking

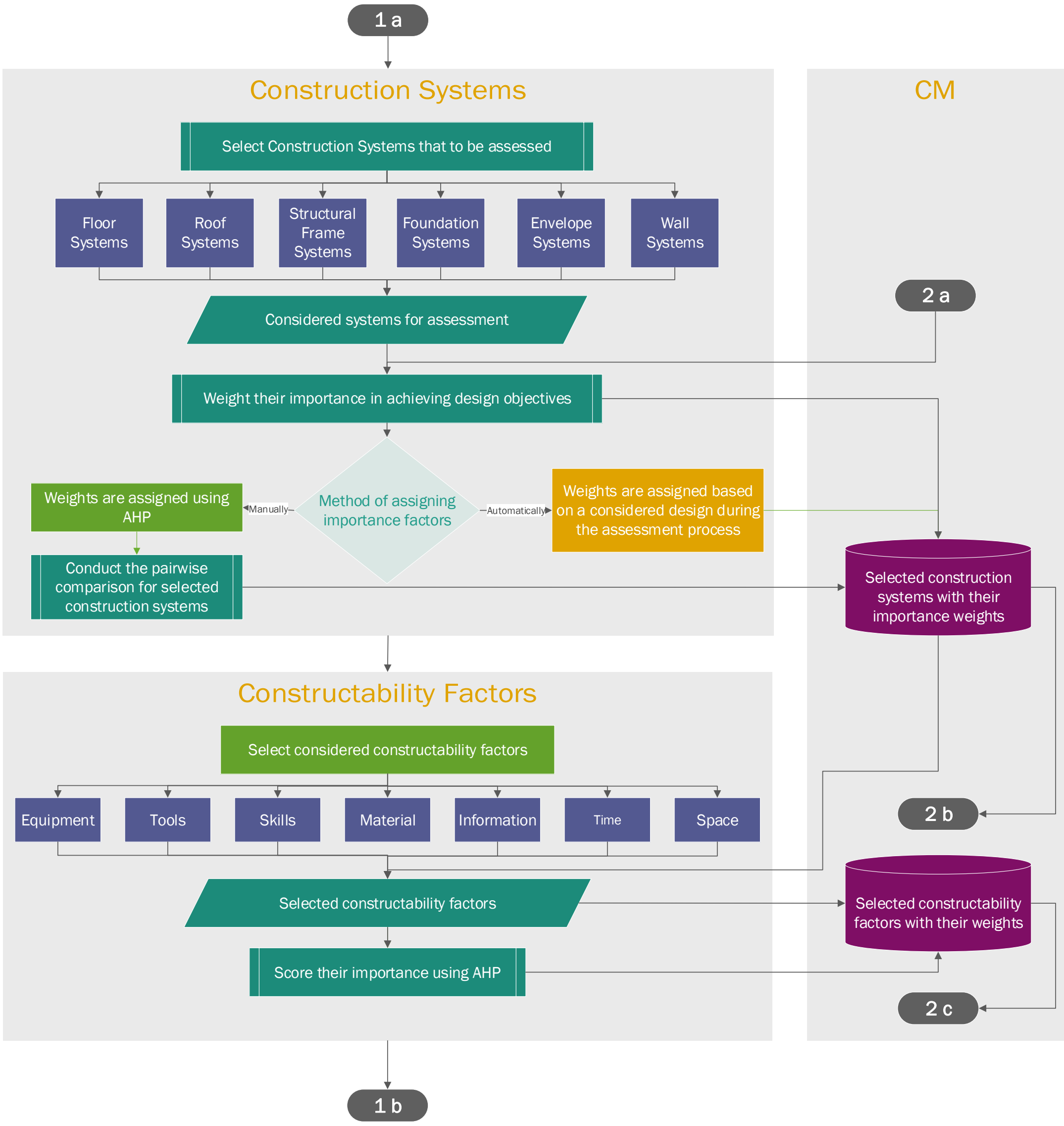


Figure 4-11: Determination of assessed construction systems and criteria of assessment (constructability factors)

To demonstrate how this works, if a user is to decide between various types of external walls (e.g. brick, concrete, masonry, etc.), they will go through a pairwise comparisons to rate their performances with respect to the considered constructability factors. For instance, Figure 4-12 shows that the factors skills, equipment, tools, and materials are selected in the case of ranking wall types. To decide on the importance of each of these factors towards the selection of the most constructible wall, pairwise comparisons are carried out at this level to assign them weights, as Table 4-7 illustrates.

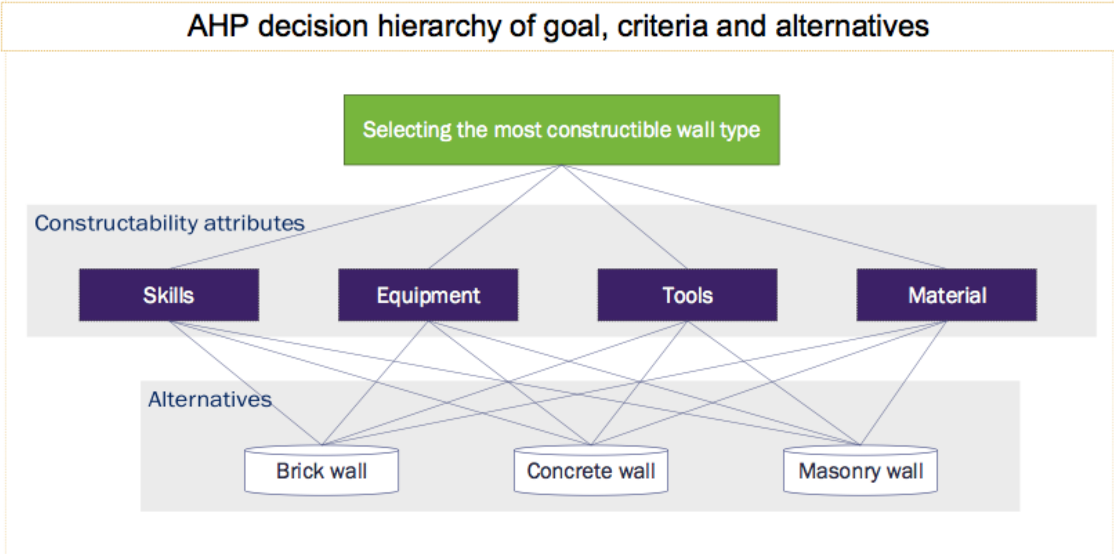


Figure 4-12: Example of a decision problem's structure to rank constructability of wall types

Table 4-7: Pairwise comparisons of considered constructability factors

Wall type	Skills	Equipment	Tools	Materials	Pairwise comparisons	Priority vector
Skills	1	5	3	1	$(1 \times 5 \times 3 \times 1)^{1/4} = 1.968$	1.968/4.67 = **0.421**
Equipment	1/5	1	1/3	1/3	$(1/5 \times 1 \times 1/3 \times 1/3)^{1/4} = 0.386$	0.386/4.67 = **0.083**
Tools	1/3	3	1	1	$(1/3 \times 3 \times 1 \times 1)^{1/4} = 1.0$	1.0/4.67 = **0.214**
Materials	1	3	1	1	$(1 \times 3 \times 1 \times 1)^{1/4} = 1.316$	1.316/4.67 = **0.282**
Total					4.67	1

Once relative constructability factors are selected, and their importance weights are assigned, the next step is to rank the alternatives performance (i.e. considered types of wall systems in the example) with respect to them. This results in producing representative constructability indices for the alternatives. However, it is challenging to obtain representations of modelled design features, given the way they are composed. For instance, the brick wall type in the previous example might not be formed only from bricks, but also could include layers of other construction materials. The next section lays out how the proposed CM addresses this challenge, establishing a mechanism that is capable to represent various construction system alternatives.

Mechanism of obtaining representations of design features for modelling constructability

Depending on the type of assessed system, the design elements of some construction systems are decomposed into their basic features and components, as described in Table 4-8. The rationale behind this is to attract designers' attention to simple details about their features, rather than focusing only on the high level with ignoring critical aspects in elements formulation. Another reason is to allow for the assessment of different combinations of basic components/materials constituting design elements. For instance, Figure 4-13 shows an external wall with multiple layers of various construction materials. These layers will be categorised into interrelated groups to be assessed for their alternatives, or alternatively to be ignored if they do not substantively affect system constructability.

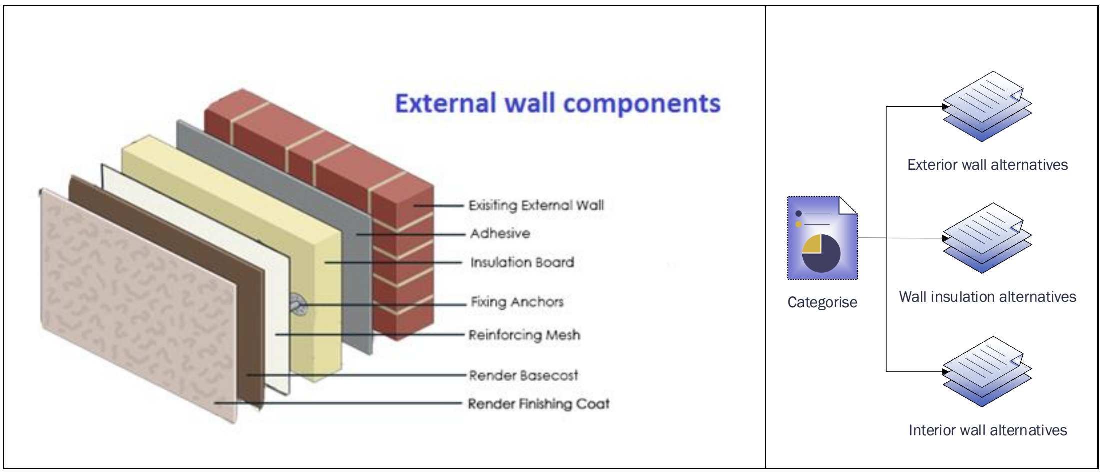


Figure 4-13: Categorisation of a wall components into groups

Constructability indices for other construction systems (e.g. columns and beams) are directly associated with their *design* elements instead of materials; this is due to the nature of such elements, and the way they are represented. For instance, a structural column of a specific type (e.g. a concrete or steel column) is assessed according to that type, and not according to its components (i.e. reinforcement and aggregates). The criteria of ranking such types can be established based on shape, type of reinforcement, or type of loading. This ranking method of element constructability simplifies the scoring process when customising the CM, obviating sub-scoring processes.

However, it restricts the model's use to assess only designs constituted from similar families and objects.

Table 4-8: Representations of design construction systems

System	Representations in model constructability
Roof system	Since roofs usually compromise layers of composite materials (i.e. structural layer and sub-structural layer represented in various types of insulations, and finishing layers for ascetic aspects of the building roof), the concept proposes to assess each of these layers individually, with respected aspects or alternatives, rather than including all of them in one group competing with each other.
Floor system	The system considers each floor system as a single component, since there is no point in assessing *in situ* cast concrete without its metal decking, timber joists, and finishing wood. This allows the user to evaluate the full picture comprehensively, rather than considering individual elements.
Structural framing system	Different types of structural element (columns, beams, girders etc.) are assessed based on their construction materials (e.g. concrete, steel, precast). This also accounts for changes in characteristics of the same construction material (e.g. steel grade or concrete strength) to be considered as different types.
Foundation system	The system assesses all components used for building foundations, including piling sheets and precast components. Based on assigned scores for each component separately, the cumulative score is a representative of this construction system.
Envelope system	The envelope systems are considered as a single system in the assessment, since different layers of any curtain wall are wrapped together. Also, envelope options are usually assigned to sub-contractors or external suppliers, who are supposed to complete the task as a design-bid-build job.
Wall system	Walls are treated in the same way as roof systems, since both of them usually comprise different construction layers. However, the concept here benefits from individual assessment for layers, to allow for different combinations of such layers using various construction materials. In addition, this provides room to assess the way in which layers are integrated during the construction process, to ensure that they would fit smoothly during their construction. Another reason is that each of the layers can be used on its own to build a wall, thus it needs to be assessed separately. Users can cluster wall layers into groups for assessment purposes, based on their categories (i.e. finishing layers, structural layers, or sub-structural layers).

In the example of exterior wall types, the concept of a wall system is applied, as explained in Table 4-8, consisting of various layers as featured in the BIM model. Obtaining a list of such layers for the calculation purpose is either automatically extracted from the BIM model or manually input by users. Table 4-9 shows the calculated indices of considered alternatives to rank their constructability performance, following the described procedure (Figure 4-14). This ranking only represents the preferences and capabilities of the user who originally performed the scoring when customising the CM.

Table 4-9: Pairwise comparisons of exterior wall layer alternatives

Constructability factor	Global weight	Alternatives	Bricks	Concrete	Masonry	Local priority	Global priority
Skills	42.1%	Bricks	1	5	3	0.637	0.268
		Concrete	1/5	1	1/3	0.105	0.044
		Masonry	1/3	3	1	0.258	0.109
Equipment	8.3%	Bricks	1	1/5	1/3	0.105	0.009
		Concrete	5	1	3	0.637	0.053
		Masonry	3	1/3	1	0.258	0.021
Tools	21.4%	Bricks	1	1	1	0.333	0.071
		Concrete	1	1	1	0.333	0.071
		Masonry	1	1	1	0.333	0.071
Material	28.2%	Bricks	1	1	3	0.429	0.121
		Concrete	1	1	3	0.429	0.121
		Masonry	1/3	1/3	1	0.143	0.040

The scoring method (AHP) assumes only one ideal solution among alternatives, that satisfies all defined criteria to realise the targeted goal (i.e. accomplishing the highest constructability performance). This means that the assigned value of 1 to such an ideal solution will be distributed between design alternatives (if applicable). This is done in accordance with their partial satisfaction for defined criteria, and hence the value represents a fraction of the assigned one. For instance, if the concrete wall option achieved 0.35, it indicates that this option satisfies 35% of defined criteria (i.e. resources restrictions in skills, equipment, tools and materials), compared to 65% for the brick option.

The challenge presented here is that the more options are considered, the lower indices are obtained, as they start competing each other, leading to lower overall constructability scores. These indices result from the comparison of the individuals relative to each other, to enable their ranking, but this does not indicate the performance of individuals on their own. As a result, this would restrict the use of obtained indices to cases where only the same set of individuals are considered, without adding or omitting any alternatives; hence, each problem will have a unique scoring process that requires separate considerations.

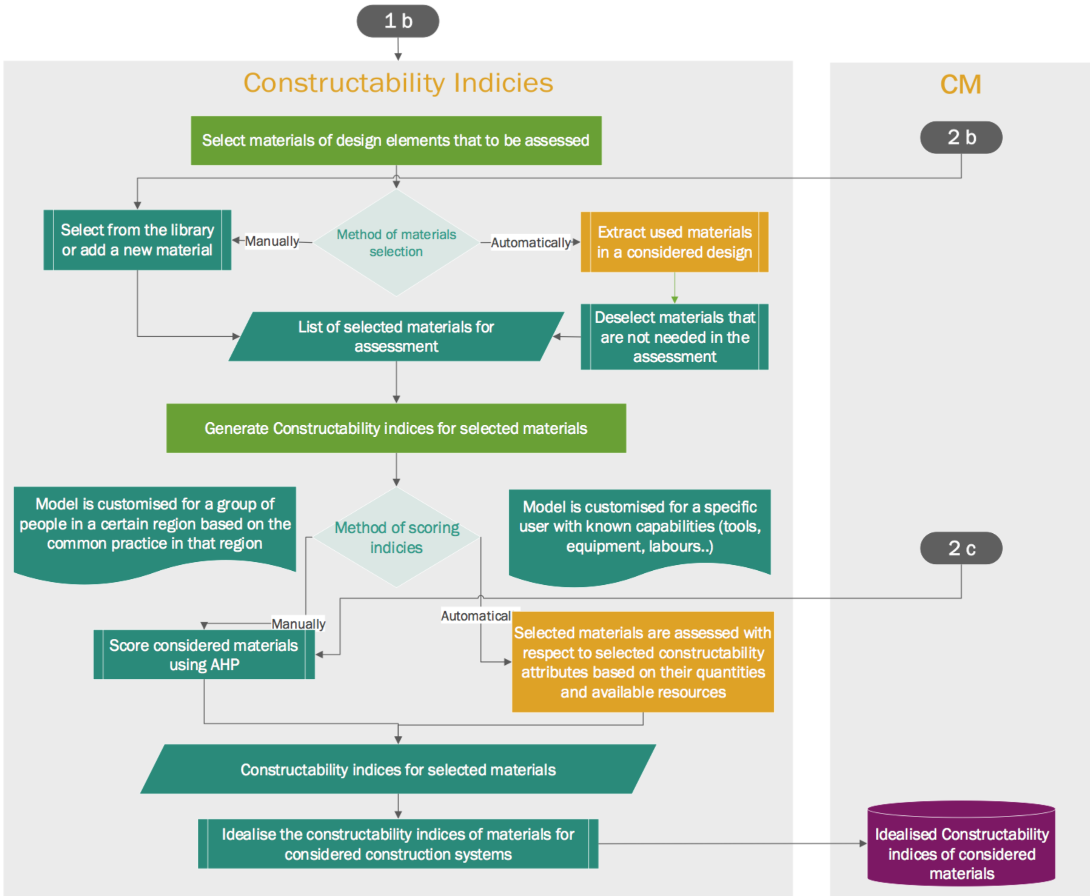


Figure 4-14: Generation of constructability indices of considered construction systems

One way to avoid this is to idealise the obtained indices from a scoring process that considers all possible alternatives, to indicate their absolute performance. This is done by assuming that the highest ranked alternative, which is the optimum solution, scored as 1, while others are scored relatively with respect to it, as Table 4-10 demonstrates with regard to the previous example.

Table 4-10: Calculated constructability indices of external wall type alternatives

Alternative	Constructability Index	Idealised Constructability Index
Bricks	(0.268 + 0.009 + 0.071 + 0.121) = **0.469**	0.469/0.469 = **1.0**
Concrete	(0.044 + 0.053 + 0.071 + 0.121) = **0.289**	0.289/0.469 = **0.616**
Masonry	(0.109 + 0.022 + 0.071 + 0.040) = **0.242**	0.242/0.469 = **0.515**

Rules of Thumb

This part of the CM seeks to translate the constructability related knowledge into a readable-machine rule language to automatically reason about constructability. Such a process is usually composed of four stages as depicted in fig. These are:

1. *Rule representation:* Generally, rules are written in human language. As such, this stage seeks to interpret their logical content and represent them in a parameterised format, typically using the "IF-THEN" statement.
2. *Model preparation*: This stage prepares the necessary information to carry out the rule checking. Different model views can be used to define the required semantic data obtained from extracted design features.
3. *Rule execution*: This stage carries out the checking of formulated rules against design features.
4. *Rule reporting*: This stage reports achieved results from rule checking in a graphical and non-graphical format.

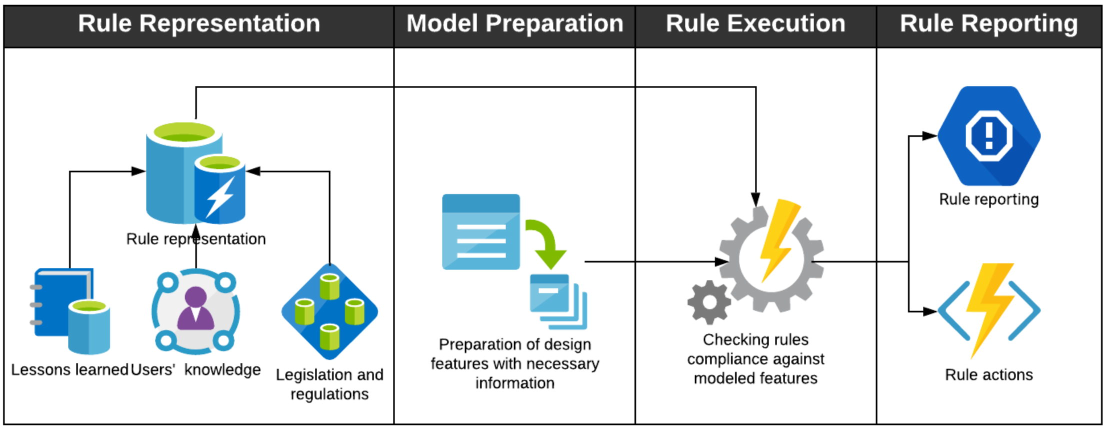


Figure 4-15: Workflow to implement a rule-based system

As a part of customising this section of the CM, users define/ enables set of applicable rules, and then assign values or limitations for the parameters of these rules to be checked later for their compliance with defined boundaries on actual designs. Below sections provide the study insight of how these rules are developed and incorporated in the scope of constructability assessment, as well as discussing typical challenges associated with such processes.

1) Constructability constraints

When customising this part of the CM, users operate rules that impose their design constraints (e.g. restrictions of weight, height, length, and width of loads). Such restrictions could be introduced for various reasons, such as availability of elements, mode of transportation, site accessibility, available storage space, methods of construction/installation, and available working space (Figure 4-16). Applicable rules are required to be defined and set at the stage of CM customisation in order to be executed at the assessment process by the AM.

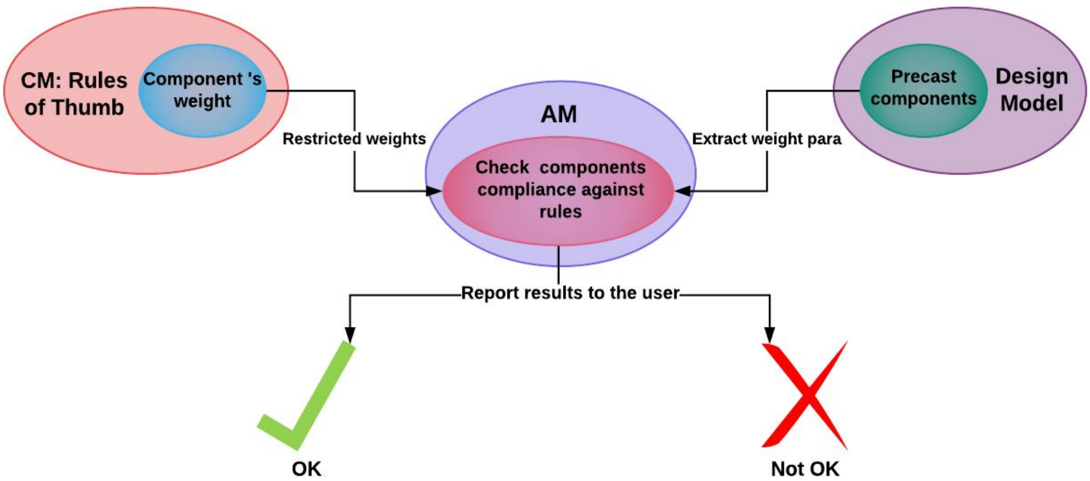


Figure 4-16: Example of a design rule restricting weights of pre-cast units to comply with the crane lifting capacity

During the assessment process, the AM verifies the compliance of assessed designs with enabled rules and assigns them weights scored by users to obtain the constructability status of this section.

Constructability constraints: Rule representation:

The primary goal of this step is to formulate rules that reflect construction constraints and reinforce them on design products. As these constraints are typically introduced to reflect user's construction capabilities or lessons learned; hence, they are the best to interpret these rules and articulate their content to suit requirements. This usually comes down to buildings professionals who are currently responsible to carry out constructability review (i.e. design team and consultants), using established methods and practice (i.e. checking lists, custom rules, etc.). However, these are extendable to other project stakeholders (i.e. contractors and sub-contractors, etc.) as per Table 4-4.

This study presents a strategy that brings the perspective of linked data to assist in the development of objected-oriented rule repositories. This will not only facilitate the automation of reasoning about constructability, but will establish a solid practice to documenting constructability related knowledge by coupling accumulated construction experience to physical design objects (i.e. virtually represented as BIM objects).

To this end, rules creators need to interpret their documented lessons learned and custom practice to be expressed as design constraints. Initially, these could be written in human language to express the knowledge content. This means that the all "IF" part will be linked into a design parameter such as length, width and area of specific design object (i.e. column, beams, slabs). It is, however, possible that the same design parameter is restricted in many instances due to its association with various constructability rules. In such cases, rules creators need to intervene to decide on the best-assigned value to suit the multi-purpose objective. The format of produced rules consists of the following:

<table>
<tr><td rowspan="3">"IF"</td><td>Model input</td><td>Rule condition</td><td>Rule value</td><td rowspan="3">"THEN"</td><td>Rule status</td><td colspan="2">Rule reporting</td></tr>
<tr><td rowspan="2">"Restricted design parameter/s that is associated with a specific design element"</td><td rowspan="2">"Logical operator"</td><td rowspan="2">"Restricted Element Parameter value"</td><td>True</td><td>"highlight the element that requires attention"</td><td>"possible implications on calculated constructability score"</td></tr>
<tr><td>False</td><td colspan="2">No further action to be taken</td></tr>
</table>

Figure 4-17 illustrates some of the possible combinations of rules that can be defined using the described approach. It presents an example of constructability constraints that can be covered under the scheme, and how they are tightened to design objects to generate sought rules. In the implemented prototype, a standard package of rules is defined as an example of how this can be applied, shown in Table 4-11. However, this could be extended to cover many other areas.

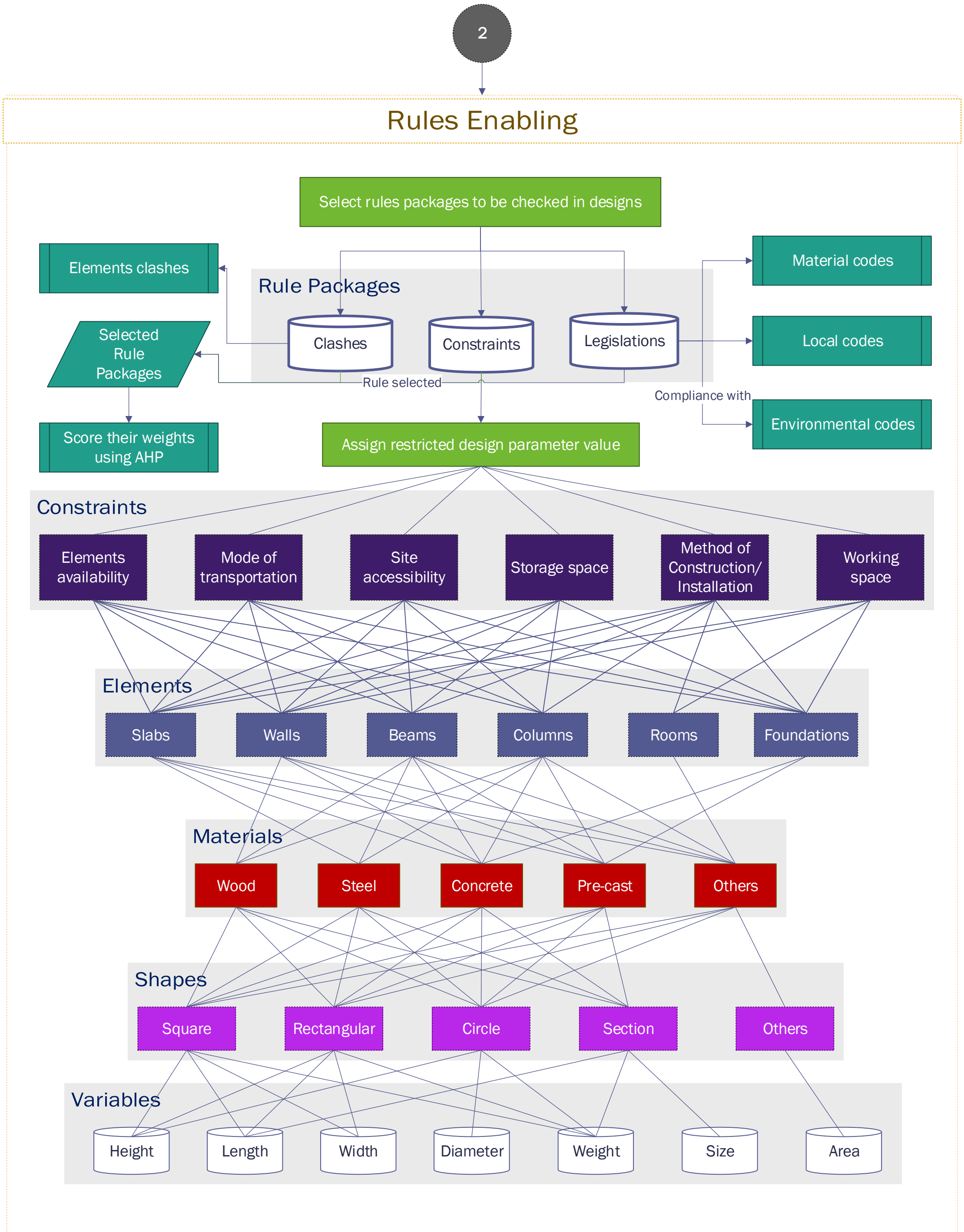


Figure 4-17: Possible combinations of Rules of Thumb that can be defined in a CM

Table 4-11: Examples of implemented rules in the proposed assessment system

Room Spacing

<table>
<tr><td>Restricted Design Element</td><td>Restricted Element Parameter</td><td>Provider of Rule Boundaries</td><td>Rule Actions if Satisfactory</td></tr>
<tr><td>Room space</td><td>Calculated space in a different room</td><td>Model user/ potential contractors or sub-contractors</td><td>No further action to be taken</td></tr>
<tr><td colspan="2">Rule Purpose</td><td colspan="2">Rule Action if Unsatisfactory</td></tr>
<tr><td colspan="2">This is to check available working space during the construction process. It ensures that workers and equipment will have enough space to move around the building. For example, the needed space when carrying out the wall finishes (plastering and painting etc.).</td><td colspan="2">Highlight unsatisfactory rooms in the design model as a way of notification for addressing.
Anticipate implications for the calculated Constructability score.</td></tr>
</table>

Column Formwork

<table>
<tr><td>Restricted Design Element</td><td>Restricted Element Parameter</td><td>Provider of Rule Boundaries</td><td>Rule Actions if Satisfactory</td></tr>
<tr><td>Concrete columns.</td><td>Column shape, width, and depth.</td><td>Model user/ potential contractors or sub-contractors/ suppliers</td><td>No further action to be taken</td></tr>
<tr><td colspan="2">Rule Purpose</td><td colspan="2">Rule Action if Unsatisfactory</td></tr>
<tr><td colspan="2">This is to ensure that decided concrete column dimensions are compliant with available formworks.</td><td colspan="2">Highlight unsatisfactory columns in the design model as a way of notification for addressing.
Anticipate implications for the calculated Constructability score.</td></tr>
</table>

Component Dimensions

<table>
<tr><td>Restricted Design Element</td><td>Restricted Element Parameter</td><td>Provider of Rule Boundaries</td><td>Rule Actions if Satisfactory</td></tr>
<tr><td>Pre-casted/ pre-fabricated beams, columns, and girders</td><td>Component length, width, and depth.</td><td>Model user/ potential contractors or sub-contractors/ supplier</td><td>No further action to be taken</td></tr>
<tr><td colspan="2">Rule Purpose</td><td colspan="2">Rule Action if Unsatisfactory</td></tr>
<tr><td colspan="2">This is to check that pre-casted/ pre-fabricated structural components' dimensions are within the specified range. This is to facilitate lifting and fabrication processes.</td><td colspan="2">Anticipated implications on the calculated Constructability score.</td></tr>
</table>

Once sought rules are formulated in the described format, their transformation into a machine-readable language is achievable. Whilst this may carry some element of challenge to non-programmer users. They, however, are able to use BIM tools to validate design compliance with established rules. They can use element filter functionality, which is available in nowadays BIM-based tools, to identify targeted object/category/type. Though the automation rules execution streamlines the process and saves time and labour efforts. Ideally, users of the system would like to simply select applicable rules from a standard package defined in the CM, with possible customisation to their restricted parameters to suit requirements, through a user-friendly interface.

Constructability constraints: Rule execution:

By introducing the Rules of Thumb feature, the proposed constructability assessment mechanism is the first of its type to combine a numerical assessment system and a rule-based system, allowing for both quantitative and qualitative approaches. While the developed rules enable constructability improvement through identification of design instances that require attention. However, it is the study goal to present a comprehensive assessment system that can accommodate all constructability aspects and attributes. Such a system can be then customised by their users to suit their requirements. It can also be employed by governmental bodies, requiring achievement of specific scores from design submissions to grant approval, to enforce the concept implementation.

That said, the CM has a scope to incorporate the performance of Rules of thumb module in the calculated constructability score. Though the piloted scoring scheme for this section is at a high level of details, they, however, provide a fair insight on how to combine the two schemes (i.e. numerical assessment system and a rule-based system). The assigned scores can be expressed in different ways, as Table 4-12 shows for illustrative rules in Table 4-11. Delivered scores should act as indicators to the severity of the situation being represented and its potential impacts on constructability performance.

Table 4-12 Assigned scores for implemented constraints rules

Implemented Rule	Assigned score to reflect the performance
Room Spacing	1, No. of identified non-compliant rooms = 0 0, No. of identified non-compliant rooms > 0
Column Formwork	No. of compliant columns / Total No of columns
Component Dimensions	1, No. of non-compliant components = 0 0, No. of non-compliant components > 0

2) *Design clashes*

It is clear that a clash-free design product supports the smooth delivery of the construction phase, which contribute to the project constructability. As a result, many tools are already made available to check design clashes exploiting BIM-based design platforms (Zhang et al., 2011). For instance, Solibri Model Checker (SMC) is a powerful tool that can be employed to reason about constructability rules. Its functionality can be extended to support the establishment of a rules database (Pauwels and Zhang, 2015). Other tools include but not limited to: Autodesk Navisworks, Autodesk Revit inference checker, and Dynamo clash detection checker.

To articulate this within the focus of the study, the assessment framework has a scope of assigning incentive score for the compliance of achieving clash-free design product, using any of the aforementioned checking tools. At this stage, it allocates a zero score for this aspect in the total calculated constructability score if any clashes are recorded, or the clash detection check is not carried out at all. Consequently, this encourages users to resolve the detected clashes and conflict before going onsite to embark on construction, exploiting the BIM capabilities in visual analysis. Though the current scheme seeks simplicity when presenting accomplished scores. However, this can be advanced by introducing a linear scoring system that best described the quality of the presented design solutions. This would entail tailoring fitness functions that simulate not only numbers of detected clashes, but also their implications on construction process and disciplines that be may be involved to get identified issues resolved.

3) Legislation and regulations

As discussed earlier the assertion of designing for regulatory compliance of design product contributes to the enhancement of their constructability. Thus, the developed framework for calculating the Constructability score takes this aspect into considerations.

Regulatory rules are typically provided by their legislators (e.g. governing bodies and institutes). While these could be presented in different formats such as codes, specifications or annexes, they aim to enforce particular restrictions and limitations to achieve specific goals or avoid potential problems. As such, the providers of these regulations are the best to formulate their contents to suit the design practice and the current available tools. The proposed approach to formulate object-oriented rules provides an ideal environment for reasoning with such rules. Therefore, this research suggests that regulations are to be provided in a digital format that can be easily accessed by targeted users to validate their enforcement. This entails legislators to adopt new practice when transforming regulatory rules into machine-readable formats. As these endeavours may carry many challenges including aspects such as the compatibility of the format of these rules with different software. It, however, becomes necessary to work out a solution in order to achieve such a reality.

Complexity

Customisation of this section includes enabling sections and subsections that user would like to include in the assessment (i.e. simplicity, automation etc.). Some of such aspects are shown in Figure 4-18, however, users can add extra dimensions as required. Following this, they need to assign importance weights for enabled sections if they contribute differently towards achieving the constructible design. Finally, the configuration of each section is carried out as illustrated in Figure 4-18.

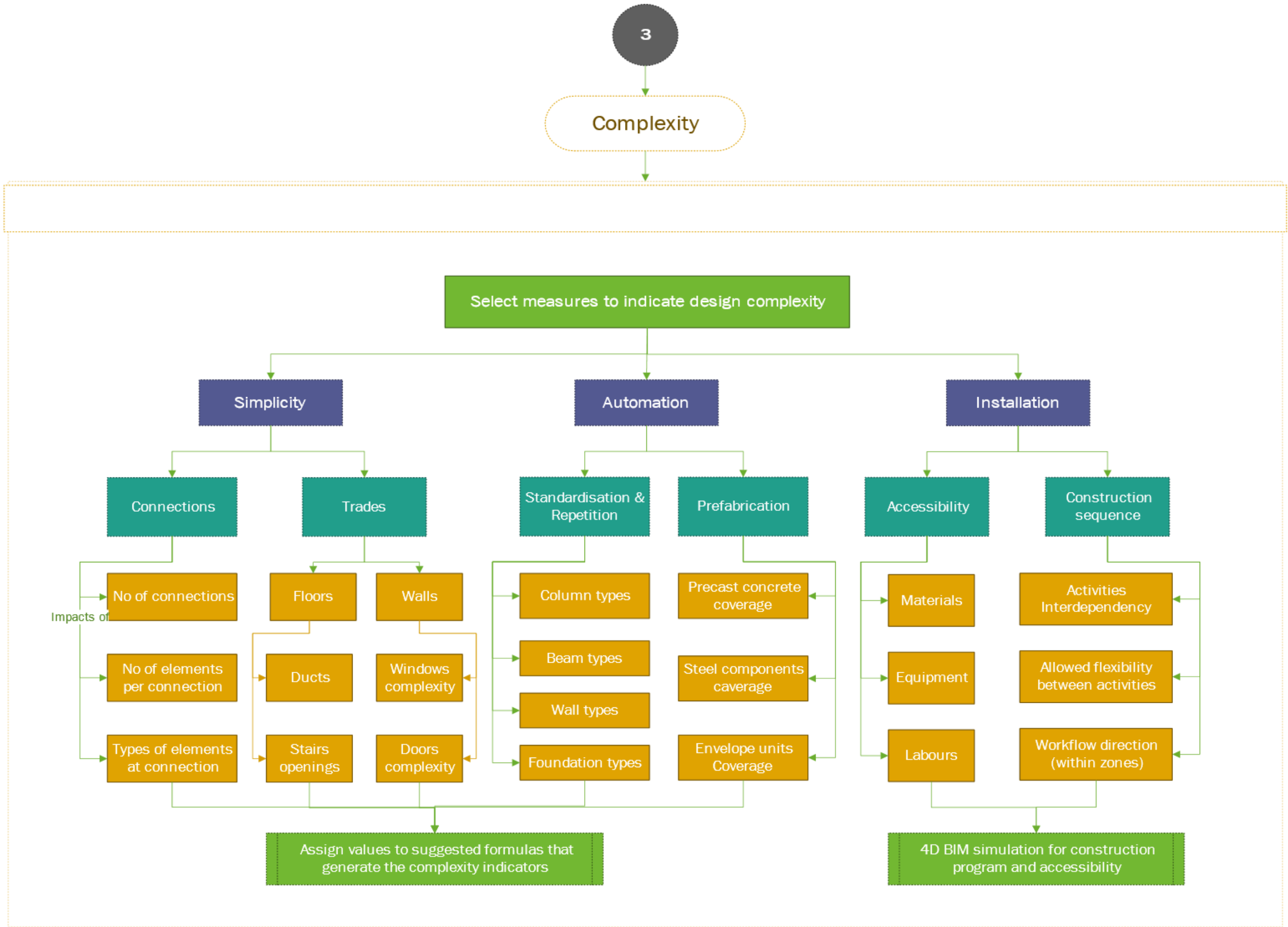


Figure 4-18: Assessed design aspects to inform its complexity

1) Simplicity

To drive design simplicity, the CM assesses design aspects that inform decision making, including the following aspects.

❖ *Simplicity of design connections*

The level of simplicity of design connections is based on factors such as the number of elements per connection, the structural types of such elements, and the variety of their sizes. Though there are many other factors that could be added, the proposed model is only intended to demonstrate how such obtained data from the BIM platform could be utilised as constructability indicators.

$$\textbf{Obtained score per column joint} = A^*R_{no} + B^*R_{types} + C^*R_{sizes}$$

Where:

A: Impact of elements' number on the joint's complexity

R_{no}: Assigned rate for the joint based on the number of connected elements

B: Impact of connecting different elements type on the joint's complexity

R_{types}: Assigned rate for the joint based on types of connected elements

B: Impact of elements' size variation type on the joint's complexity

R_{sizes}: Assigned rate for the joint based on elements' size variation

R_n = {1, No. of connected elements =< Ideal no. of elements per joint

0, No. of connected elements > Ideal no. of elements per joint}

$$R_{types} = 1 - \Sigma \text{ (Bcon x Cb + Brcon x Cbra)}$$

Where:

Bcon: Number of beams connected to the column

Cb: Complication of connecting a beam to column

Brcon: Number of bracings connected to the column

Cbra: Complication of connecting a bracing to the column

Rsizes = {1, No. of elements size per joint =< Maximum recommended no. of elements size per joint

0, No. of elements size per joint > Maximum recommended no. of elements size per joint}

The total score for connections complexity = Average obtained score per each joint

❖ *Simplicity of trades (host and hosted design components)*

Various components such as windows, doors, or ducts are assigned a Complexity score based on their types and their hosted walls or roofs, reflecting how complex they are in the construction process. These are assigned by users from their viewpoint. The scores are used as a reference to calculate the complexity of assessed design models based on actually used components. Table 4-13 demonstrates an example of such scoring.

Table 4-13: Assigned Complexity scores for hosted components based on the host type (i.e. wall)

	Windows		**Doors**		**Ducts**	
	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2
Wall Type A	Easy (0.25)	Moderate (0.5)	Easy (0.25)	Complicated (0.75)	Easy (0.25)	Moderate (0.5)
Wall Type B	Easy (0.25)	Easy (0.25)	Easy (0.25)	Moderate (0.5)	Easy (0.25)	Easy (0.25)

❖ *For walls*

Obtained score per wall = 1- Σ (Wno x Cw + Dno x Cd)

Where:
Wno: No. of hosted windows per wall in question
Cw: Complication of fixing a window in such wall (a type of window and door and hosted wall)
Dno: No. of hosted doors per wall in question
Cw: Complication of fixing a door in such wall
Scale of complication: (Very easy: 0, Easy: 0.25, Moderate: 0.5, Complicated: 0.75, Very complicated: 1)
The total score for walls complexity = Σ (Obtained score per each wall x Area of the wall) / Sum of walls area

2) *Automation*

❖ *Design standardisation and repetition*

Columns [shape, section size, material]/per floor

Obtained score per floor = $A^*(1/N_{shape}) + B^*(1/N_{size}) + C^*(1/N_{material})$

Where:
A: Impact of using different column shapes
N_{shape}: Number of used column shapes
B: Impact of using different column sizes
N_{size}: Number of used column sizes
C: Impact of using different construction materials for columns
$N_{material}$: Number of used materials in constructing columns
The total score for automation = Average of obtained score per each floor

- *Pre-cast/ prefabrication*

The model suggests assessing this aspect by obtaining the ratio between prefabricated components within a design model to elements that need on-site fabrication. However, the level of prefabricated elements and their sophistication varies from one element to another. Also, the extent of their completeness or necessity to perform additional finishing activities onsite is another factor. For instance, delivering prefabricated concrete girders that are ready to install is different from sub-assembled truss units that need to be erected together onsite. The connectivity between such various units and the amount of work required is a critical aspect that may turn the installation process into a disaster instead of speeding up its rhythm.

3) Installation

The installation part of the CM model aims to gauge the complexity of a design based on its facilitation for the following aspects.

- *Accessibility*

With the powerful features of 4D animation in the construction process, BIM enabled the assessment of accessibility with construction projects. This includes accessibility for people, machinery, tools, and site deliverables. Through the visualisation of 4D animation and the sequential mapping of activities, designers are able to identify any potential issues that may affect the construction workflow. To articulate this within the proposed assessment framework, it identifies a set of aspects that usually experience challenges in relation to their accessibility. Users will be asked to investigate these issues within the context of their design using 4D animation tools such as Navisworks, then they assign scores for such aspects to indicate their accessibility within the project environment. Also, weighting factors could be allocated to indicate the importance of assessed elements.

- *Construction sequence*

Earlier in the AEC Systems, the model target was to assess the availability of construction resources to meet their demand, based on a predetermined construction program. However, such a balance can be easily achieved by adjusting the schedule itself, to factor-in constraints on construction resources. For example, when two tasks are performed by a specific person simultaneously, they will have to be rescheduled to overcome this time constraint.

There are many techniques for resource levelling within a construction project, such as fast-tracking or crashing (Figure 4-19), including the use of critical path calculations. However, the scope of this part within the assessment framework is to evaluate the suitability of the construction schedule based on construction resources accessible to constructors, representing their construction capabilities. The outcome of this evaluation is expressed as a percentage of resources utilisation throughout the project. It indicates any over- or under-utilisation of resources to meet the needs of project construction tasks.

Figure 4-19: Techniques for levelling construction resources (RAJ, 2018)

Location

This section appraises the design consideration for aspects related to the project location, such as weather, adjacent buildings, transportation, and site information, as explained in Figure 4-20.

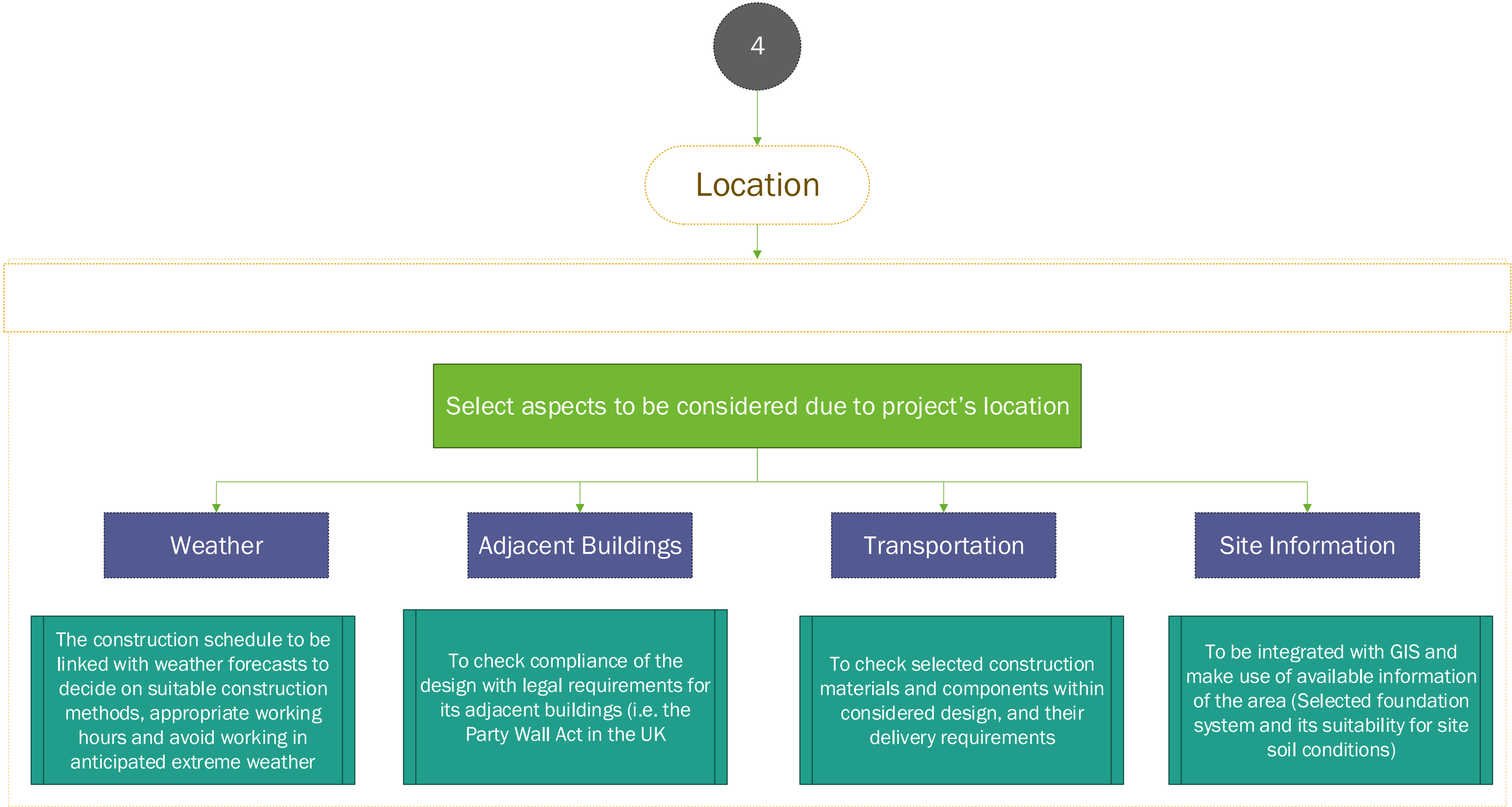


Figure 4-20: Aspects to be considered in design solution due to its location

The proposed system examines only the transportation aspect, at a high level, to accomplish the assessment set of the proposed assessment method. Remaining aspects are classified for further studies to be built upon the current research work.

To articulate how transportation aspects need to be incorporated into design decisions for constructability considerations, Figure 4-21 shows limitations related to the vehicle types when used for transportation. Such limitations in load capacity and dimensions should be accounted for when deciding on sizes of design elements, in line with other considerations. Transportation compliance will be checked against DFT specifications based in the UK, as shown in Appendix 1.

Typical vehicle sizes and weights

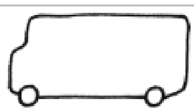
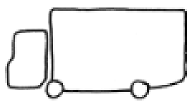
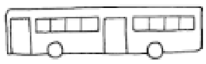
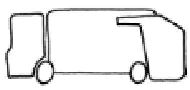
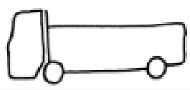
Vehicle type		Weight, *W* (kg)	Length, *L*	Width, *L* (m)	Height, *H* (m)	Turning circle (m)
3.5 tonne van		3500	5.5	2.1	2.6	13.0
7.5 tonne van		7500	6.7	2.5	3.2	14.5
Single decker bus		16,260	11.6	2.5	3.0	20.0
Refuse truck		16,260	8.0	2.4	3.4	17.0
2-axle tipper		16,260	6.4	2.5	2.6	15.0

Figure 4-21: Limitations in load capacity and dimensions related to Vehicle types

(Cobb, 2012)

Once enabled parts are customised and their components are configured for their assigned parameters, the model can be saved either in the user library or as a standard CM. Users are able to employ new CM for assessing targeted design solutions, as explained in the next section,

4.6. AM

This process maps the customised CM on the actual design model to benchmark its constructability. The design model is assessed based on AEC Systems, satisfaction with enabled rules, complexity, and considerations of the project location. The AM extracts necessary information from the BIM model to process configured sections within the CM. The mechanism for calculating the Constructability score using the introduced model is as illustrated in

Figure *4-22*.

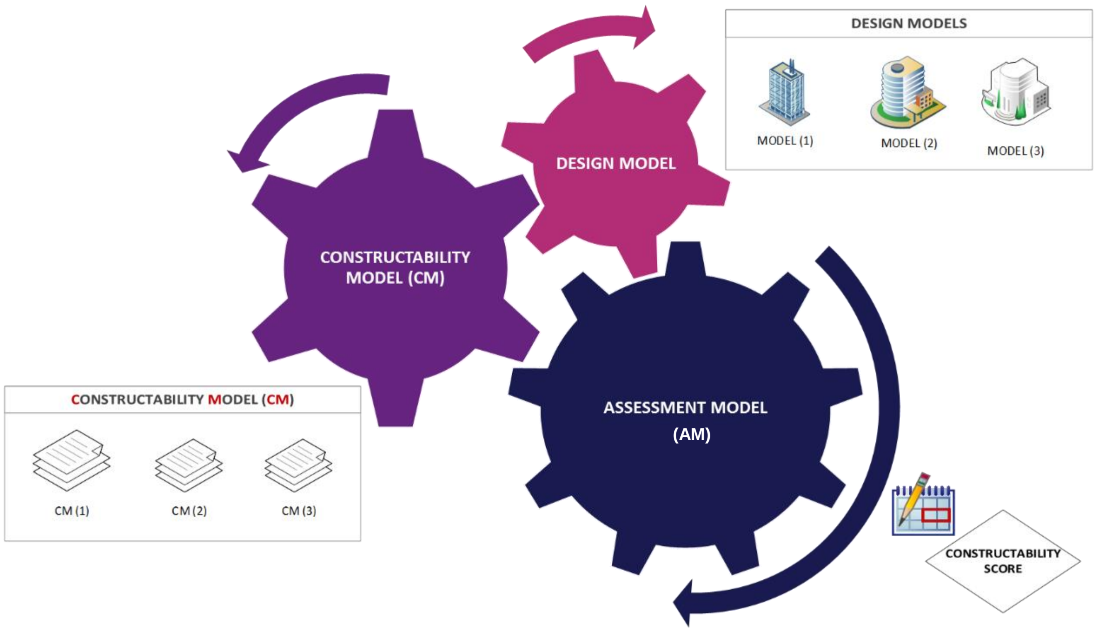


Figure 4-22: Constructability assessment mechanism

4.6.1. Calculating AEC Systems Constructability scores

When triggering the assessment process, the AM extracts types and quantities of used construction systems from the design model. Based on their types, the reasoning process takes place to recall their assigned scores in the selected CM. A score is then obtained representing the performance of the AEC Systems for the examined design, as demonstrated in Figure 4-23.

4.6.2. Calculating Rules of Thumb scores

Based on enabled design-rules on the utilised CM for the assessment, they are then checked against the examined design model and the compliance of its parameters with any assigned boundaries. Then a score reflecting such compliance is presented, as well as highlighting non-compliant elements for the user's attention to be addressed.

4.6.3. Calculating Complexity score

The model engine extracts the required information from the BIM model to execute enabled formulas proposed in section 4.5.5. The calculations result in providing indicators of the complexity of constructing such a design solution from the user perspective. A representative score is then assigned to this category based on the assigned weights of various complexity aspects.

4.6.4. Calculating Location score

Given the level of satisfaction of defined aspects in CM on the assessed design, a score is then assigned representing this category within the performed assessment process.

4.6.5. Calculating overall Constructability score

The obtained scores from various parts of the model collectively comprise the total system score. Based on the assigned importance of each part indicated by weighting, these scores are factored and summed to deliver the final Constructability score of the examined design. This informs its overall constructability status and how each section performed to satisfy defined objectives in the benchmarked CM.

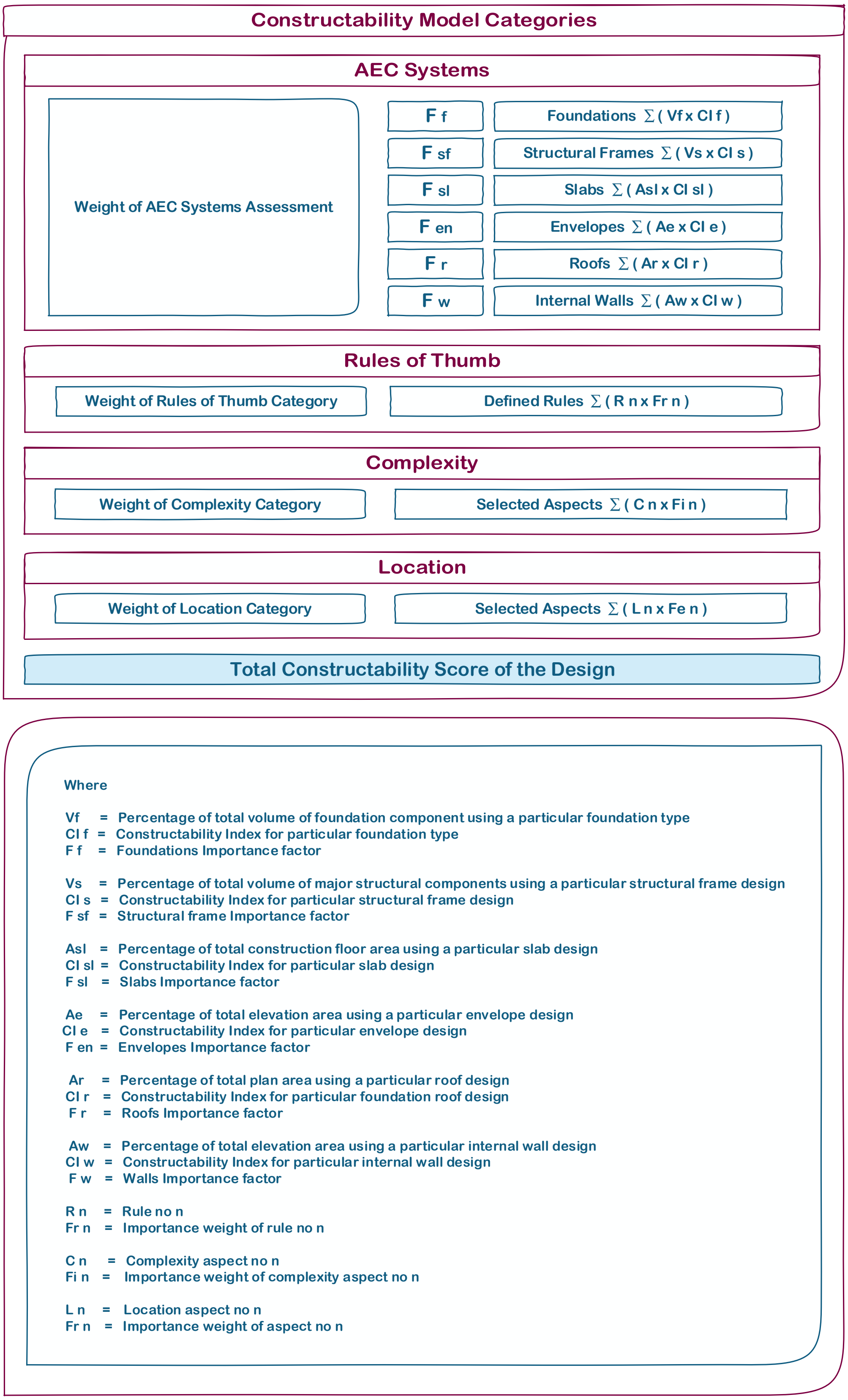


Figure 4-23: Equation framework for calculating the Constructability score using a customised CM

4.7. Advanced section: AEC Systems scoring automation

The scoring process is necessary to quantify the tacit knowledge of users that is hard to index and interpret in design rules. It allows encapsulation of construction conditions in assigned scores for design components to reflect their fitness for purpose. However, some users may find it challenging to compare subjective options and score their constructability performance. Though the AHP method is employed to eliminate such challenges, this may still be an issue for some practitioners.

This section explores the possibility of automating the scoring process for the AEC Systems part of the proposed assessment system. It seeks to employ the semantic information of BIM models for such purpose, exploiting their full capabilities during constructability assessment. The following subsections describe general ways in which this could be accomplished.

4.7.1. Constructability indices assignment for construction systems

With BIM-enabled, accurate estimation of design quantities, materials, and specifications, it is now possible to approximate demand for construction resources based on a scheduled program. This can be matched against accessible resources for design-builders to evaluate if they are capable to build it. Such evaluation between the demand for resources with the available supply can be automated, having the first part accessible within the BIM model while building a resources database for the second part, which reflects users' construction resources. Consequently, the lack of a specific type of resources could be flagged up at a specific stage of construction, for the entire project period. Scores and indices may be assigned reflecting the intensity of observed shortage of resources. For instance, consider a scenario where building a specific part of the structure to finish on time demands 10 skilled workers, working simultaneously, based on their standard production rate; of the contractor knows that only 5 of the 10 required workers can be assigned to the associated task, then a score of 0.5 should be assigned in this case.

Table 4-14: Automation of assigning weighting factors to designs' construction systems based on accessible BIM semantic data

Construction system	***Cost objective (assigned 35%)***		***Time objective (assigned 30%)***		***Safety objective (assigned 35%)***		***Final assigned weights***
	Obtained cost from BIM	**Assigned cost weights**	**Obtained time from BIM**	**Assigned time weights**	**Recorded number of incidents**	**Assigned safety weights**	
Slabs	£150,000	(150/600) = 0.250	4 weeks	(4/24) = 0.167	1	(1/8) = 0.125	(0.25*0.35) + (0.167*0.3) + (0.125*0.35) = **0.18135**
Roofs	£50,000	(50/600) = 0.083	2 weeks	(2/24) = 0.083	2	(2/8) = 0.250	(0.083*0.35) + (0.083*0.3) + (0.25*0.35) = **0.14145**
Foundations	£100,000	(100/600) = 0.167	4 weeks	(4/24) = 0.167	N/A	0.000	(0.167*0.35) + (0.167*0.3) + (0.0*0.35) = **0.10855**
Structural framing	£150,000	(150/600) = 0.250	8 weeks	(8/24) = 0.333	1	(1/8) = 0.125	(0.25*0.35) + (0.333*0.3) + (0.125*0.35) = **0.23115**
Envelopes	£100,000	(100/600) = 0.167	4 weeks	(4/24) = 0.167	4	(4/8) = 0.500	(0.167*0.35) + (0.167*0.3) + (0.5*0.35) = **0.28355**
Walls	£50,000	(50/600) = 0.083	2 weeks	(2/24) = 0.083	N/A	0.000	(0.083*0.35) + (0.083*0.3) + (0.0*0.35) = **0.05395**
Total	£600k	1	24 weeks	1	8 incidents	1	1

This is a practical and accurate way of assessing design constructability based on actual available resources, but it does not allow room for assessors to use their specialist knowledge in the process, considering intangible aspects of production that are more difficult to reflect in assigned scores. It does not provide constructors and contractors with the opportunity to better understand their design with critical evaluation of what they can build. In addition, the model assesses constructability at different design stages, which might not be applicable here due to constraints on accessible LOD during early design stages, including concept design, when decisions are crucial for determining the status of design constructability. Therefore, the earlier described scoring process using AHP was adopted in the proposed assessment method.

4.7.1. Generation of construction systems' weighting factors

Weighting factors of construction system types are applied to indicate their contribution towards satisfying targeted design objectives (e.g. financial and time costs). The proposed system suggests manual user scoring of weights using AHP, as explained earlier. However, this can be generated automatically from representative features of the examined design solution. For instance, if the cost of used components for a slab system is £50,000, based on associated semantic data within the BIM model, while the wall system costs £25,000, this indicates that the slab system would be given double the importance of the wall system from a cost perspective. Table 4-14 demonstrates an example of how this can be processed.

4.8. Summary

This chapter presented and described the proposed CM in detail, discussing aspects of how to configure the CM to reflect users' construction capabilities, and the rationale behind them. Also, a description of the model operation during the assessment process was provided. In addition, advanced sections describing some alternative ways to carry out the scoring process were presented, paving the way to automate the process for future studies. The implementation aspect of the model is covered in the next chapter.

5. Implementation of the Constructability Assessment Prototype

5.1. Introduction

This chapter describes the actual implementation of the introduced constructability assessment framework as a prototype using Application Programming Interface (API) in the Revit extension. This includes the prototype generation and the composition of its components and functions. It extends to include the prototype operation aspects and sequences of its delivered outcomes.

5.2. Implementation environment

This is the hosting platform where constructability is modelled on design features. It is interfaced with the design environment (BIM-authoring tool) to enable extraction of semantic information for the modelling purpose. It also has access to a designed database, where customised data are formulated, as shown in Figure 5-1.

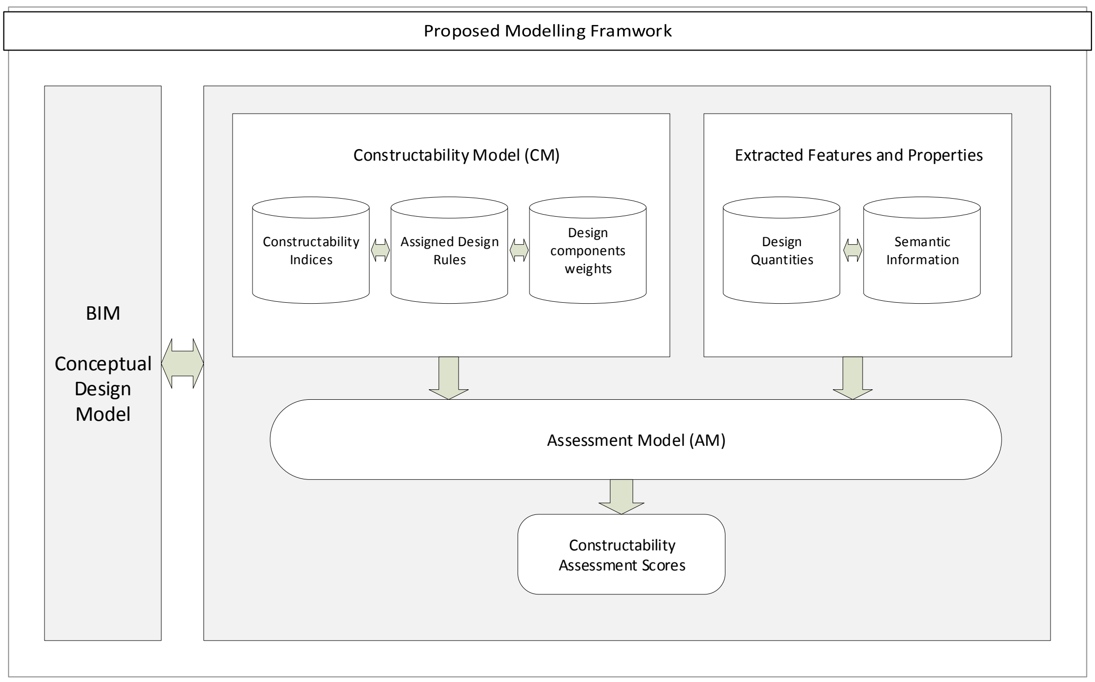


Figure 5-1: Proposed (implemented) modelling framework

The research motivation stems from the availability of advanced technologies to enable the constructability assessment of buildings design. As such, the implementation environment employs a set of technological tools and techniques to exploit their functional capabilities for the desired prototype. This is carried out while maintaining compatibility between platforms to provide a harmonic working environment that intuitively interacts with users. The following are the key elements that constitute the implementation environment.

5.2.1. Visual studio & Revit

This is the program environment where the prototype is built as a dynamic-link library (DLL), and deployed to Revit files to be loaded when the program is initiated. Using Revit .NET API, programmers are able to communicate and work with Revit to establish the functionality they seek within its environment. This enables writing instructions for Revit to be executed using any .NET programming language, such as C++, C#, and Visual Basic. In this implementation C# is used, as most programming libraries and resources are written in this language. This facilitates the employment of such resources within the implementation environment.

5.2.2. SQL database

The SQL database facility was employed to store the contents of customised CMs, including basic model information, enabled components, assessed construction systems, weighting factors, and assigned scores. The reason for this is to give persistent access to the model data even after restarting the Revit program or terminating the transaction session. This enables the reusability of the model by ensuring accessibility to its data at all times.

5.3. Design environment

This represents the hosting platform for design solutions to be assessed for their constructability. The assessment framework is built upon extracting its inputs directly from BIM models. This requires BIM authoring tools that support object-based modelling features. For this study, Autodesk Revit software was employed to host the implemented prototype, because of its popularity among other BIM tools in the UK (Figure 5-2), as indicated by the National BIM Report

(2018). However, the proposed framework is valid to be implemented with other BIM tools due to its generic conceptualisation and design.

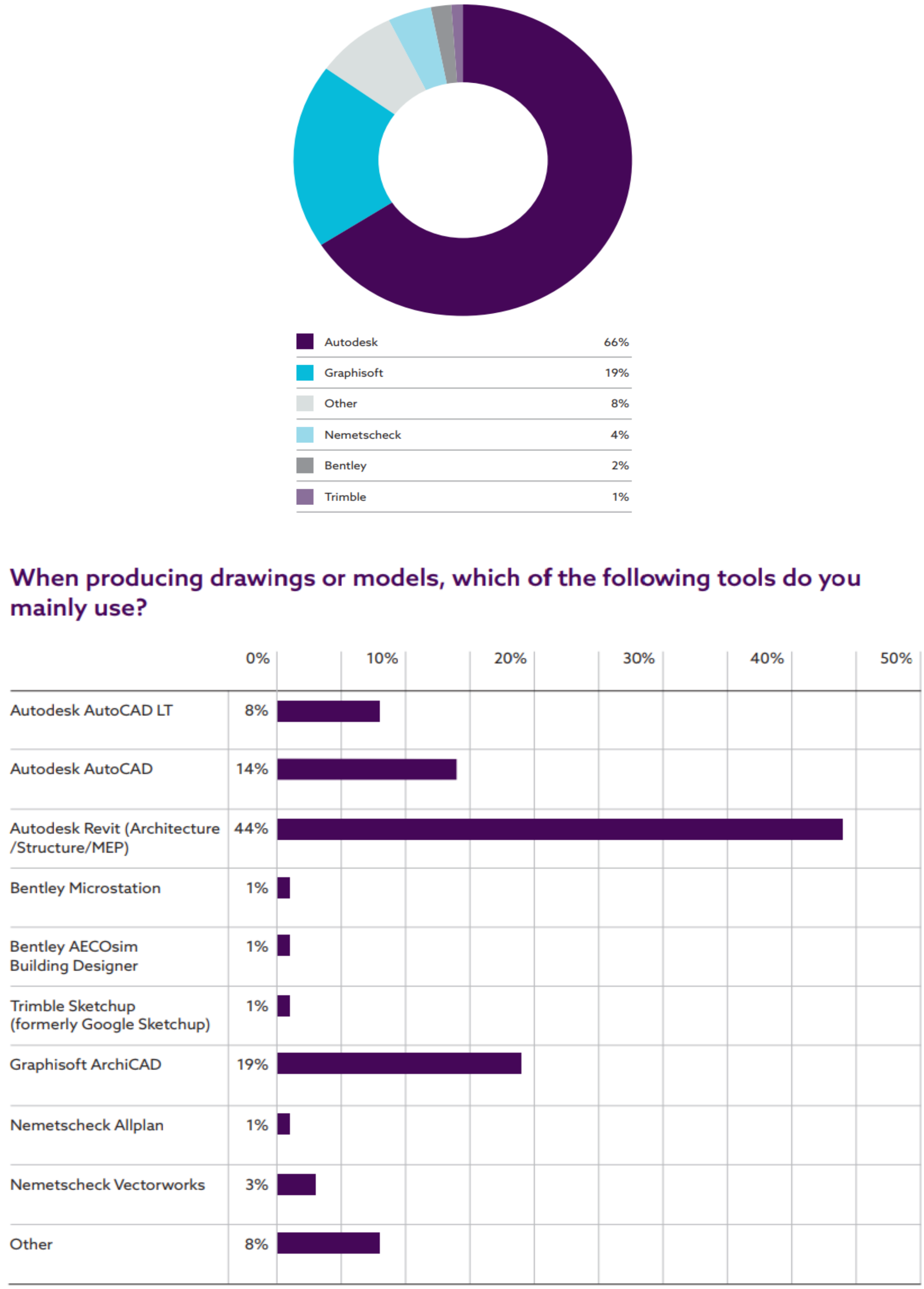


Figure 5-2: Employed software and tools to produce design models (NBS, 2018)

5.4. Constructability assessor as a Revit plug-in

By plug-in for Revit, it is possible to add the constructability assessment functionality to the software using its Revit API. The plug-ins will be loaded with Revit on start-up, and be executed to assess hosted design models when particular commands are executed by the end user.

The rationale behind interfacing with Revit UI is to ease users' accessibility to the prototype. Though the employment of IFC schema would facilitate the interoperability of the prototype among other BIM-tools implementing the schema, this would entail extra hassle for users to import/export their BIM models every time they would like to carry out assessment. This could discourage them from accessing the tool or optimising their models' constructability performance by exploring more alternatives.

5.5. Prototype development and operation

Prototype development is based upon the elicited use-case to guide the programming direction, as demonstrated in Figure 5-3. It shows the prototype functioning in four parts, namely: customising a new constructability model, modifying the customised model for another use, interacting with the developed BIM model (initial analysis for its quantities), and assessing the design constructability. To perform the functionality of each of these tasks a combination of objects, classes, and events is developed. This section highlights the relationship between these entities and how they interact in their operation.

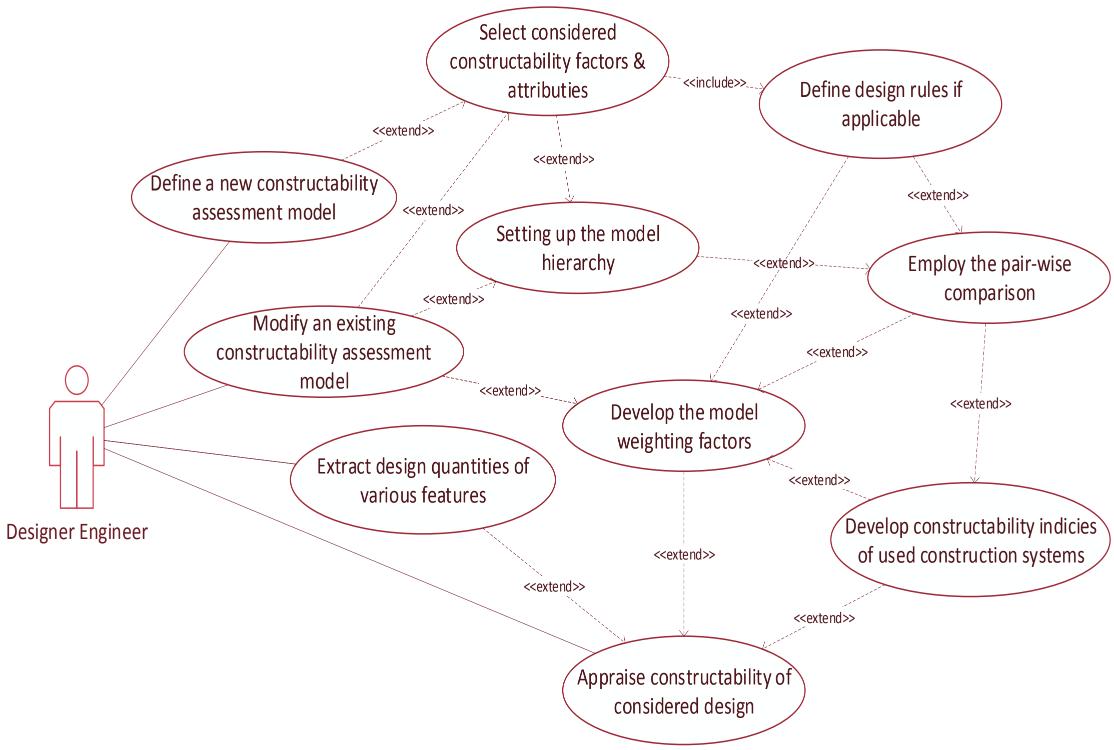


Figure 5-3: Use-Case

(Fadoul et al., 2018b)

5.5.1. Customisation of new CMs

This section describes the implementation of the functionality of customising a new CM, as described in section 4.5.5. The vital aspect of this part is the design of the database system required to hold CM data generated throughout the customisation process. Developing an effective database management system (DBMS) facilitates the data collection while ensuring accessibility when required.

5.5.1.1. Description of the system database management

Various SQL tables are established to accommodate the data of customised CMs (Table 5-1). Such data includes scored indices of various construction systems and assigned weighting factors to indicate the importance of various aspects.

Table 5-1: Description of SQL Tables that hold customised CMs information

Table Name	Description
ConstructabilityModels	Holds CMs' information, such as their names and what they assess. It is also the entry point to link any recalled model with other corresponding tables.
StandardConstructabilityModels	This is dedicated to storing standard customised models that are developed by professionals to be utilised or adjusted as required by specific users.
DesignObjectives	Holds weights of selected design objectives (cost, production rate, quality, safety etc.) as prioritised by the user.
ConsSysPriorities	Holds assigned weighting factors for construction systems categories (roofs, slabs etc.) as per contribution to satisfy defined objectives.
ConstAttributesPriorities	Holds derived priority scales for enabled constructability attributes as decision criteria.
RoofsPriorities	Holds indices of prioritised materials of roof elements to be assessed.
RoofsSubPriorities	Prioritises elements with respect to enabled sub-criteria before synthetisation with criteria.
FloorsPriorities	Holds priorities of scored materials of the floor's elements that to be assessed.
FloorsSubPriorities	Prioritises elements with respect to enabled sub-criteria before syntisation with criteria.
FoundationsPriorities	Holds priorities of scored materials comprising foundation elements to be assessed.
FoundationsSubPriorities	Prioritises elements with respect to enabled sub-criteria before syntisation with criteria.
StructuralFramesPriorities	Holds priorities of scored materials comprising roof elements to be assessed.
StructuralFramesSubPriorities	Prioritises elements with respect to enabled sub-criteria before syntisation with criteria.
EnvelopesPriorities	Holds priorities of scored materials comprising envelope elements to be assessed.
EnvelopesSubPriorities	Prioritises elements with respect to enabled sub-criteria before syntisation with criteria.
WallsPriorities	Holds priorities of scored materials comprising wall elements to be assessed.
WallsSubPriorities	Prioritises elements with respect to enabled sub-criteria before syntisation with criteria.
SelectedRules	Contains list of enabled rules to be checked under specified CM.
ColumnRules	Contains values of restricted design parameters (dimensions, sizes etc.) to be verified in examined design.
RoomRule	Contains restricted values of Room Space rule to be checked against considered design.
Transportation	Represents values of restricted design parameters that need addressing to conform with any transportation legislation.

5.5.1.2. The process of triggering the prototype as an add-in integrated within the Revit UI.

Figure 5-4 demonstrates the sequence of invoking the implemented prototype to operate its various functionalities, accessible through the GUI of Revit software. Figure 5-5 shows the database designed to hold CM data.

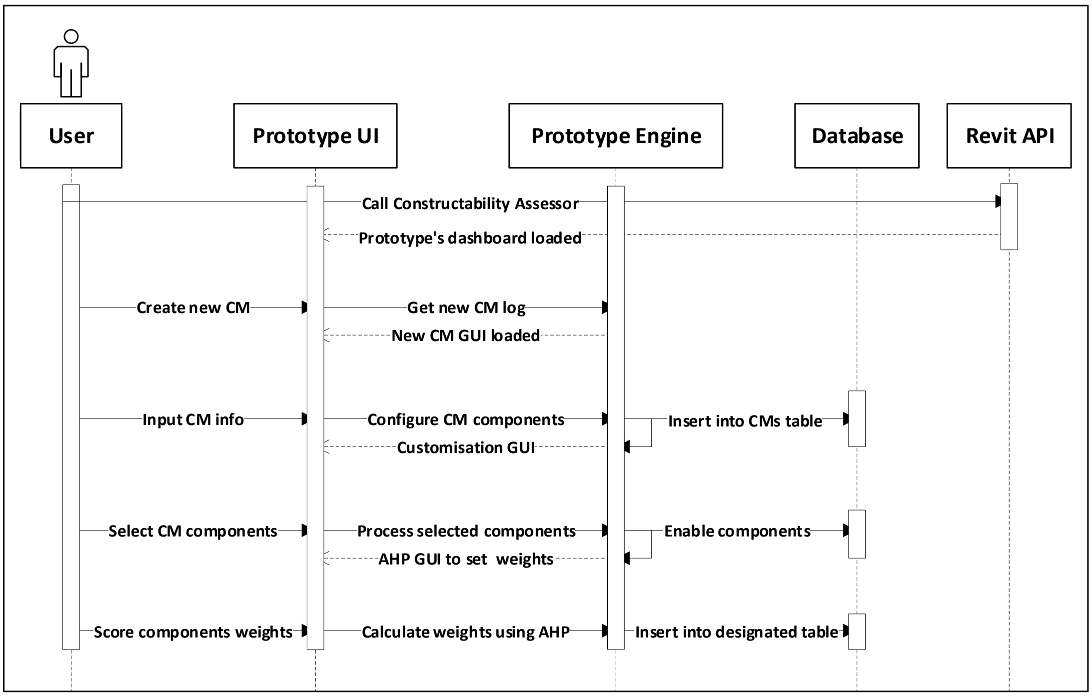


Figure 5-4: Steps to customise a new CM

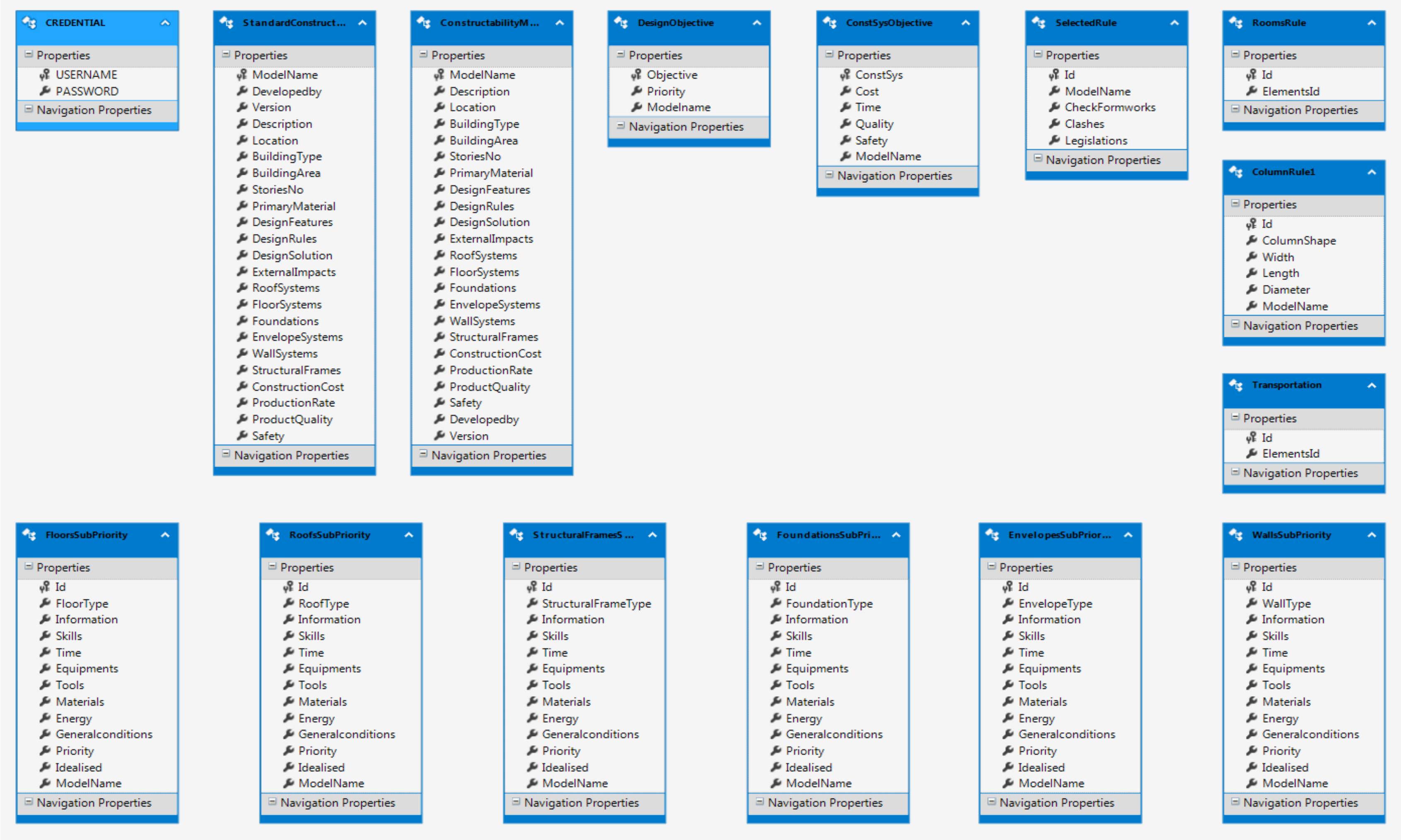


Figure 5-5: Designed database to hold CM information

5.5.1.3. Customising AEC Systems

As described in section 4.5.5, Figure 5-6 represents a sequence diagram for AEC Systems implementation. It shows the executed mechanism of receiving users' inputs and processing their expressed preferences towards various construction systems and techniques. Consequently, it configures a representation for this section within customised CMs.

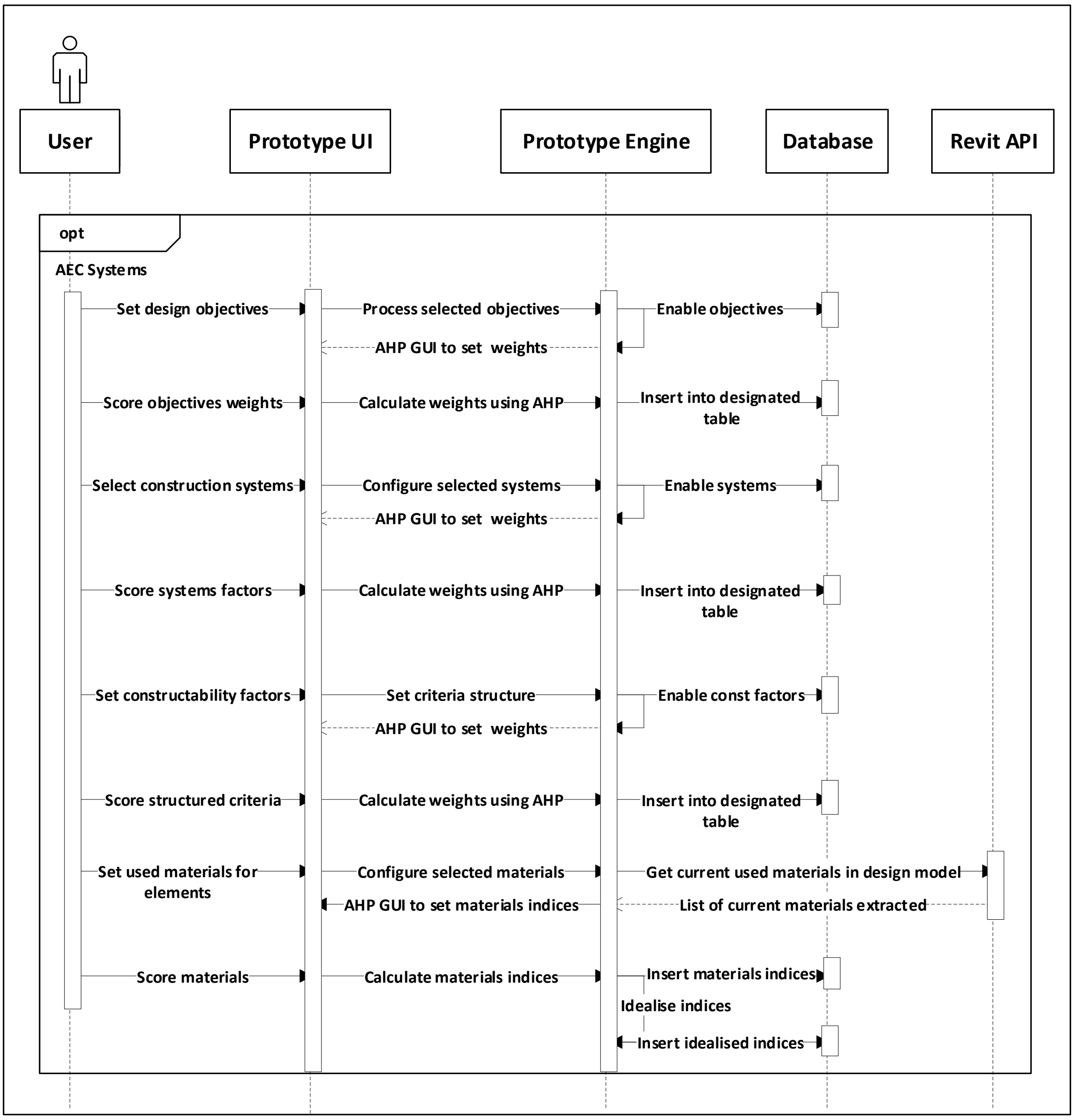


Figure 5-6: Implementation sequence diagram for triggering the prototype and customising AEC Systems of CM

5.5.1.4. Rules of Thumb

Under this section, new custom rules are defined for checking specific constructability limitations within design models (e.g. elements' size, design layout, dimensions etc.). This is performed using the powerful part of Revit API called the Performance Adviser. It has been added since Revit 2012 to allow developers to customise their own rules, or execute already built-in ones.

To employ the Performance Adviser within the developed prototype, it defines an adviser class that implements the IPerformanceAdviserRule interface. This class must contain specific methods, as described in Table 5-2, to enable the interface implementation.

Table 5-2: Methods required in custom adviser class implementing IPerformanceAdviserRule interface

Method	Description
GetName	Returns the name of the defined rule.
GetDescription	Provides a description of the custom rule.
InitCheck	Carries out initial checks before the rule execution (including tasks such as clearing containers that store non-compliant elements checked against the previous rules).
WillCheckElements	Determines if the rule will check all elements or not.
GetElementFilter	Defines an element filter that specifies a group of elements to work with the rule based on their type or category.
ExecuteElementCheck	This is the main method for rule implementation. It examines elements managed to pass through the filter for the rule logic and classifies those who fail to satisfy the rule criteria.
FinalizeCheck	This method checks if there are elements that fail the rule test, lists non-compliant elements' names and information (if applicable), and issues the typical warning failure message. It is called PerformanceAdviser to carry its tasks after elements are filtered by the GetElementFilter method, and tested by ExecuteElementCheck method.

The defined class for customising rules is also able to register them with Revit as the PerformanceAdvisor.AddRule method, which is required at the start-up of Revit using the OnStartup event of IExternalApplication. Otherwise, Revit will not include the customised rule with its default loaded rules. Similarly, the Performance Adviser rules are unregistered at the OnShutdown event.

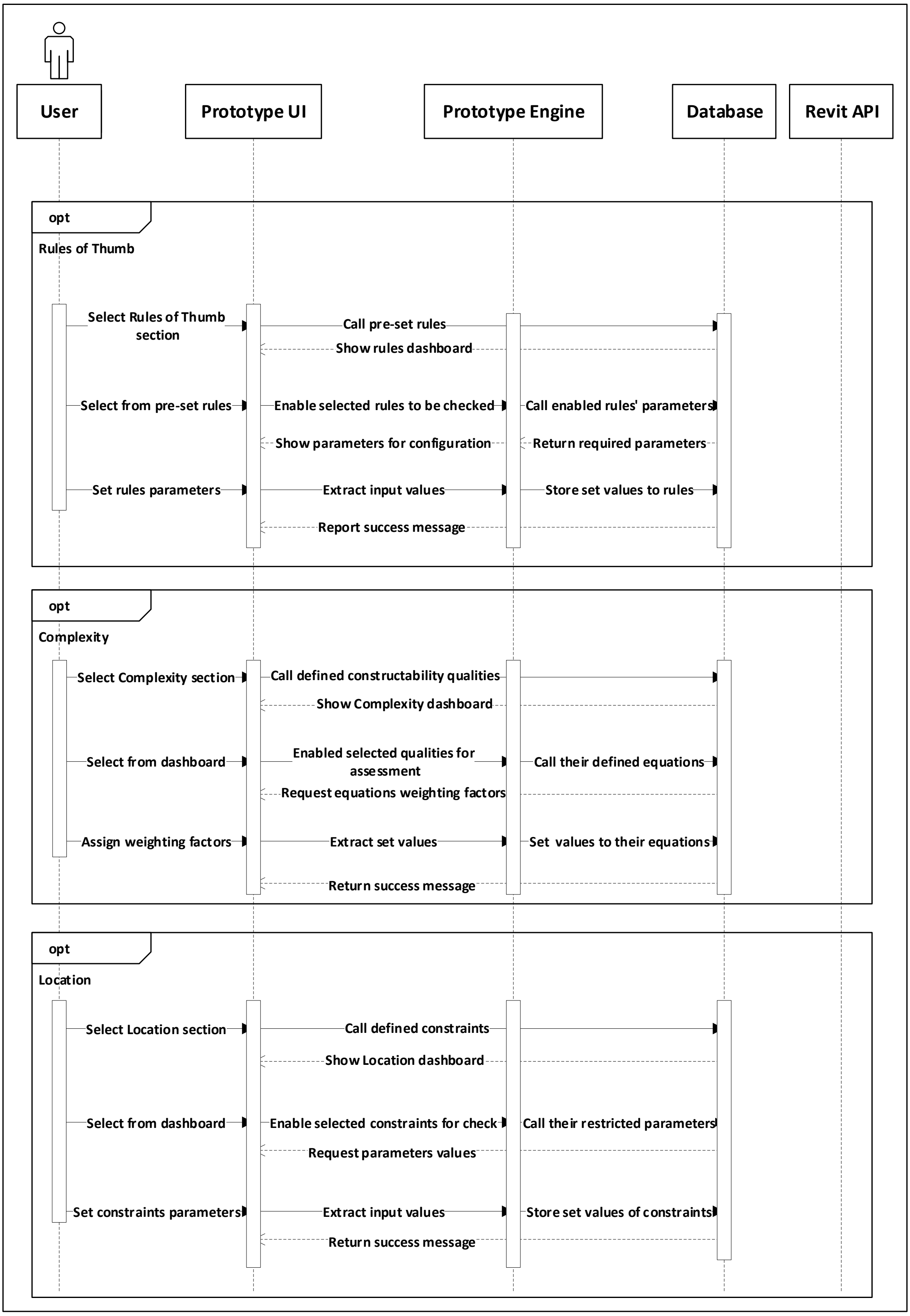


Figure 5-7: Sequence for customising Rules of Thumb, Complexity, and Location

5.6. Viewing CMs

To view a pre-configured CM selected from a list of models, the prototype issues a query to the database to retrieve the relevant data. This recalls all generated information when the model was customised and displays it in designated view tabs and data grid views. The sequence diagram in Figure 5-8 explains how this process is carried out to present CM data to end users.

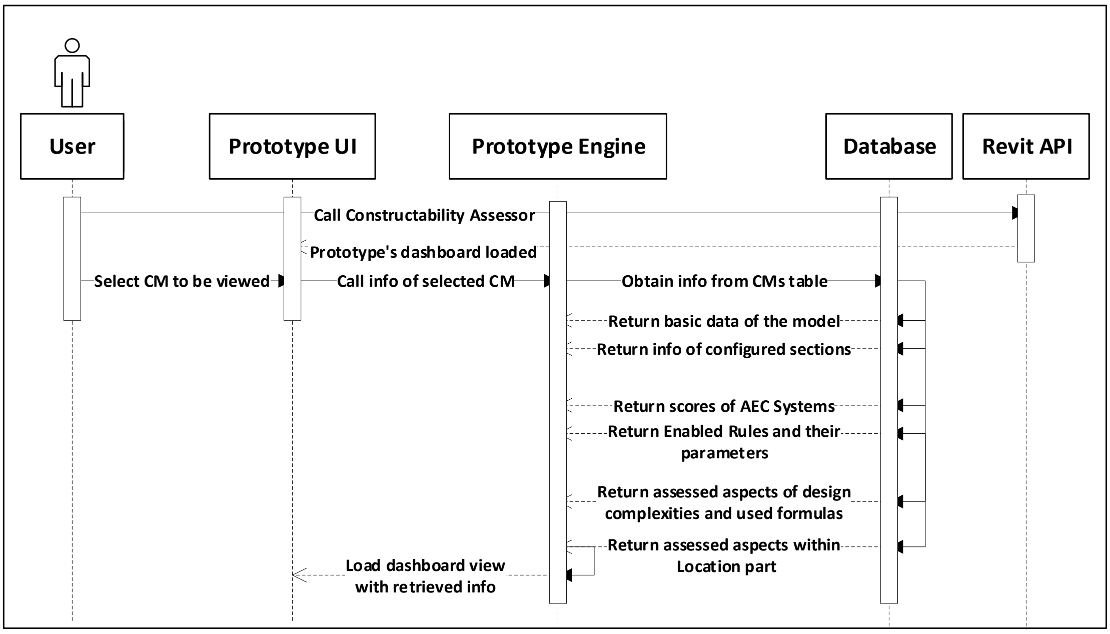


Figure 5-8: Sequence for viewing established CMs

5.7. Extraction of design data and material quantities

Since material quantity extraction is a basic requirement for any model analysis, Revit API provides methods to assist with such tasks. This includes direct access to material names, volumes, and areas, which is also used by Revit for producing material take-off schedules.

Table 5-3: Revit API methods for querying elements materials (Tammik, 2010)

Method	Description
Element.Materials	Gets a list of materials used in an element.
Element.GetMaterialVolume	Gets the volume of a specific material in an element.
Element.GetMaterialArea	Gets the area of a specific material in an element.

These methods are applicable to groups of elements whose Category.HasMaterialQuantities property is true (i.e. walls, roofs, floors, ceilings, and stairs). They also cover 3D families that have assigned materials, such as windows, doors, columns, and generic model families.

Though these methods can extract as-modelled materials from the Revit document, the calculations performed within the prototype require gross material quantities of host elements, such as walls, floors, and roofs, where quantities are needed before being cut or modified by hosted components (e.g. during the installation of windows and doors etc.). The 'hide' method is not appropriate for this task, as it only removes the display of hosted components, while leaving their holes behind, as shown in Figure 5-9 and Figure 5-10.

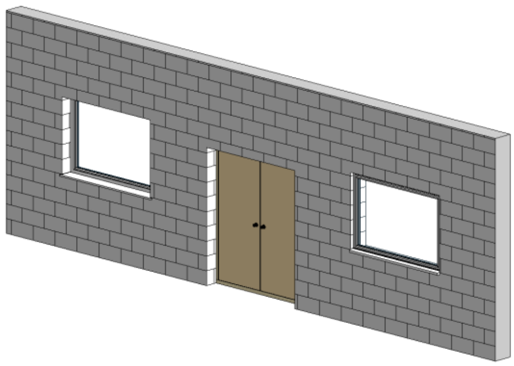


Figure 5-9: Wall before hiding of hosted elements

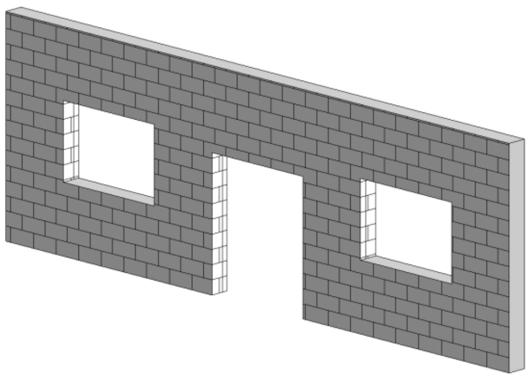


Figure 5-10: Wall after hiding of hosted elements

Extraction of gross materials is carried out using the temporary element suppression feature provided in Revit API. It employs the delete method temporarily for deleting cutting elements within host components (Figure 5-11).

Once gross material quantities are calculated, it restores the hosted components to their original state. It simply creates a transaction, deletes cut elements, extracts targeted quantities, and then aborts the performed transaction (Conover, 2009).

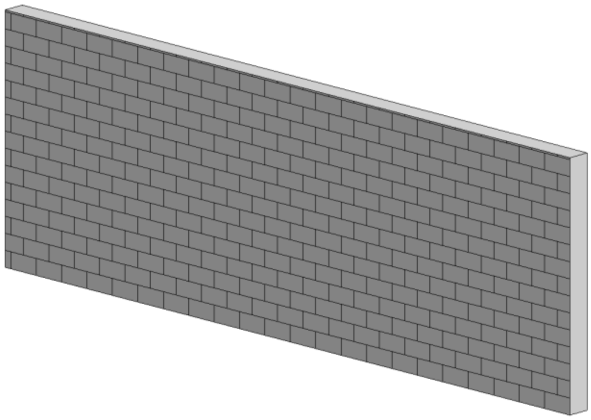


Figure 5-11: Wall after deletion of hosted elements

The Revit Software Development Kits (SDK) provided a sample of material quantities calculation. Therefore, the developed prototype customised its implementation to extract material quantities of design construction systems (e.g. slabs, floors, and roofs etc.). Extracted material quantities from design models are then cast into designated tables for different systems to be held temporarily (Table 5-4). Once the model is changed (and thus its quantities), then previous data is erased and replaced with new quantities.

Table 5-4: Description of SQL tables used for extracted materials quantities

Table Name	Description
RoofsQuantitiesTable	Contains quantities of extracted materials of targeted construction system based on the actual design in the active document.
FloorsDesignQuantitiesTable	
FoundationsDesignQuantitiesTable	
StrFramesDesignQuantitiesTable	
CurtainWallsDesignQuantitiesTable	
WallsDesignQuantitiesTable	

5.8. Assessment of design constructability

Figure 5-12 describes the mechanism of the assessment process executed by the prototype engine. It shows the performed calculations within each section of the model in order to obtain their representative scores. The CM contains specially designated containers and tables that are established in its database to hold achieved scores. Table 5-5 and Figure 5-13 demonstrate these tables and fields. Their data is populated following the assessment mechanism described earlier in section 4.5.5.

Table 5-5: Description of SQL tables used for the assessment process of design constructability

Table Name	Description
CalculatedFloors	Contains calculated scores of assessed systems based on actual extracted quantities and their corresponding assigned priorities. It also contains the final achieved score from their summation.
CalculatedRoofs	
CalculatedFoundations	
CalculatedStructuralFrames	
CalculatedEnvelopes	
CalculatedWalls	
NonCompliantColumns	
ObjectivesSatisfaction	

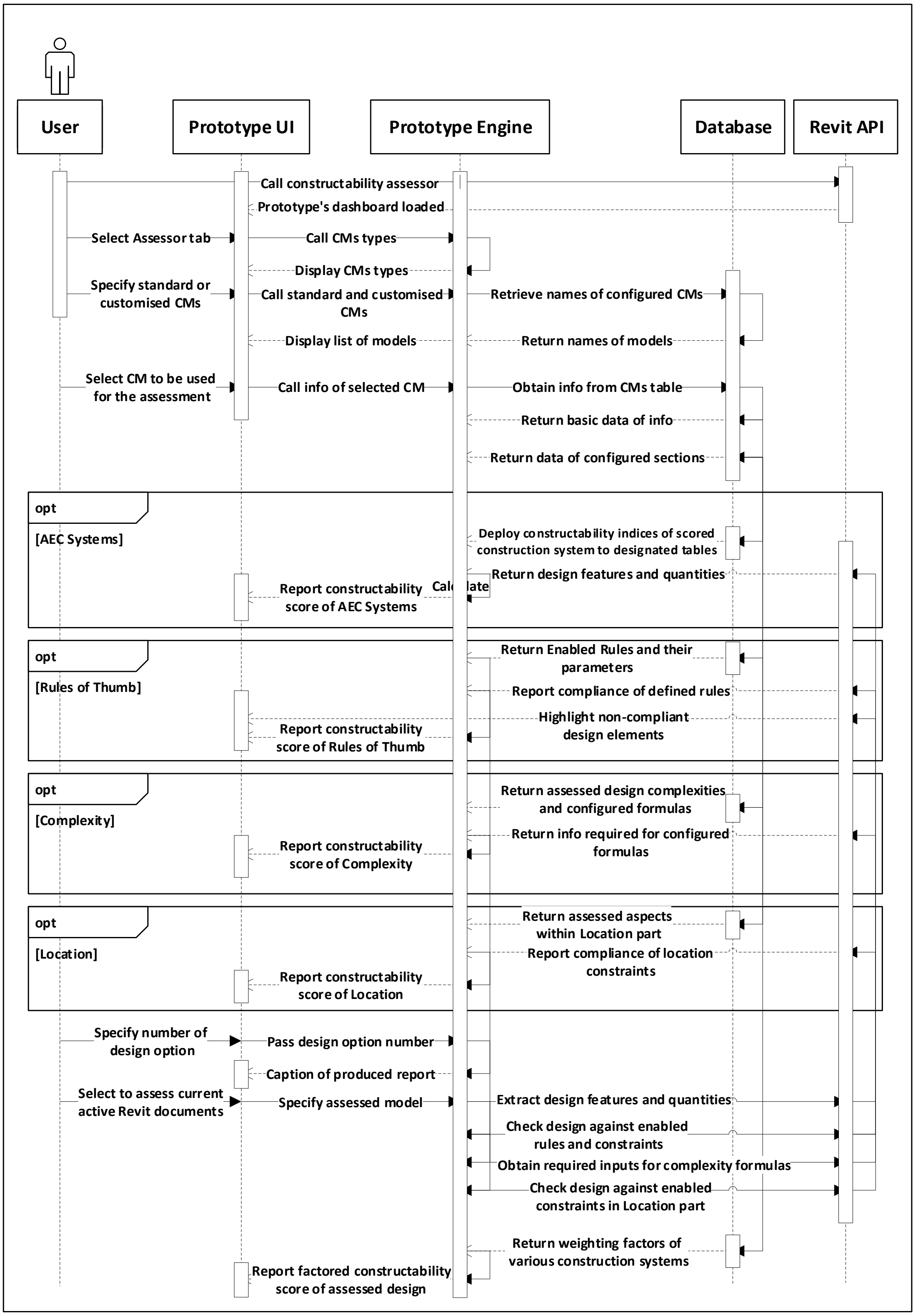


Figure 5-12: Sequence for carrying out the assessment process

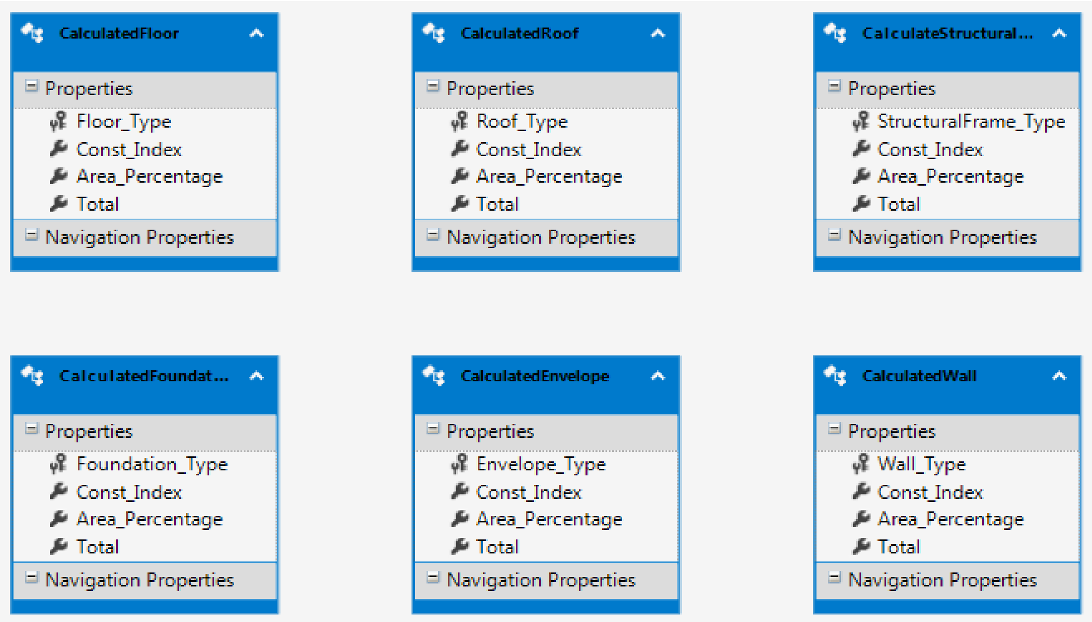


Figure 5-13: Containers within the established database to hold extracted data from the design model and be reasoned with stored info within CMs

5.9. Accessing performance adviser rules

In the Rules of Thumb part, to access predefined/customised rules, the Performance adviser is employed through its PerformanceAdviser singleton class, which acts as a registry of all rules, as well as an engine to execute them. The static method PerformanceAdviser.GetPerformanceAdviser is used to get an instance of the singleton class PerformanceAdviser. The PerformanceAdviser object enables accessibility to a list of all registered rules' IDs within the application, using GetAllRuleIds method. Also, rules data can be obtained by iterating each rule ID using the methods GetRuleName and GetRuleDescription.

5.10. Summary

The chapter described the implementation of the proposed assessment system through a plug-in to the Revit platform. The implementation environment and its components are discussed, and key features of the prototype development are presented. Aspects of the prototype operation are also covered through implementing a combination of classes and event handlers to deliver the sought functionality. Case studies are presented in the next chapter for further illustration of the implemented prototype and to demonstrate its operation.

6. A Case Study Using the Proposed Prototype

6.1. Introduction

This chapter demonstrates the employment of the implemented prototype in a typical case study. It seeks to illustrate its effectiveness in capturing the constructability of examined conceptual designs. A proposed design for a new central library based in Nottingham City is considered for examination purposes. Various design options are tested to understand their sensitivity to the constructability assessment, as well as the prototype behaviour in capturing such responses. Aspects related to the case study goal, its implementations, and obtained outcomes are analysed and discussed within the course of this chapter.

6.2. Case study goal

The ultimate goal of the case study is to demonstrate the usefulness of the implemented prototype in quantifying design constructability. It is believed that using a typical design case for this purpose can prove such usefulness. However, the example must achieve other targeted aspects, namely to:

- Demonstrate the prototype operations and access of its features within the Revit platform, exploring its tabs and describing their functionalities.
- Demonstrate how to customise a CM, decide on its components, and score its elements. This should provide guidance for users on how to configure their own CMs. It also provides an insight into the assessment mechanism, and how to input data at the stage of customisation, which will affect the obtained results when the model is utilised.
- Illustrate how to view the contents of the existing CM or adjust their configurations to suit other design cases.
- Demonstrate how to utilise a configured or standard CM for assessing the constructability of design alternatives.
- Explain how to read obtained assessment results and analyse their implications on assessed design versions.

- Examine the sensitivity of design constructability to the assessment process and the prototype performance in capturing this.
- Use the obtained results to draw a strategy for improving the constructability of examined designs while delivering solid and tangible recommendations.
- Discuss the efficacy of the introduced system in enabling the design team to improve their design constructability.

6.3. Case study brief

The proposed design is for a new central library to be built in Nottingham City Centre. It is intended to be a landmark building located in an area of the city currently undergoing regeneration. This is a good example to use for validation purpose due to the criticality of project location and constructability aspects that require careful consideration, including site logistics and constraints, storage space, the health and safety of workers, as well as surrounding pedestrians in a busy, multi-purpose urban environment. Aspects of discussion will cover assessed parts that are addressed by the prototype given the scope of its implementation within the course of this study.

6.4. Case study implementation

6.4.1. Assessment strategy

Constructability examination is implemented in two stages for better exploration of the sensitivity of considered designs towards the assessment. It also exemplifies the effectiveness of the proposed model through its implemented prototype in capturing such behaviours. These are presented as follows.

6.4.1.1. Stage (1) constructability assessment

Three design options are assessed for their constructability performance using the implemented prototype. At this stage, the same design shape is kept, with the only difference being in the construction systems used. This allows for testing the sensitivity of constructability for the quality of design elements, instead of quantity. The dominant factor in the obtained outcomes at this stage is the customised CM itself. Assigned scores and constraints favour one design over the others. Tested types of structures include concrete, steel, and precast buildings.

6.4.1.2. Stage (2) constructability assessment

Once the impacts of using various construction systems on constructability are observed, the effect of design shape is examined. The design shape of the best-performing option from stage (1) is modified for this purpose, seeking to make changes in calculated quantities rather than system types. Therefore, the same conditions of the CM are imposed in order to distinguish the impacts of shape changes. This mainly affects obtained scores under AEC Systems, since its assessment is based on calculated design quantities. However, other CM sections may also be affected by such changes and their consequences. This includes changes in design compliance with defined constraints, or introducing any new complexities.

6.4.2. The proposed design model (BIM model)

Figure 6-1 and Figure 6-2 show the design options for the considered case study at stage (1) and (2) of the assessment (respectively). These are developed in Revit BIM-authoring tool, where the introduced assessment method is implemented. The main differences between these options are highlighted in Table 6-1. This includes aspects such as shapes, layout, sizes, dimensions and material types of used construction systems for options at stage (1). It also shows whether any standardisation or repetitions are adopted within these design solutions. The aim is to cover critical aspects that are believed to have an obvious say in informing the decision-making process from a constructability point of view. This later facilitates any course of evaluation for the proposed prototype in capturing the sensitivity of this aspect.

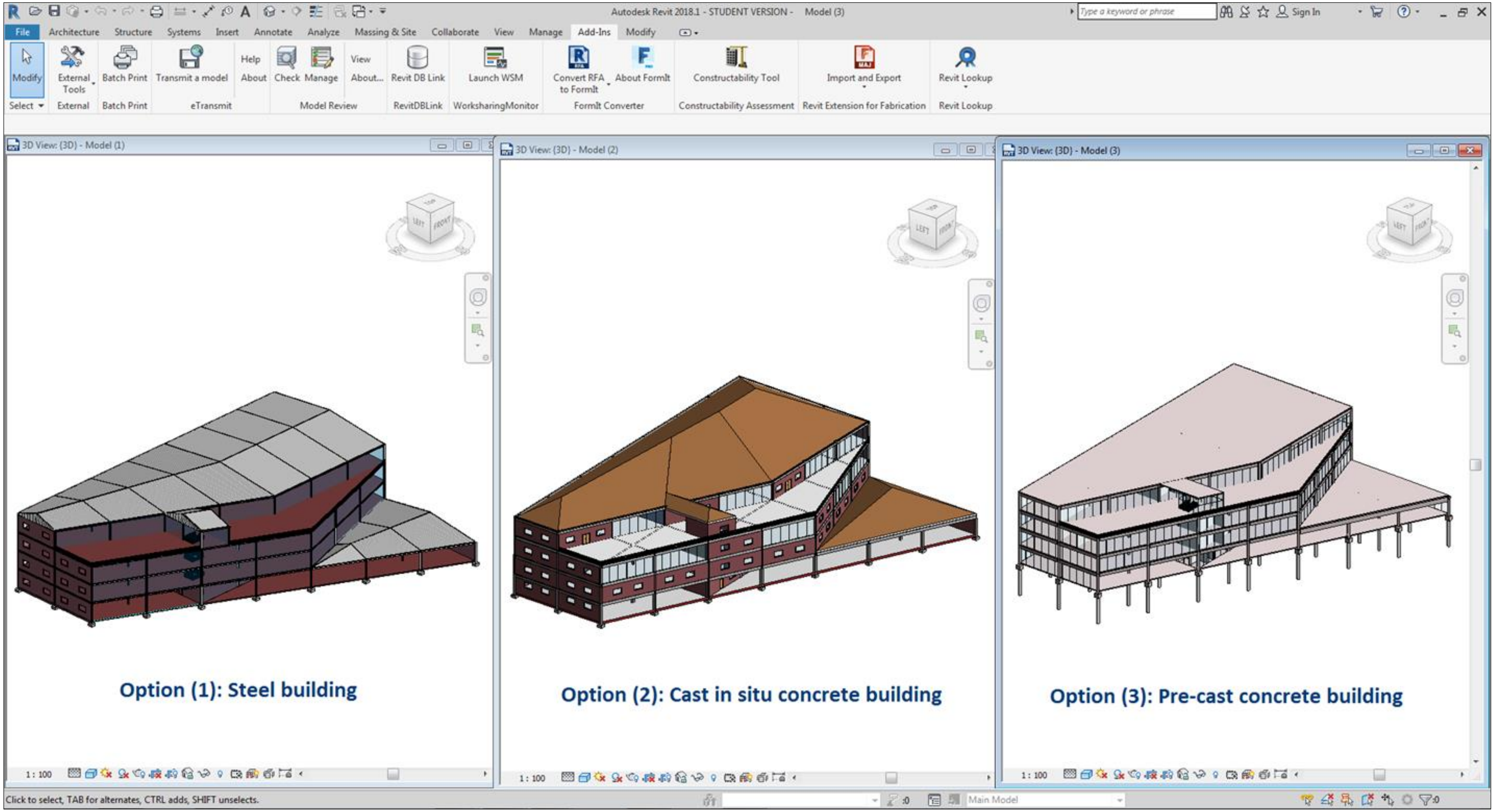


Figure 6-1: Examined 3D models for their constructability performance at stage (1)

Table 6-1: Main differences between examined design options

Construction System	***Design Aspect***	***Design Option (1)***	***Design Option (2)***	***Design Option (3)***
Building type		Steel	Concrete (cast *in situ*)	Concrete (precast concrete)
Roof	Shape	Basic roof (trusses with aluminium sheets)	Pitch roof (default roof type)	Flat roof
Floors	Structural system	Floor-upper 160mm slab with steel beams	Cast *in situ* slabs with beams	Precast flat slab (precast hollow core slab)
Curtain walls	Type	Glazing walls + default walls (with wood finishes)	Bricks + glazing walls	Curtain wall cladding
Internal walls	Material	No internal walls	Uses various types of walls (including wood type)	Use various wall types (basic wall generic 200mm -> 130mm for the project)
	Internal layout	Open space	Contains some narrow rooms (working space)	Normal layout
Columns	Shape	I section (steel)	Square (cast *in situ* concrete)	Round (precast)
	Sizes	Different sizes (per floors)	Same column size (per floors)	Same column size
Beams	Layout	Primary and secondary beams (different sizes)	Same beams size	Same beam size
	Shape	I section (steel)	Rectangular beams (concrete)	Precast cone-shaped beam
	Sizes	Contains big trusses need lifting	Normal concrete beams	Contains big girders
Connections	Type	Contains complex connections (many members with different sizes)	Simple connections	Has issues in connecting precast components together
Trades	Window and doors	Not many (mainly glazing walls)	Many windows and doors	Not many (mainly glazing walls)
	Ducts	No ducts	Some ducts in the middle for pipes to go through	No ducts
Foundations	Type	Footings (or maybe raft foundation)	Footings	Precast piles (pile cap 1 pile)
	Sizes	Same	Same	Same

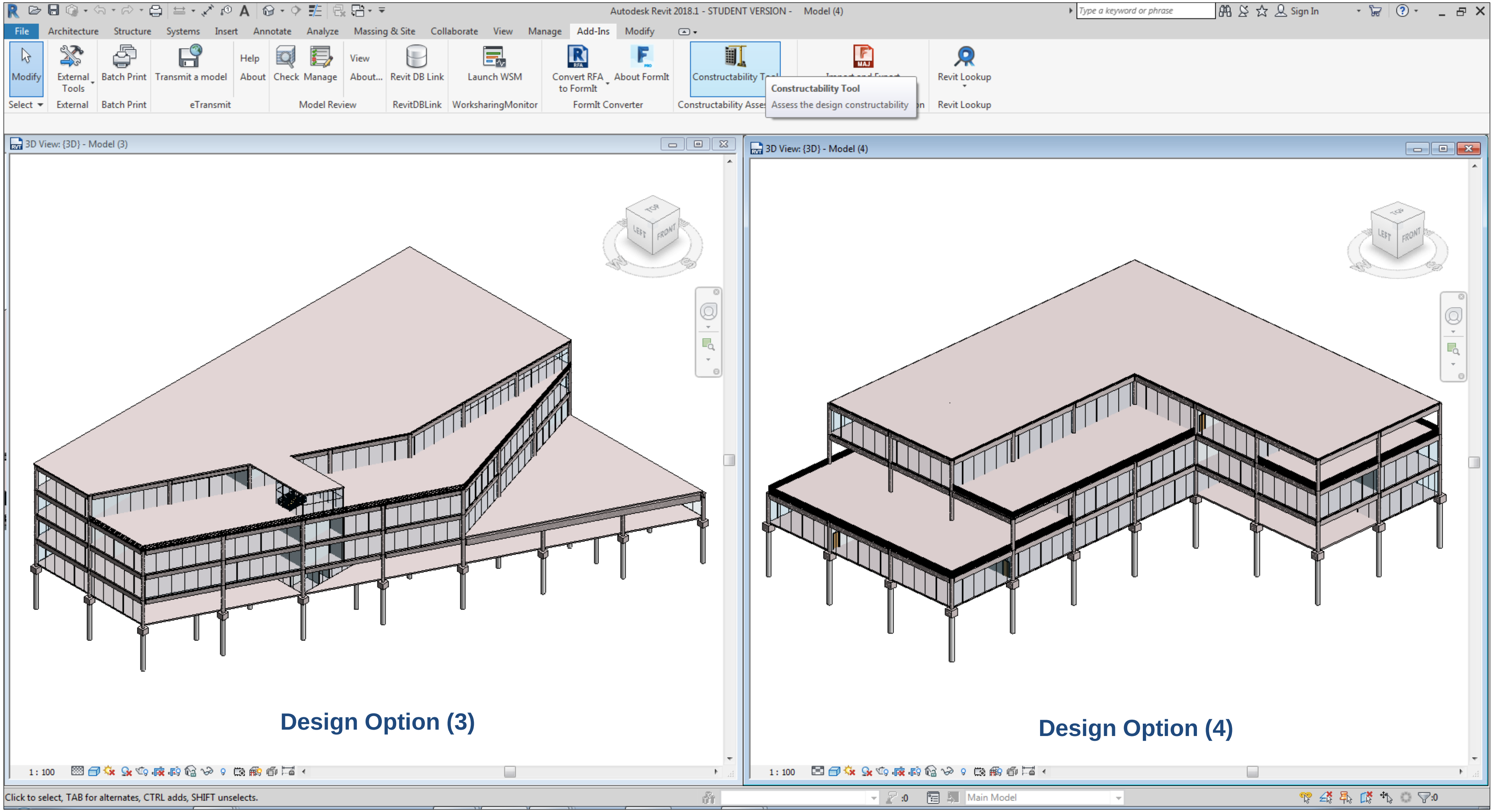


Figure 6-2: Examined 3D models for their constructability performance at stage (2)

6.4.3. Preliminary constructability analysis of proposed designs

There are some points to highlight before embarking on the assessment of considered designs, to demonstrate the element of challenge associated with the constructability concept to be implemented in design cases. The discussion and remarks tackle how these points are considered and addressed in the proposed assessment method.

- Different assessors express different opinions about the constructability of examined design alternatives. This stems from the way they approach the concept and the constructability aspects that most attract their attention. Also, their previous construction experience and usual issues they confront, will always direct their focus towards observing such familiar issues in examined designs.
- When it comes to deciding on the constructability of specific construction systems, there is a fine line between utilising accumulated construction knowledge from previous projects effectively, and stereotyping the re-use of these systems without consideration of novel contexts and surrounding circumstances.
- Observers will be able to identify some constructability issues in these design solutions, but struggle to identify all potential issues. Furthermore, they might not be able to draw a conclusion that favours one design over others to optimally satisfy the targeted objectives, except in unusually clear decisions. This is because of the complexity of overlapping and interrelated aspects from numerous stakeholders involved in projects (the underlying rationale for designing the CM and this research itself). Unless this is broken down into simple chains of reasoning, as the research suggests, a decision regarding what the most constructible design will be challenging to make.

6.5. Customising CM

A detailed description of how to configure a new CM and the rationale were explained in section 4.5.5. This section demonstrates the use of the implemented prototype to create a new CM. Whilst the presented scores in figures of this section are subjectively determined by the views of their scorers, they demonstrate users can now influence the process to represent their situations. The illustrative CM aimed at ascertaining that the proposed system accommodates such subjectivity based on the users' input. The validation of the true representation of scored numbers to reflect their scorers is beyond the scope of the study, and has already addressed by previous studies that used AHP to extract and represent construction knowledge based on surveys and conducted interviews (Hei, 2007, Lam et al., 2012).

6.5.1. Accessing the Constructability Assessor Prototype UI

The prototype's main user interface consists of four tabs: dashboard, analyser, assessor, and explorer. The dashboard section is designed to contain all previous customised CMs as well as standard CMs developed by professional bodies for public use in specific regions. Its functionality includes options to view these models, modify their contents for a new user, or even customise new CMs if needed (Figure 6-3).

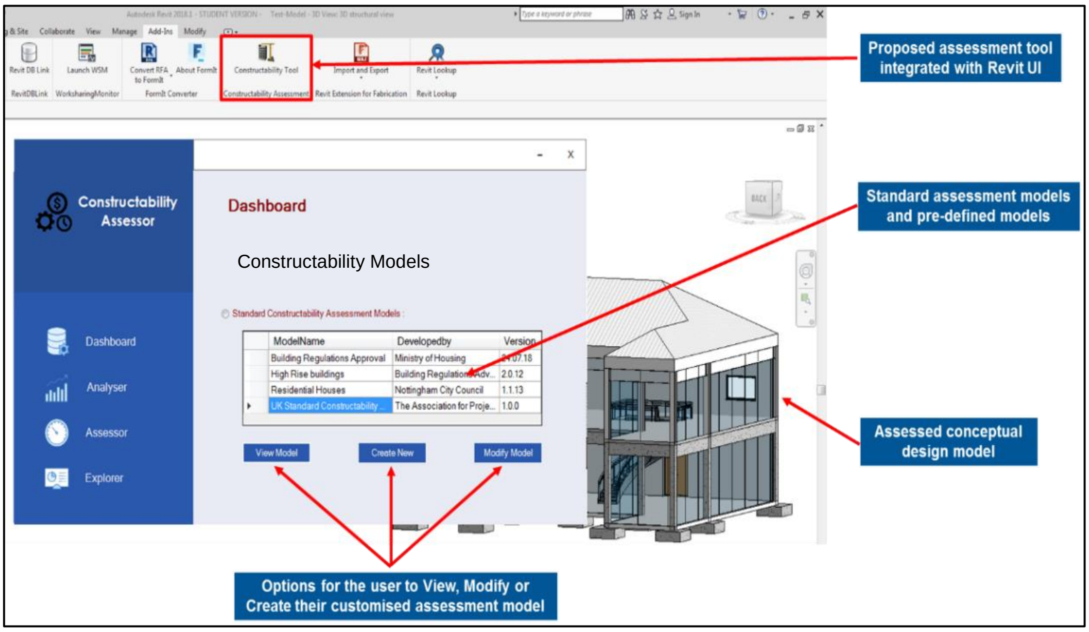


Figure 6-3: Viewing, creating and modifying CMs within the prototype's dashboard

6.5.2. Customisation of a new CM

6.5.2.1. Establishing the new CM template

Users are always able to customise a new CM or adjust an existing one to suit the assessment of specific design case. The implemented prototype guides its user to go through such a process intuitively and interactively. It adapts the customisation process based on the users' response and captured requirements.

The process of configuring new CM starts by creating the shell that will contain its contents (Figure 6-4). This includes providing basic information about the model (i.e. name, description, etc.) as well as the CM modules that are to be customised (AEC System, Rules of Thumb, Complexity, and Location). Following this, each enabled module is to be customised separately to establish their elements and aspects to be assessed.

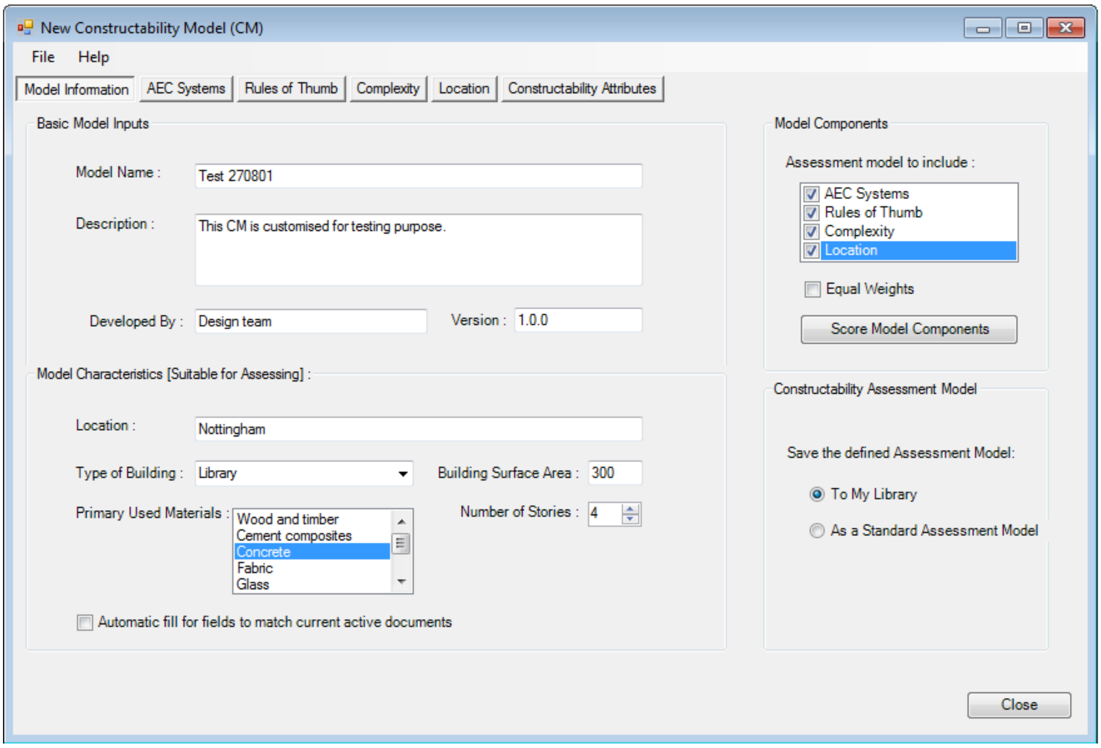


Figure 6-4: Customisation of a new CM

The input information shown in Figure 6-4 is meant to document the types of buildings for which such a model could be used to assess constructability. It facilitates the subsequent searching process by different users to find a suitable model, using any keywords associated with these models.

Figure 6-4 shows that the four CM sections (i.e. AEC Systems, Rules of Thumb, Complexity, and Location) are enabled for the model being customised (Test 270801). As such, they will accordingly appear for users to assign them weighting factors, reflecting their relative (customised) importance in relation to constructability performance.

6.5.2.2. Assignment of weighting factors for enabled CM modules

To assign weighting factors that reflect the importance of the assessed aspects by enabled modules, the AHP technique is used following the described procedure in section 4.5.5. A series of pairwise comparisons for enabled modules will articulate the user perspective to establish relative importance weights. For example, Figure 6-5 shows that what the AEC Systems assess is considered to be three times as important as what the Rules of Thumb assess, given the situation that this particular CM addresses. It implies that the scorer is concerned about matching the design necessities for construction resources against the constructors' capabilities more than the satisfaction of a set of defined rules. The prototype feature to calculate the consistency ratio (1.1% in this case) meant to inform users of the accuracy of performed pairwise comparisons to ensures the integrity of obtained weights. The recommendation is to keep such consistency ratio less than 10%, as explained in section 3.3.1.

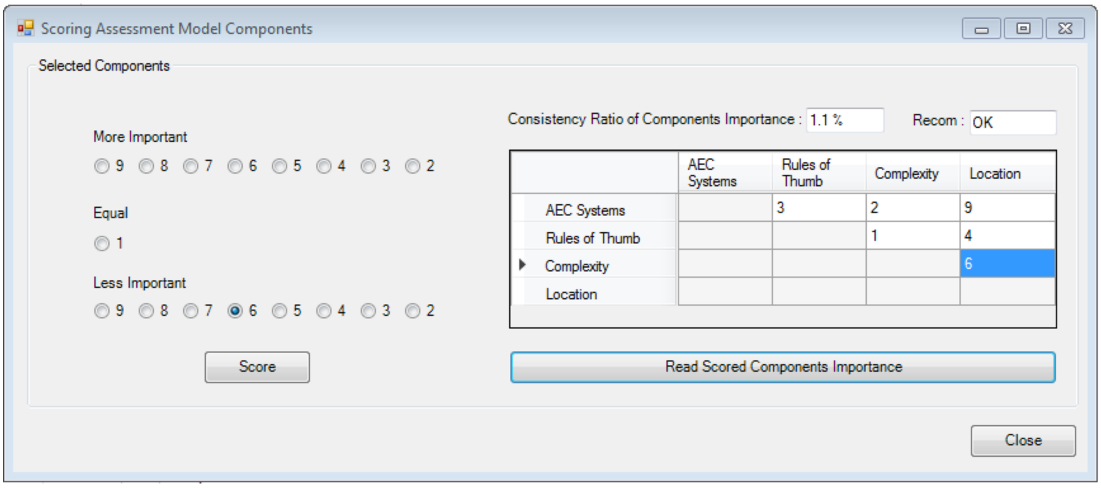


Figure 6-5: Assigning importance weights for selected CM model components using AHP scores

Using the input scores in Figure 6-5, the prototype generates a weighting factor for each part to mark its contribution to the overall obtained Constructability score. Table 6-2 illustrates the performed calculations in the background to transform the scores into weights. Once these are calculated (Figure 6-6), they are deployed by the prototype to designated tables in the database to be associated with this CM (Test 270801). This is confirmed by a success message delivered to the user (Figure 6-7).

Table 6-2: Assignment of Weighting Factors for enabled CM modules

CM module	AEC Sys.	Rules of Th.	Comp	Loc.	Pairwise comparisons	Priority vector
AEC Systems	1	3	2	9	$(1 \times 3 \times 2 \times 9)^{1/4} = 2.711$	2.711/5.363 = **0.50**
Rules of Thumb	1/3	1	1	4	$(1/3 \times 1 \times 1 \times 4)^{1/4} = 1.075$	1.075/5.363 = **0.200**
Complexity	½	1	1	6	$(1/2 \times 1 \times 1 \times 6)^{1/4} = 1.316$	1.316/5.363 = **0.25**
Location	1/9	1/4	1/6	1	$(1/9 \times 1/4 \times 1/6 \times 1)^{1/4} = 0.261$	0.261/5.363 = **0.05**
Total					5.363	1

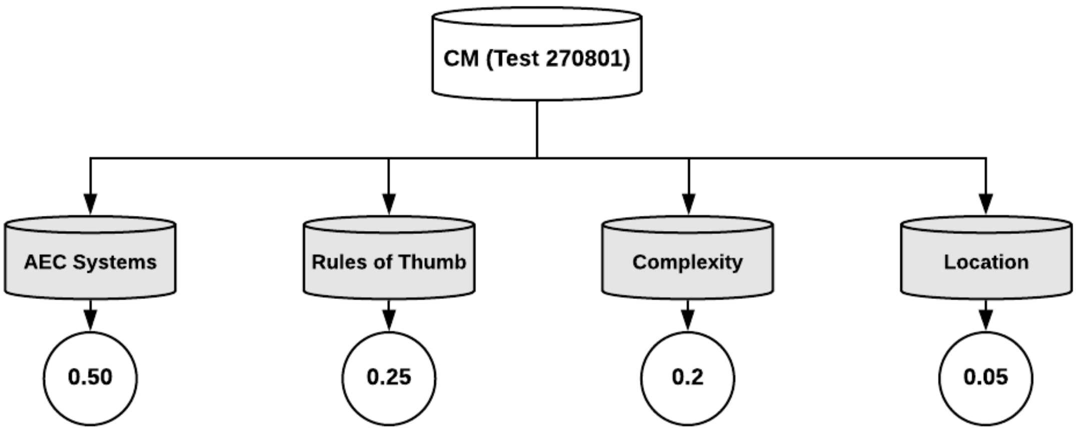


Figure 6-6: Established weights of CM components

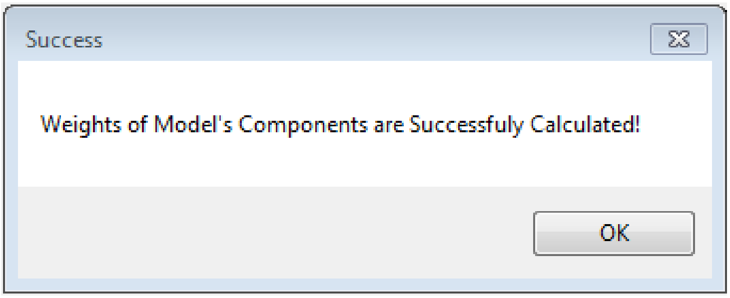


Figure 6-7: Success Message Confirming calculation of Model Weighting factors

As can be seen in Figure 6-6, AEC Systems is assigned the highest importance factor, achieving (0.50). This means that the overall calculated constructability score at the assessment stage will depend mainly (50%) on the performance of this aspect. This is followed by Rules of Thumb (0.25), then Complexity (0.2), and finally Location (0.05). The implication of this balance encourages the user to focus on the improvement of aspects that are assessed by the AEC Systems. A strategy describing how to interpret the achieved results to improve constructability is laid out in section 6.8.

6.5.2.3. Customisation of CM modules

As all four CM sections are enabled to be considered during the constructability assessment of design products, the next stage is to customise what they assess from the users' perspective.

1. *Customisation of AEC Systems Module*

The customisation of this section covers two main parts. The first part is the articulation of users' capabilities and constraints in the form of constructability indices to be assigned to the design features and elements. This includes configuration of construction systems that are to be assessed, as well as the criteria and sub-criteria of the assessment.

The second part is the development of local weighting factors that govern the contribution of various construction systems towards the calculated AEC Systems score. This is calculated based on the contribution of these systems towards the accomplishment of the design objectives in terms of cost and time etc.

In the implemented prototype, as Figure 6-8 shows, users can enable only desired parts when structuring the AEC Systems hierarchy. In this case, all construction systems (roofs, floors, foundations, envelopes, walls, and structural frames) are to be assessed for their constructability performance at the assessment stage. Also, all design objectives, which are exemplified in the implemented prototype, are enabled to shape the model's priorities. Concerning the criteria and sub-criteria of the assessment, it can be seen that some of them are not considered in the scope of the CM being customised (e.g. energy and general conditions). This demonstrates the greater flexibility of the system when structuring the CM hierarchy, relative to its predecessors.

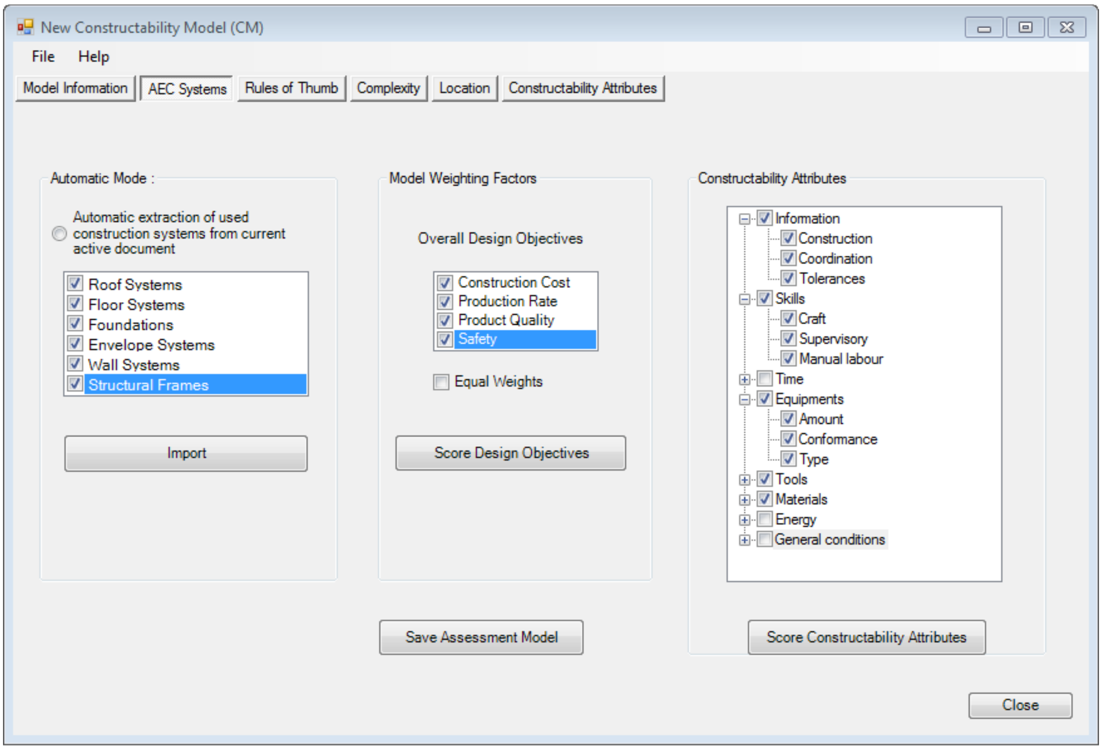


Figure 6-8: Elements of AEC Systems section to be configured within new CM

Consequently, this results in a scoring problem, as depicted in Figure 6-9. The prototype processes these inputs and reacts on that basis in the next stages.

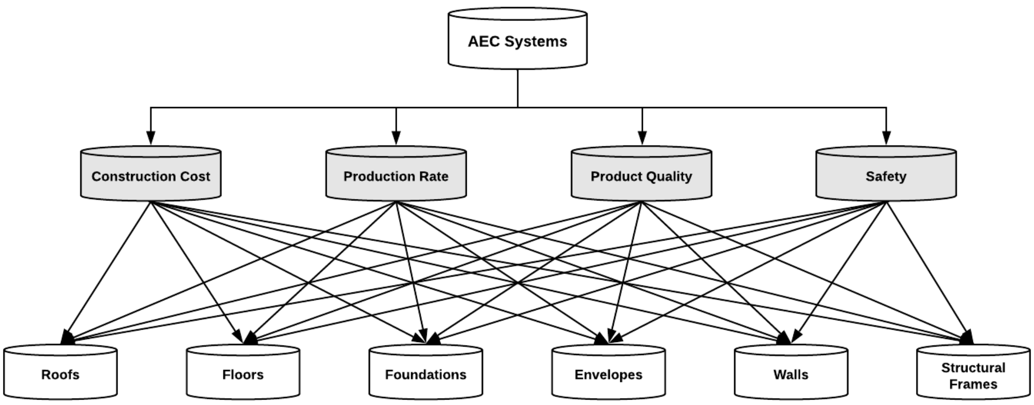


Figure 6-9: Hierarchy of CM: AEC Systems

2. *Assignment of weighting factors for construction systems*

Figure 6-10, Figure 6-11, Figure 6-12, and Figure 6-13 present the scored weights of selected construction systems based on their contribution towards satisfying the design objectives (Figure 6-9). The top part of the figures is concerned with assigning weights for considered design objectives (Cost, time, quality and safety as selected in this case study). It enables users to define what a constructible design means to them when scoring these objectives.

As an example, the mentioned figures show that the cost aspect is considered to be three times as important as the production rate. Consequently, it directs the focus towards ensuring the constructability of specific aspects, that will otherwise incur additional costs if deemed to be not constructible. Whilst the design objectives is a grey area and can be transferred from one shape to another, the pairwise comparisons are meant to simplify the problem by breaking it into parts for consideration.

The recorded weights of the objectives act as the basis of calculating the construction systems weighting factors (i.e. slabs, floors, structural systems, etc.), as discussed in section 4.5.5. This is indicated by scoring the bottom parts of the figures, remarking the contribution of each construction system in comparison to others to achieve a particular objective. For instance, if the time factor is found to be dominating, then construction systems that consume more time to build will be assigned higher importance weights. Consequently, it incentivises users to perform well in such category by considering design components that are quicker to construct.

When scoring these figures, users can adopt different strategies to communicate their requirements and conditions. As an example, the study used the discussed strategy in section 4.7.1 to automate the process of configuring construction systems weights, as a guide in scoring the current problem. It uses BIM related data to aspects such as cost, time, etc. to establish importance relativity between modelled features. For instance, if the cost of used components for a slab system is £50,000, based on associated semantic data within the BIM model, while the wall system costs £25,000, this indicates that the slab system would be given double the importance of the wall system from a cost perspective. Table 6-4 demonstrates the implementation of such a strategy to develop the scores of construction systems concerning cost and time objectives. For other objectives, these can be based on available data such as the occurred number of health and safety incidents or figures that are published by the local authorities.

The prototype uses the input scores from the user perspective to establish weights of design objectives, and respectively weighting factors for main construction systems. Table 6-3 and Table 6-4 demonstrate how these weights are generated from scored figures. Such calculations are performed in the background of the implemented prototype in response to the user inputs. The achieved weights are automatically deployed to designated database tables, ready to be used when the model is employed to assess a certain design case.

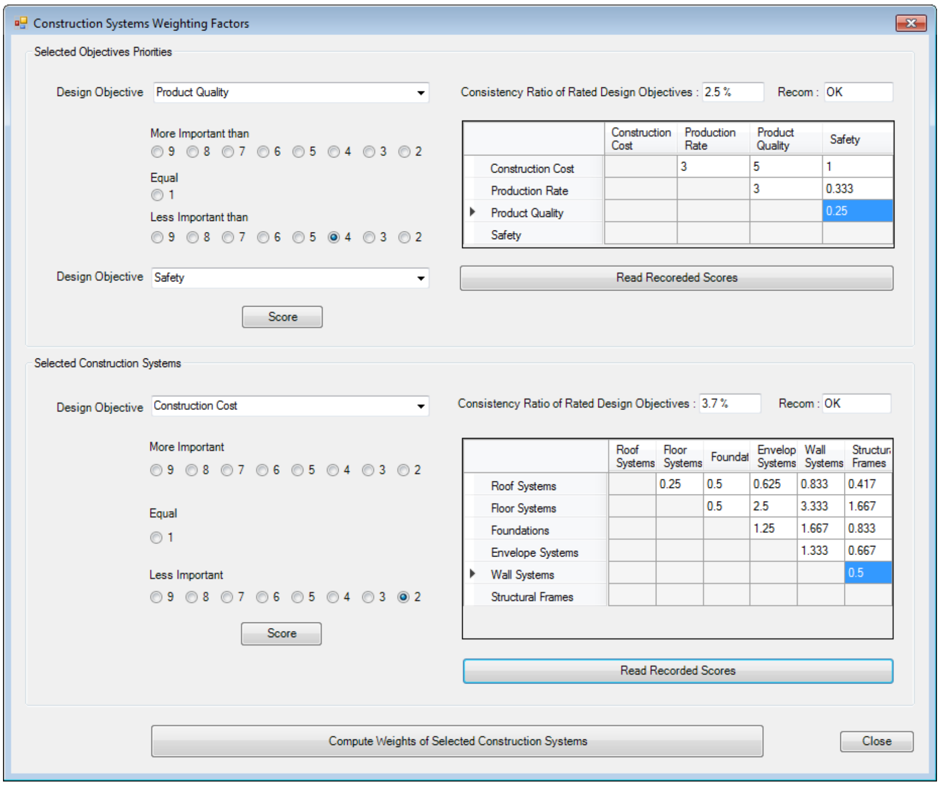


Figure 6-10: Pairwise comparison for enabled Construction systems with respect to the ***Cost*** *objective*

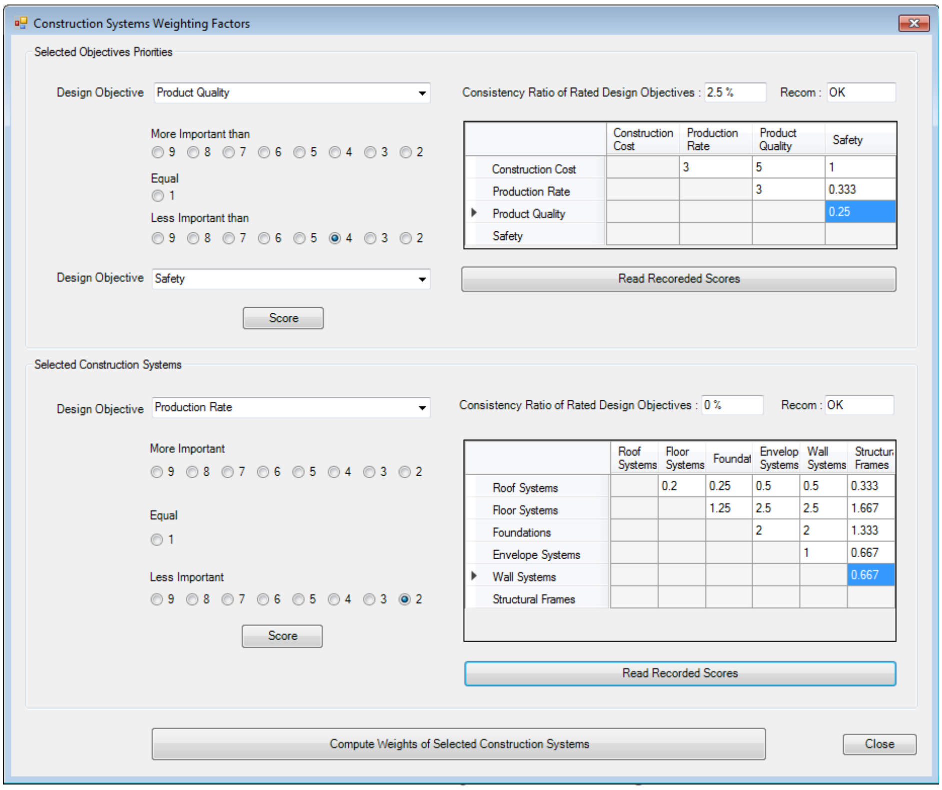


Figure 6-11: Pairwise comparison for enabled Construction systems with respect to the ***Production Rate*** *objective*

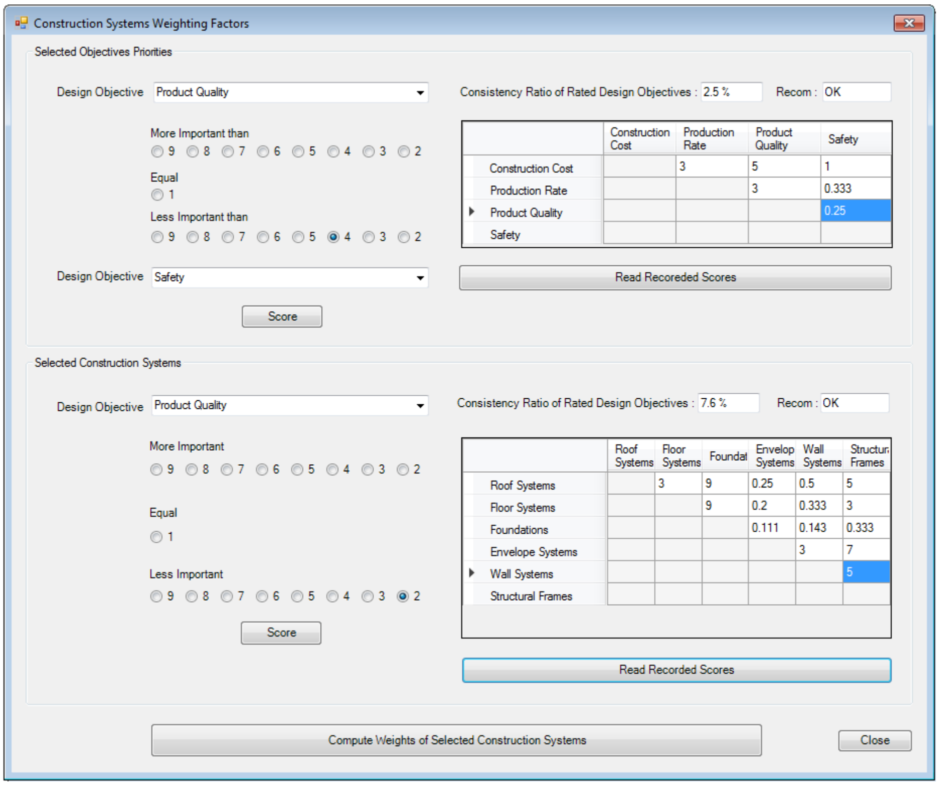


Figure 6-12: Pairwise comparison for enabled Construction systems with respect to the ***Quality*** *objective*

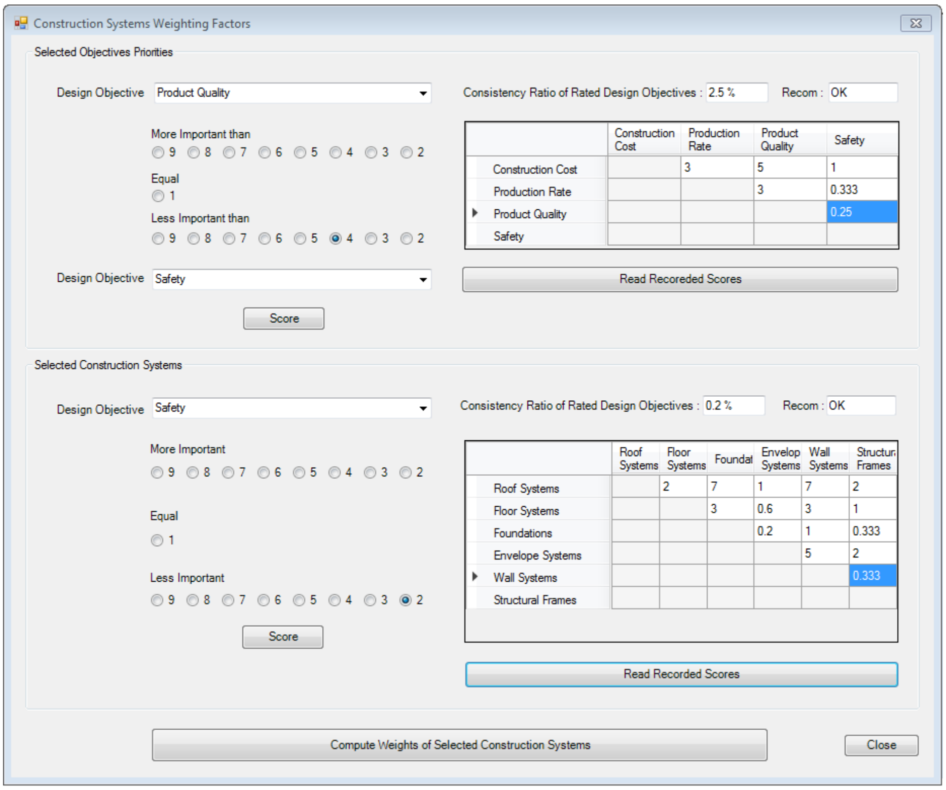


*Figure 6-13: Pairwise comparison for enabled Construction systems with respect to the **Safety** objective*

Table 6-3: Calculations of importance factors of defined design objectives

CM module	Cons. Cost	Prod. Rate	Prod. Qual.	Saf.	Pairwise comparisons	Priority vector
Const. Cost	1	3	5	1	$(1 \times 3 \times 5 \times 1)^{1/4} = 3.201$	3.201/5.677 = **0.395**
Production Rate	1/3	1	3	1/3	$(1/3 \times 1 \times 3 \times 1/3)^{1/4} = 1.495$	1.495/5.677 = **0.156**
Product Quality	1/5	1/3	1	¼	$(1/5 \times 1/3 \times 1 \times 1/4)^{1/4} = 0.669$	0.669/5.677 = **0.073**
Safety	1	3	4	1	$(1 \times 3 \times 4 \times 1)^{1/4} = 0.312$	0.312/5.677 = **0.377**
Total					5.677	1

Table 6-4: Calculations of weighting factors of construction systems with respect to established design objectives

Objective	Global weight	Const. Systems		Roofs	Floors	Found.	Envel.	Walls	Struct. Frame	Global priority
Const. Cost	39.5%	Roofs	£50,000	1	0.25	0.5	0.625	0.833	0.417	3.32%
		Floors	£200,000		1	0.5	2.5	3.333	1.667	10.54%
		Foundations	£100,000			1	1.25	1.667	0.833	8.37%
		Envelopes	£80,000				1	1.333	0.667	5.31%
		Walls	£60,000					1	0.5	3.99%
		Str. Frames	£120,000						1	7.97%
Prod. Rate	15.7%	Roofs	2 weeks	1	0.2	0.25	0.5	0.5	0.333	0.92%
		Floors	10 weeks		1	1.25	2.5	2.5	1.667	4.62%
		Foundations	8 weeks			1	2	2	1.333	3.69%
		Envelopes	4 weeks				1	1	0.667	1.85%
		Walls	4 weeks					1	0.667	1.85%
		Str. Frames	6 weeks						1	2.86%
Prod. Quality	7.3%	Roofs		1	3	9	0.25	0.5	5	1.31%
		Floors			1	9	0.2	0.333	3	0.75%
		Foundations				1	0.111	0.143	0.333	0.16%
		Envelopes					1	3	7	3.22%
		Walls						1	5	1.66%
		Str. Frames							1	0.21%
Safety	37.7%	Roofs		1	2	7	1	7	2	11.97%
		Floors			1	3	0.6	3	1	5.86%
		Foundations				1	0.2	1	0.333	1.90%
		Envelopes					1	5	2	10.38%
		Walls						1	0.333	1.90%
		Str. Frames							1	5.69%

Concerning the CM (Test 270801) being customised here, the performed calculation resulted in AEC Systems weighting hierarchy presented in Figure 6-14. It shows that Construction Cost is given the priority achieving (0.395), followed by Construction Safety: (0.377), then Production Rate: (0.156), and finally Product Quality: (0.073). All values are summed to 1.001, which is almost 1.0 given the rounding error during calculations. As a result of such assigned weights, construction systems that are deemed to have significant impacts on the cost aspects (e.g. slab systems), will be assigned higher factors to direct the attention towards improving their elements performance.

Concerning scored construction systems, achieved weights were as follows: Roof systems (0.16), Floor systems (0.20), Wall systems (0.09), Foundations (0.14), Envelopes (0.2), and Structural framing systems (0.21) from a user perspective. Again, all values are 1.0. Such results imply that the focus is mainly on the performance of the Structural framing, Floor systems, and Envelopes over other systems to some extent. This is due to their contributions towards both cost and safety objectives.

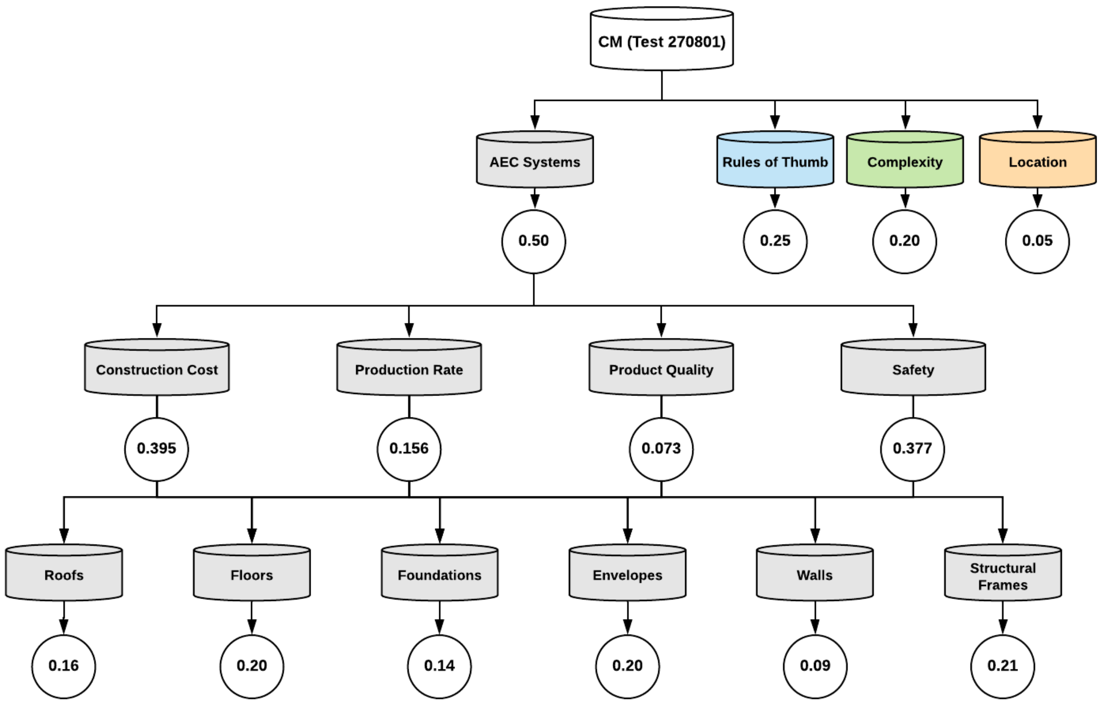


Figure 6-14: AEC Systems weighting hierarchy

3. *Scoring of enabled assessment criteria*

Having set one side of the scoring system, represented in the weighting factors hierarchy that imposes the user priorities. The next stage is to establish the constructability indices of design elements and features, mirroring their constructability status. This is carried out in line with the described procedure in section 4.5.5. Design elements and features categorised under main construction systems are to be ranked among their similar group and alternatives for enabled criteria and sub-criteria (Figure 6-8).

As it appears in Figure 6-15, the prototype depicted only enabled criteria to be considered at the assessed stage, presented in Figure 6-8, so they can be scored at this stage of customisation. Recorded scores are meant to set the importance of each criterion based on the accessibility of constructors to relative resources. For instance, and as Figure 6-15 shows, information criterion is considered to be half as important as skills, equipment and tools criteria, and quarter as important as materials criterion. This indicates that the materials aspect is given the priority here. As such, all design elements that have no materials issue will be ranked higher under this scheme. Similarly, skills criterion is considered to be twice as important as tools criterion. Subsequently, the system will favour construction options that require fewer skills in term of craft, supervisory, or manual labour (i.e. sub-criteria aspects), even if they demand more construction tools. This implies how the scoring system is meant to enable users to enforce their resources and limitations to achieve a constructible design that matches such capabilities.

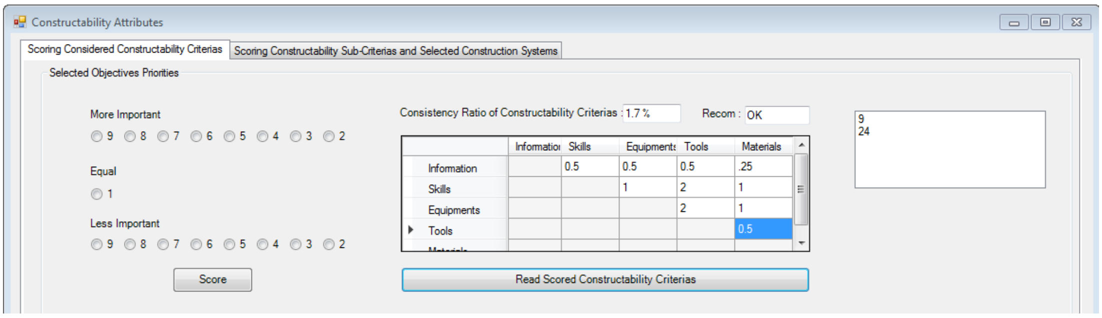


Figure 6-15: Pairwise comparison for Enabled Constructability Criteria

Using recorded scores in Figure 6-15, the prototype performed the required calculations, illustrated in Table 6-5, setting the priorities of the assessment criteria. It then deploys them to designated tables in the database to be associated with the CM (Test 270801) being customised.

As Table 6-5 shows, Materials criterion is scored as the most important criteria in this CM, achieving (0.28). This is relatively followed by Skills (0.244) and Equipment (0.244) criteria. Tools criteria achieved (0.14), while Information is scored as the least important criterion recording (0.092). These priorities are summed to 1.0 and accordingly will be reflected in weighted sub-criteria and systems alternatives.

Table 6-5: Pairwise comparisons of considered constructability factors

CM module	Info.	Skills	Equip	Tools	Mat.	Pairwise comparisons	Priority vector
Information	1	0.5	0.5	0.5	0.25	$(1 \times 1/2 \times 1/2 \times 1/2 \times 1/4)^{1/5} = 0.5$	0.5/5.414 = **0.092**
Skills	2	1	1	2	1	$(2 \times 1 \times 1 \times 2 \times 1)^{1/5} = 1.32$	1.32/5.414 = **0.244**
Equipment	2	1	1	2	1	$(2 \times 1 \times 1 \times 2 \times 1)^{1/5} = 1.32$	1.32/5.414 = **0.244**
Tools	2	0.5	0.5	1	0.5	$(2 \times 1/2 \times 1/2 \times 1 \times 1/2)^{1/5} = 0.758$	0.758/5.414 = **0.14**
Materials	4	1	1	2	1	$(4 \times 1 \times 1 \times 2 \times 1)^{1/5} = 1.516$	1.516/5.414 = **0.28**
Total						5.414	1

4. *Scoring of sub-criteria and generation of constructability indices for construction systems*

Once criteria weights are assigned, sub-criteria are to be scored with respect to their parent criteria for a specific construction system, for all systems. Figure 6-16 structures the hierarchy of established scoring problem, based on enabled items in earlier steps (Figure 6-8). In total, fifteen sub-criteria are enabled for consideration when ranking construction systems alternatives. Hence, each construction system alternatives (i.e. alternatives of floors, roofs, foundations, walls, envelopes and structural frames) are scored for their constructability with respect to these fifteen criteria. This results in five scoring matrices to be completed to generate priorities of sub-criteria clustered under parent criteria, and nineteen matrices to generate constructability indices of systems alternatives.

As an example, recorded scores of floor systems alternatives with respect to the fifteen criteria are presented in Figure 6-17 - Figure 6-31. Their top parts are concerned with prioritising sub-criteria importance when it comes to constructing floors, whilst the bottom parts are for scoring Floor options with respect to prioritised sub-criteria clustered under each criterion. The intuitiveness of the implemented prototype guides the user through such a process. Scoring figures of other 5 construction systems are enclosed in Appendix 2.

<u>Floor systems</u>

Figure 6-17 - Figure 6-31 show recorded scores to rate the constructability of three types of flooring system, representing potential alternatives for considered design solution. These options are timber joist with pine wood finish, precast concrete slab, or cast-in-place with metal decking. Their constructability indices are being calculated based on their performance with respect to set of criteria and sub-criteria decided on in earlier steps.

As an example, Figure 6-17 shows in its bottom part that the timber option is considered 3 times favourable than both of the concrete pre-cast and cast-in-situ options when it comes to the amount of information required on the construction site to install them. Such sub-criteria itself (i.e. information for construction) is considered to be 3 times less important than the required coordination efforts to install, and 2 times less important than the required tolerance in the accuracy information, for flooring systems. This can be justified as using concrete demands a higher level of coordination and has less flexibility if any dimensions are obtained mistakenly, as is the case for precast components. Similar rationales are adopted to rate the performance of considered options with respect to other criteria and sub-criteria. As described earlier, the implemented prototype allows for its users to input these flooring options manually, or to be extracted automatically from the design platform to their categorised construction system, as the case here.

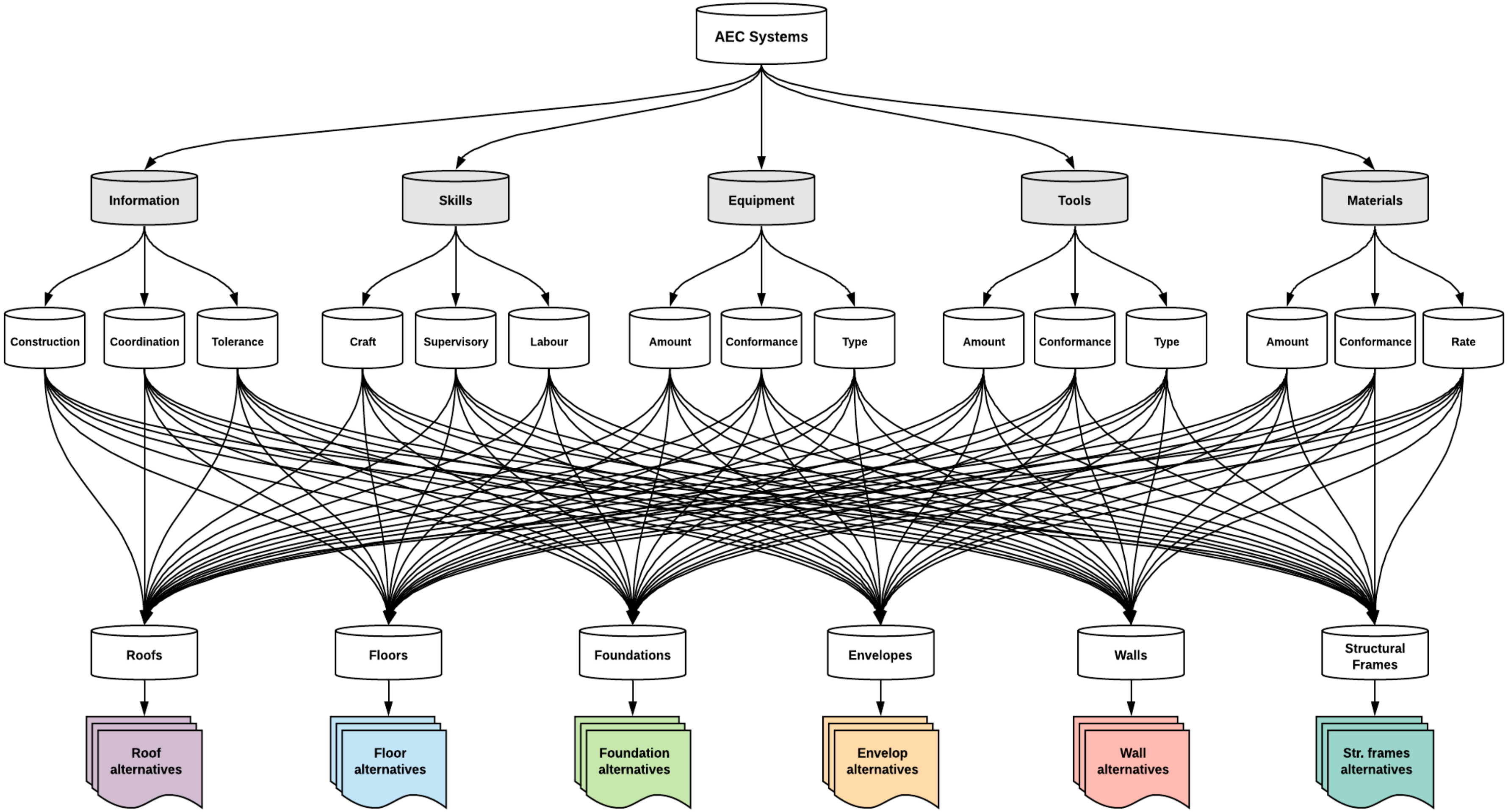


Figure 6-16: Example of established AEC Systems hierarchy by a user based on selected elements at different levels (i.e. criteria, sub-criteria, construction systems, and their respective alternatives)

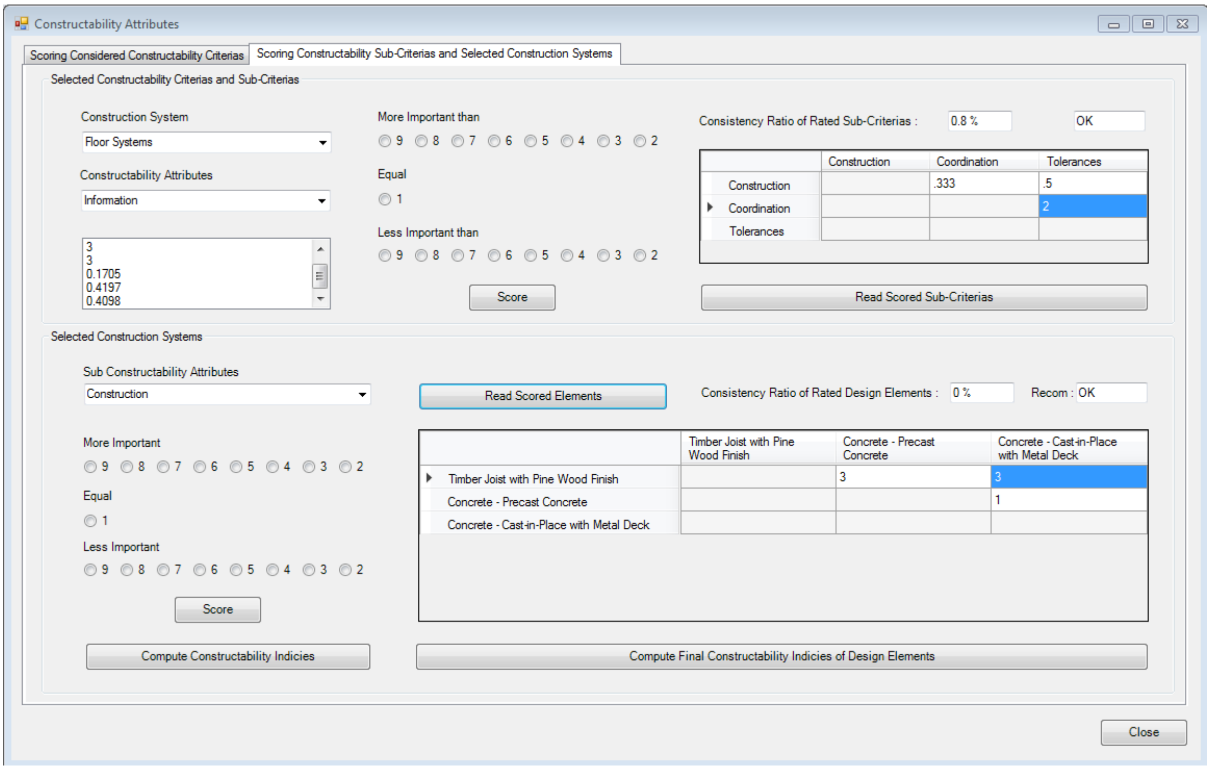


*Figure 6-17: Scoring **Floor options** with respect to **Construction** branch sub-criteria clustered under Information criteria*

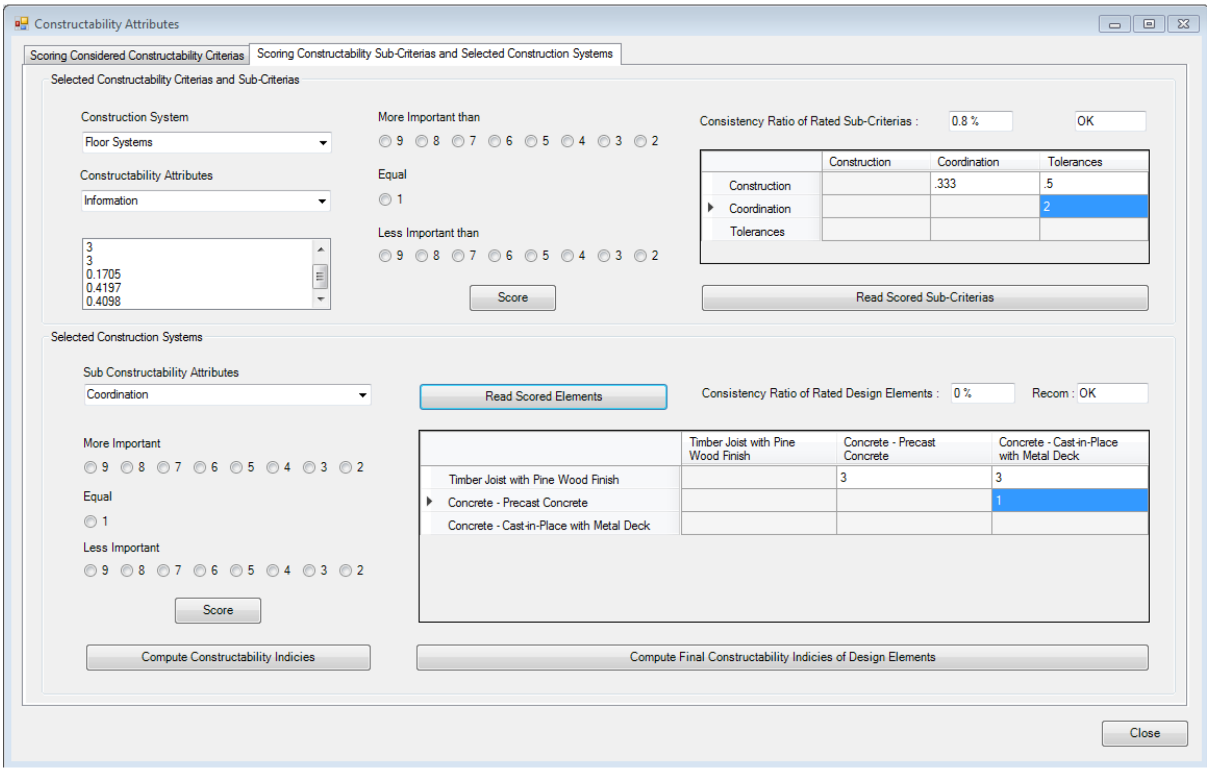


*Figure 6-18: Scoring **Floor options** with respect to **Coordination** branch sub-criteria clustered under **Information** criteria*

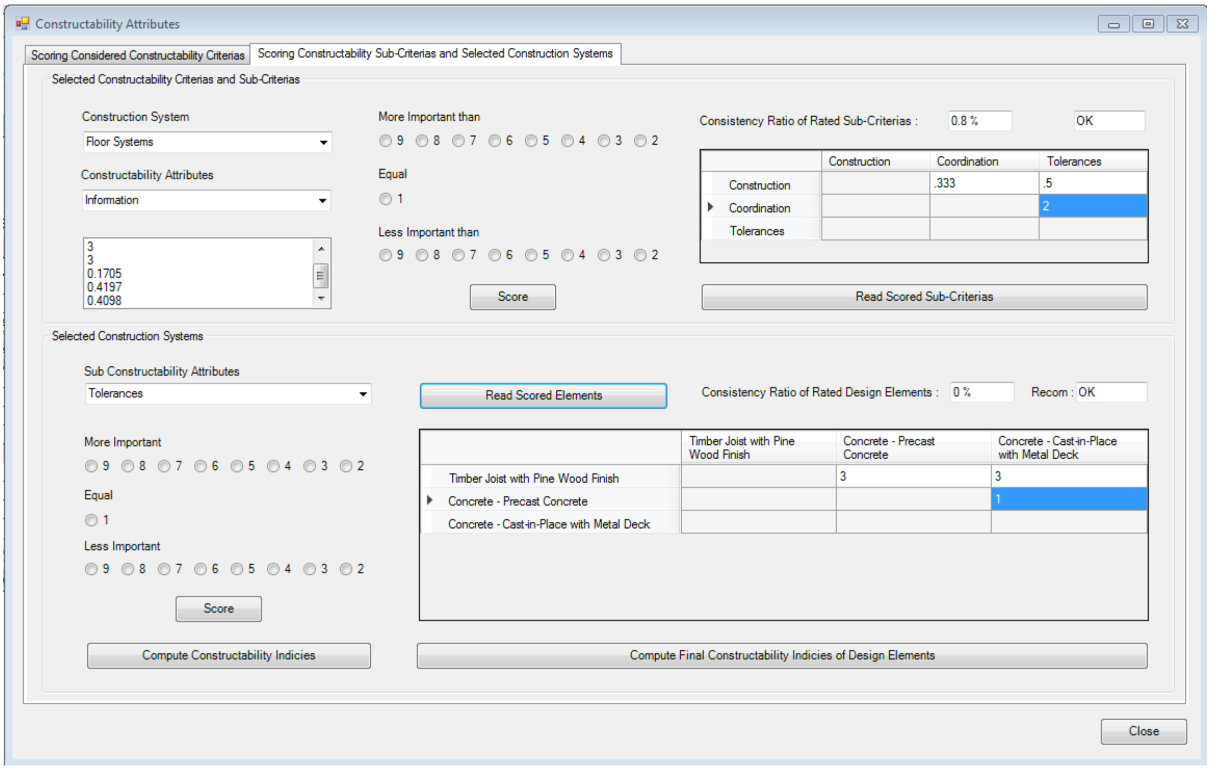


*Figure 6-19: Scoring **Floor options** with respect to **Tolerance** branch sub-criteria clustered under **Information** criteria*

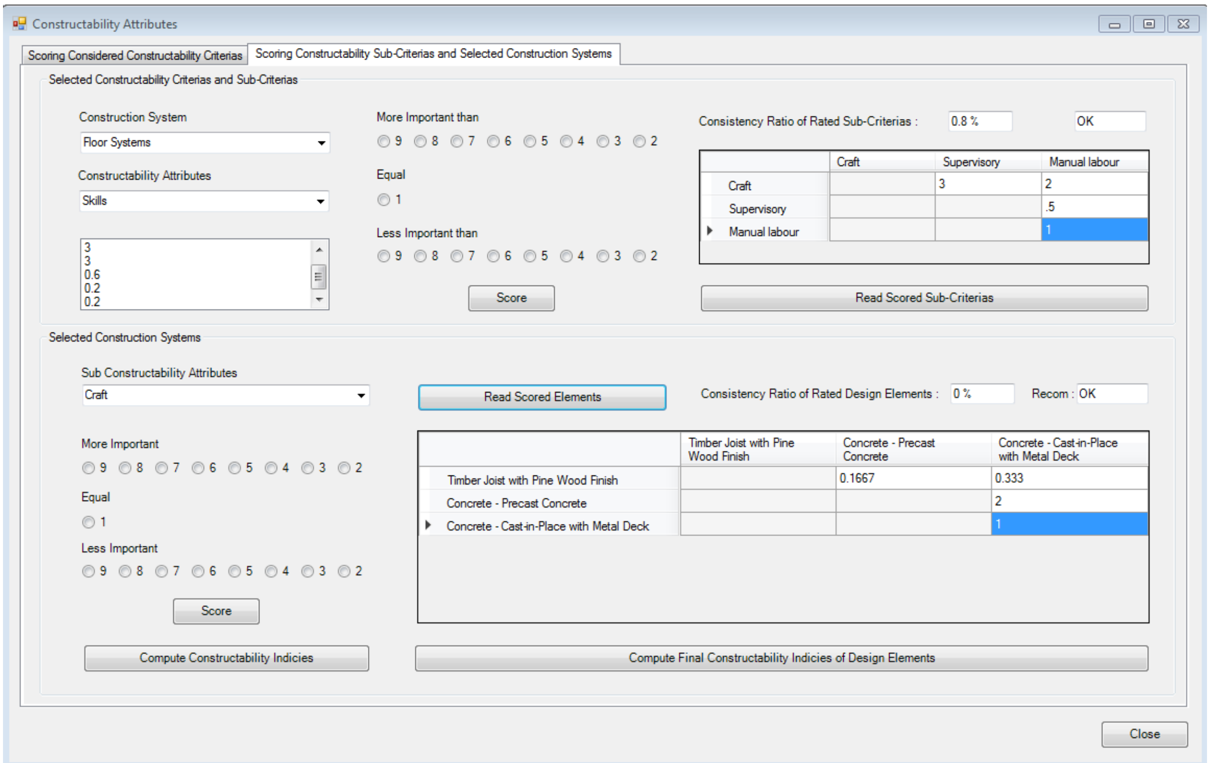


*Figure 6-20: Scoring **Floor options** with respect to **Craft** branch sub-criteria clustered under **Skills** criteria*

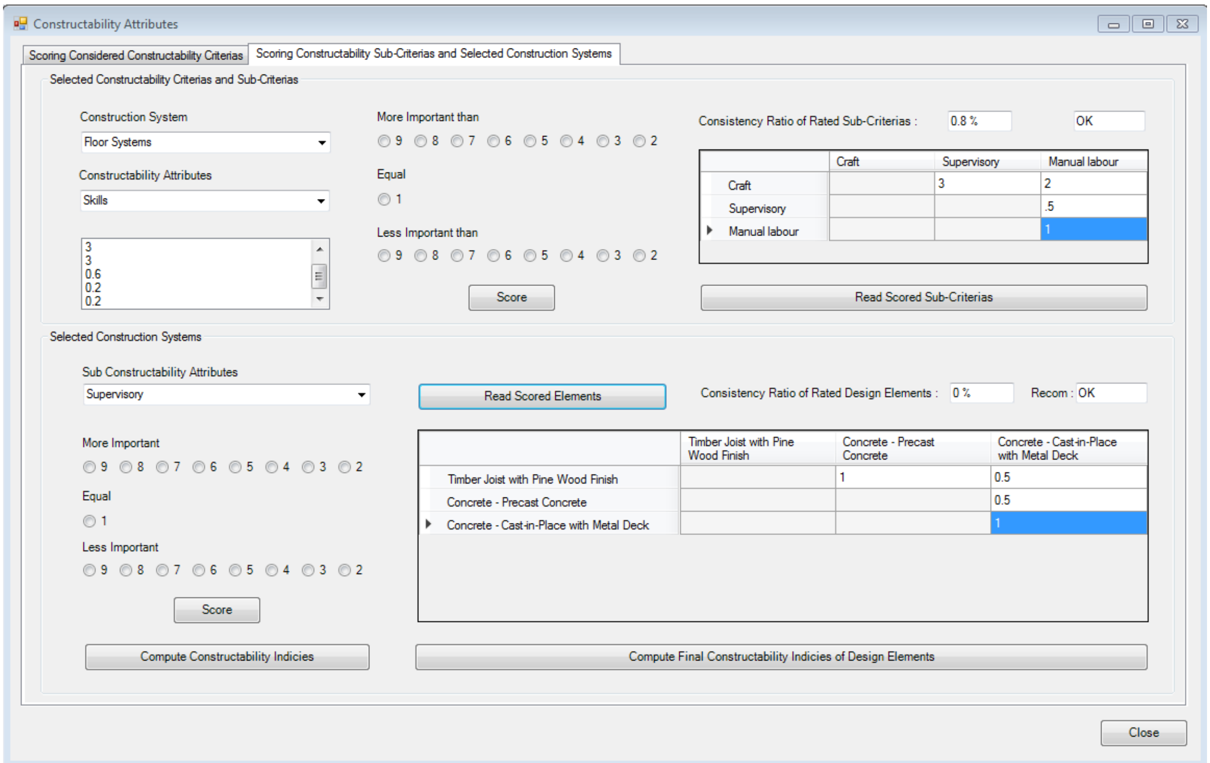


*Figure 6-21: Scoring **Floor options** with respect to **Supervisory** branch sub-criteria clustered under **Skills** criteria*

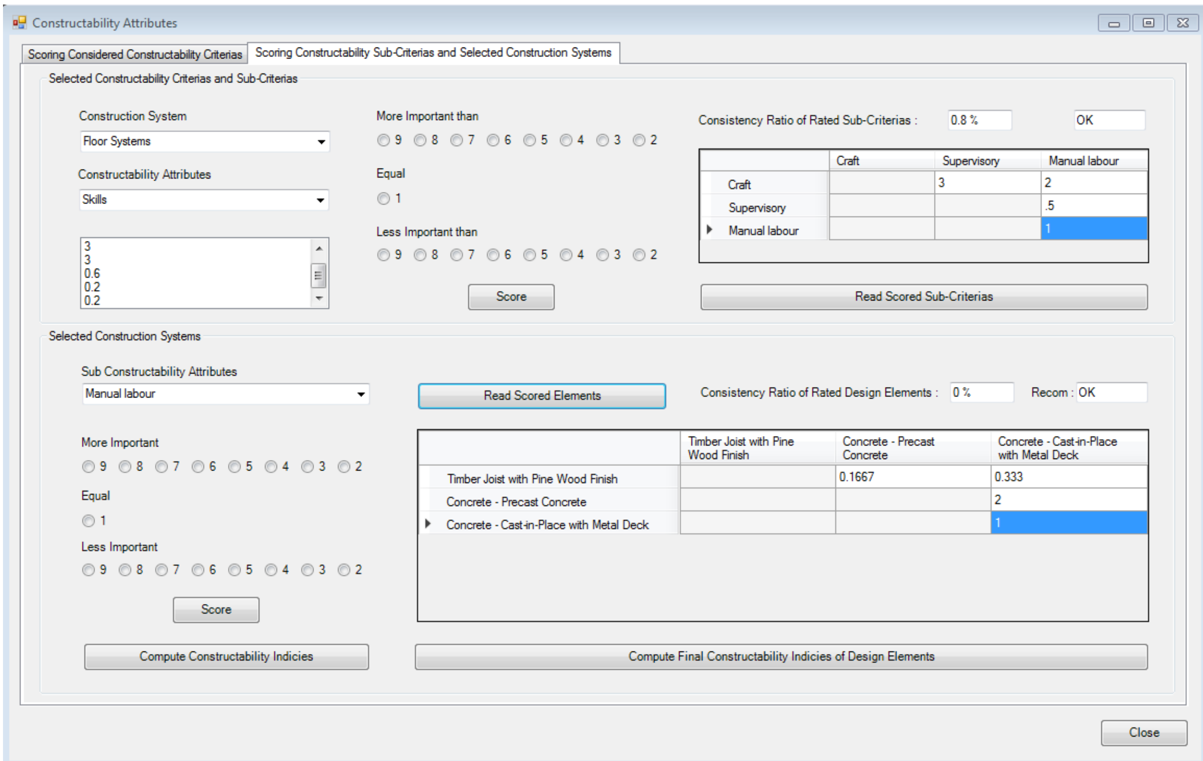


*Figure 6-22: Scoring **Floor options** with respect to **Manual Labour** branch sub-criteria clustered under **Skills** criteria*

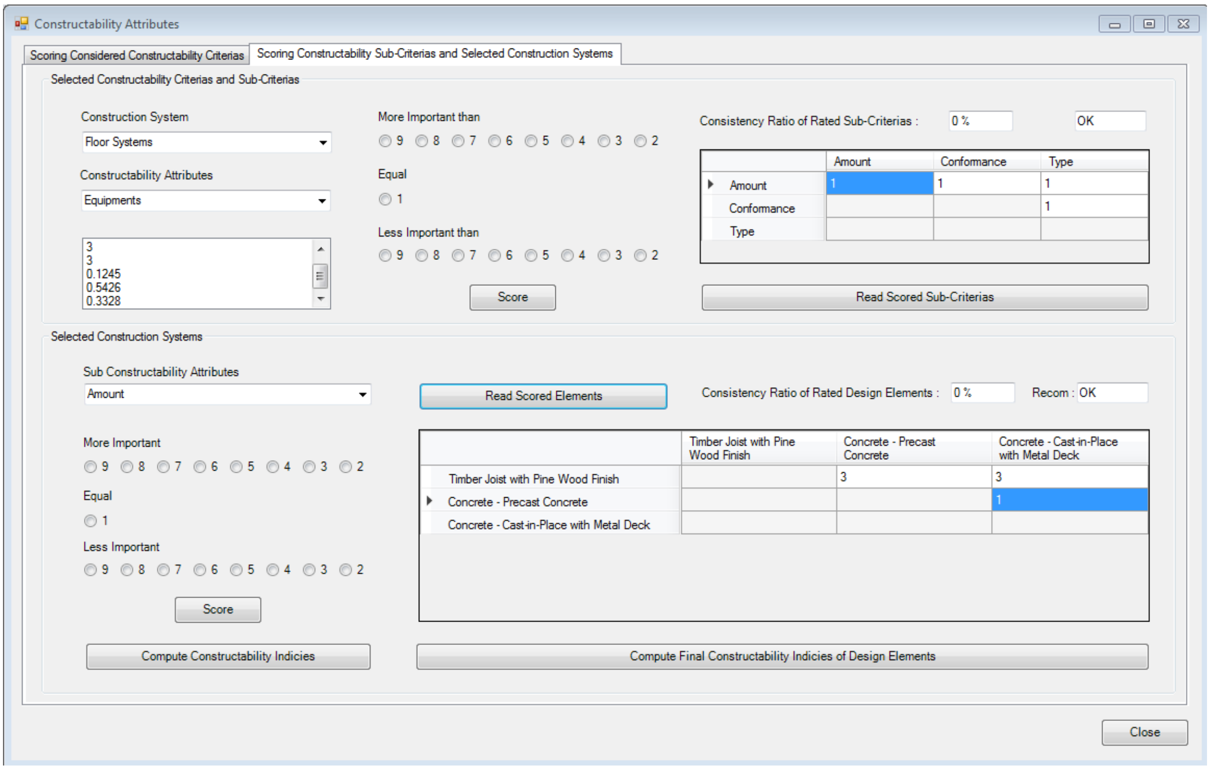


*Figure 6-23: Scoring **Floor options** with respect to **Amount** branch sub-criteria clustered under **Equipment** criteria*

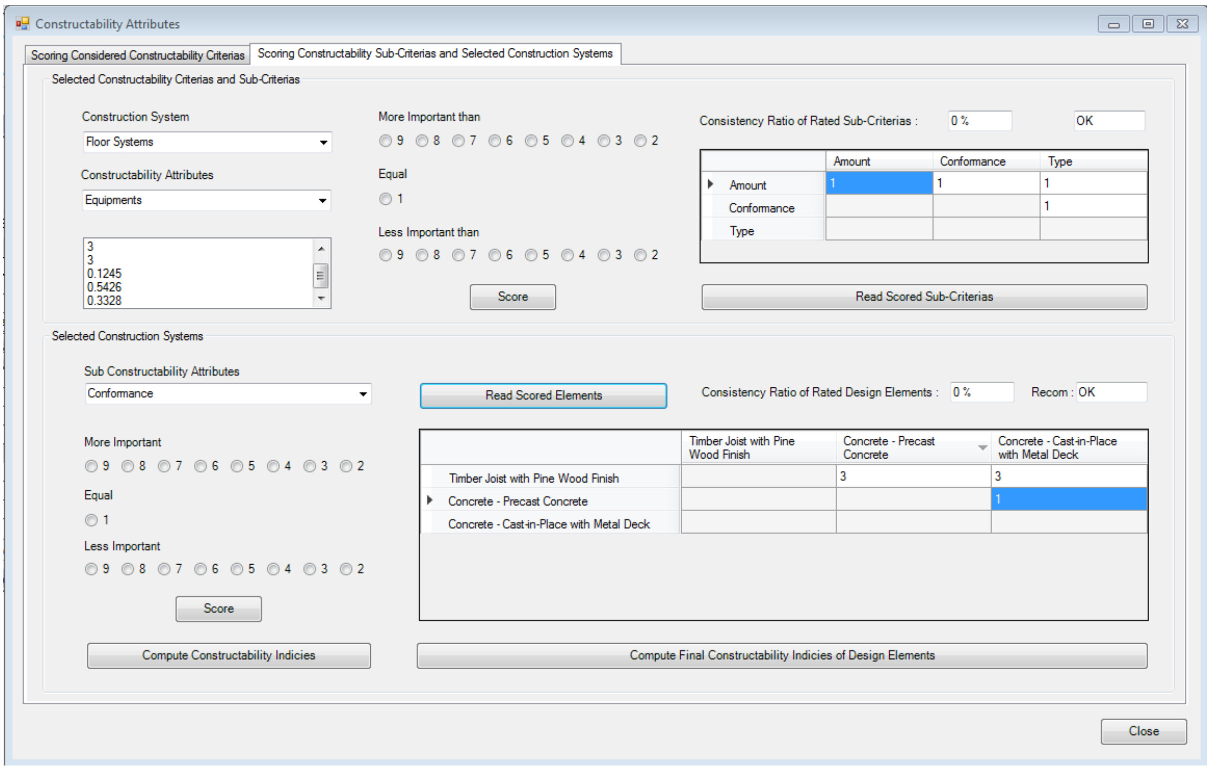


*Figure 6-24: Scoring **Floor options** with respect to **Conformance** branch sub-criteria clustered under **Equipment** criteria*

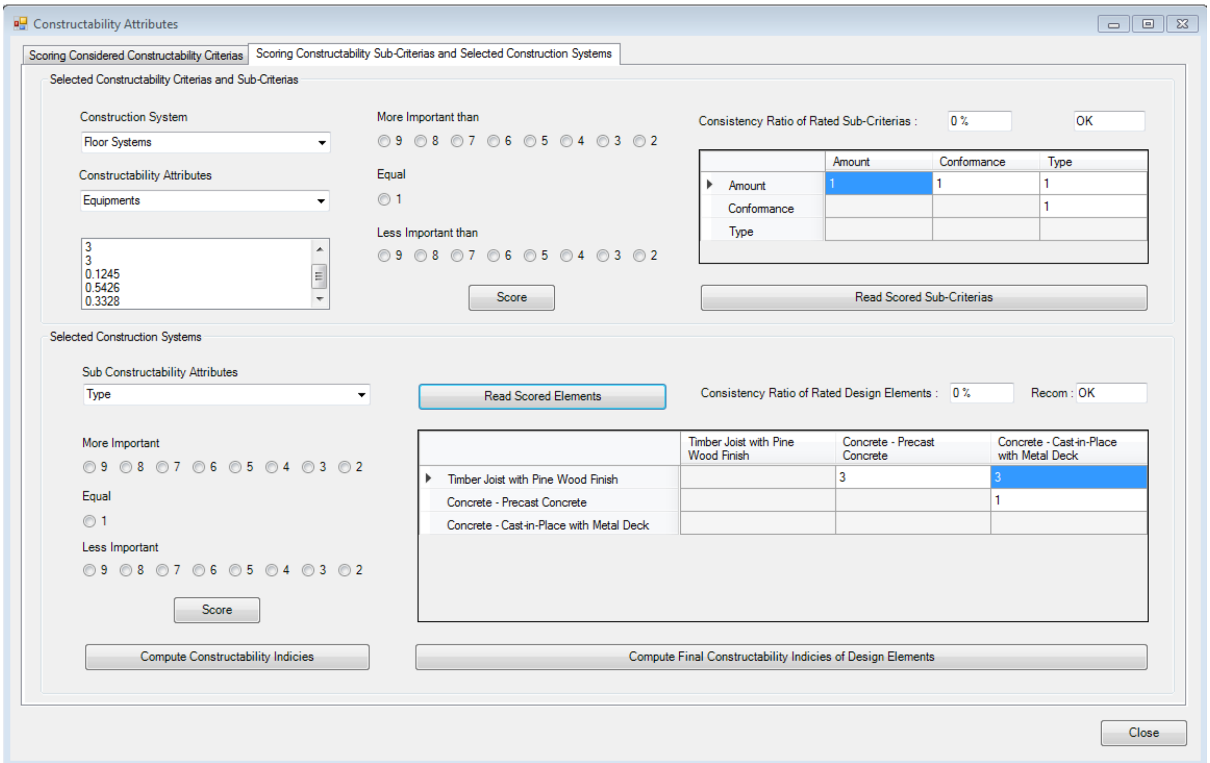


*Figure 6-25: Scoring **Floor options** with respect to **Type** branch sub-criteria clustered under **Equipment** criteria*

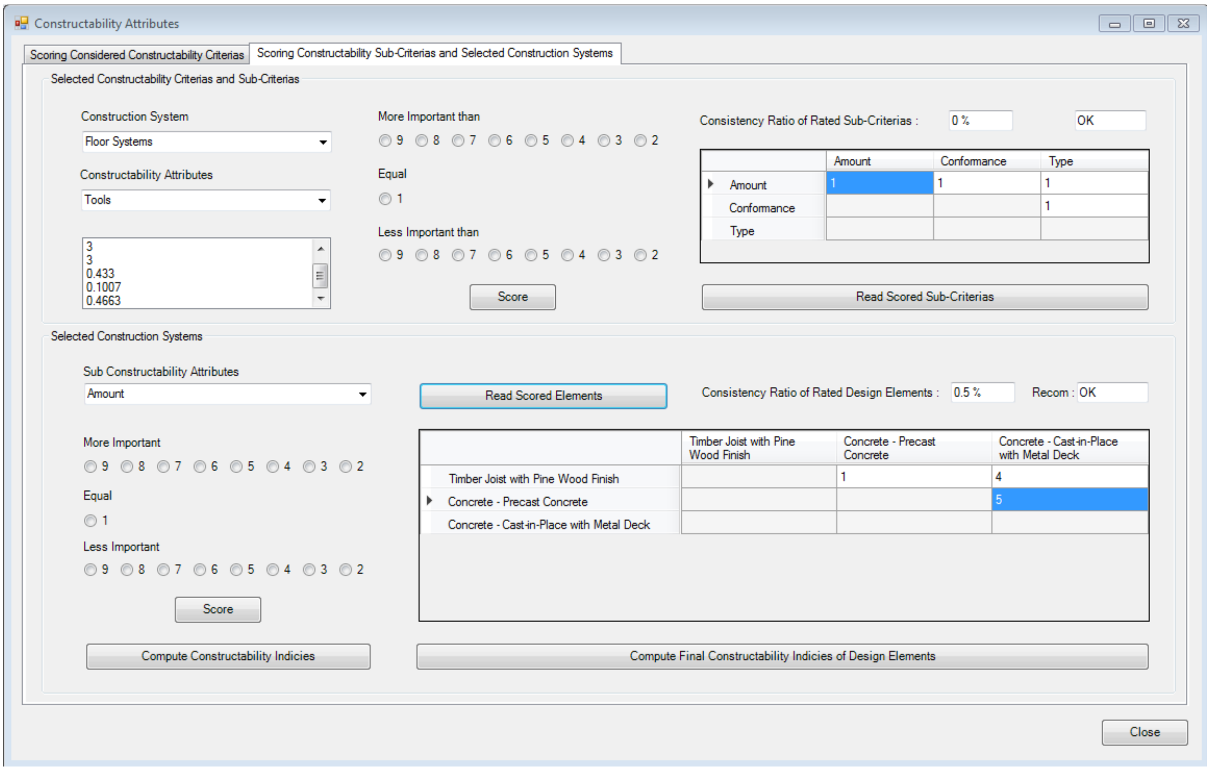


*Figure 6-26: Scoring **Floor options** with respect to **Amount** branch sub-criteria clustered under **Tools** criteria*

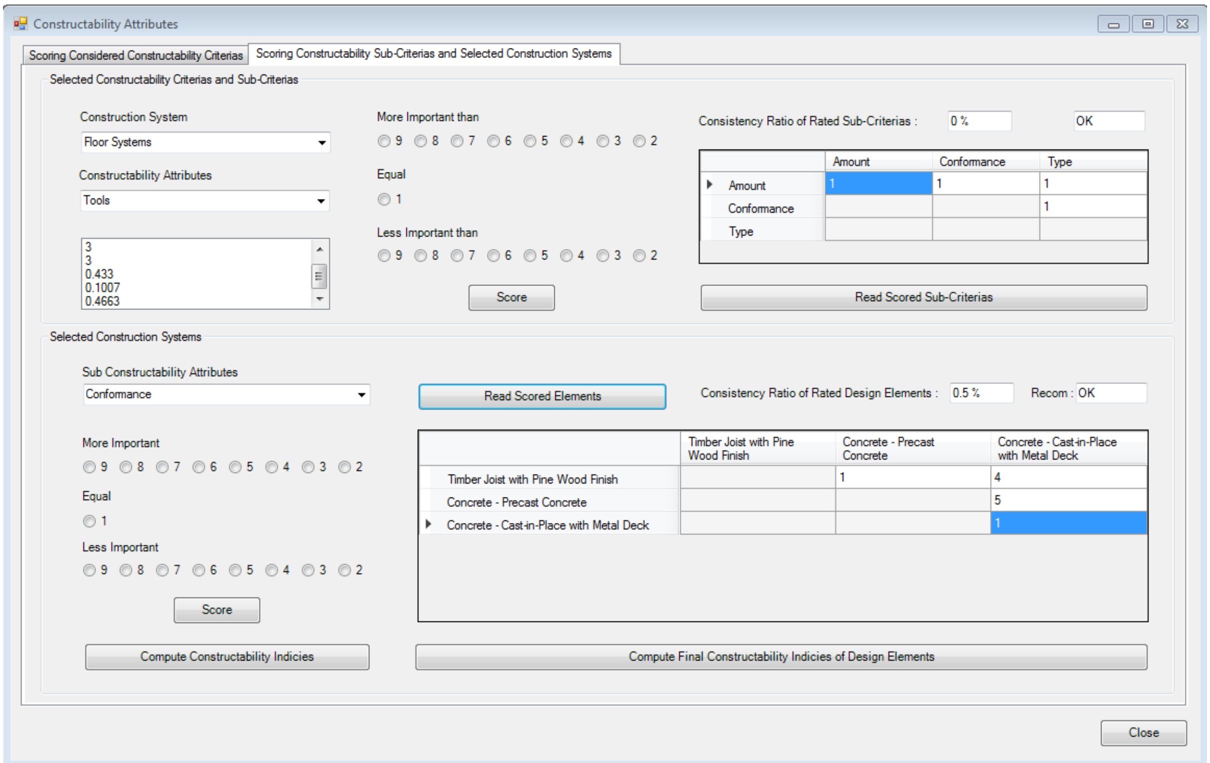


*Figure 6-27: Scoring **Floor options** with respect to **Conformance** branch sub-criteria clustered under **Tools** criteria*

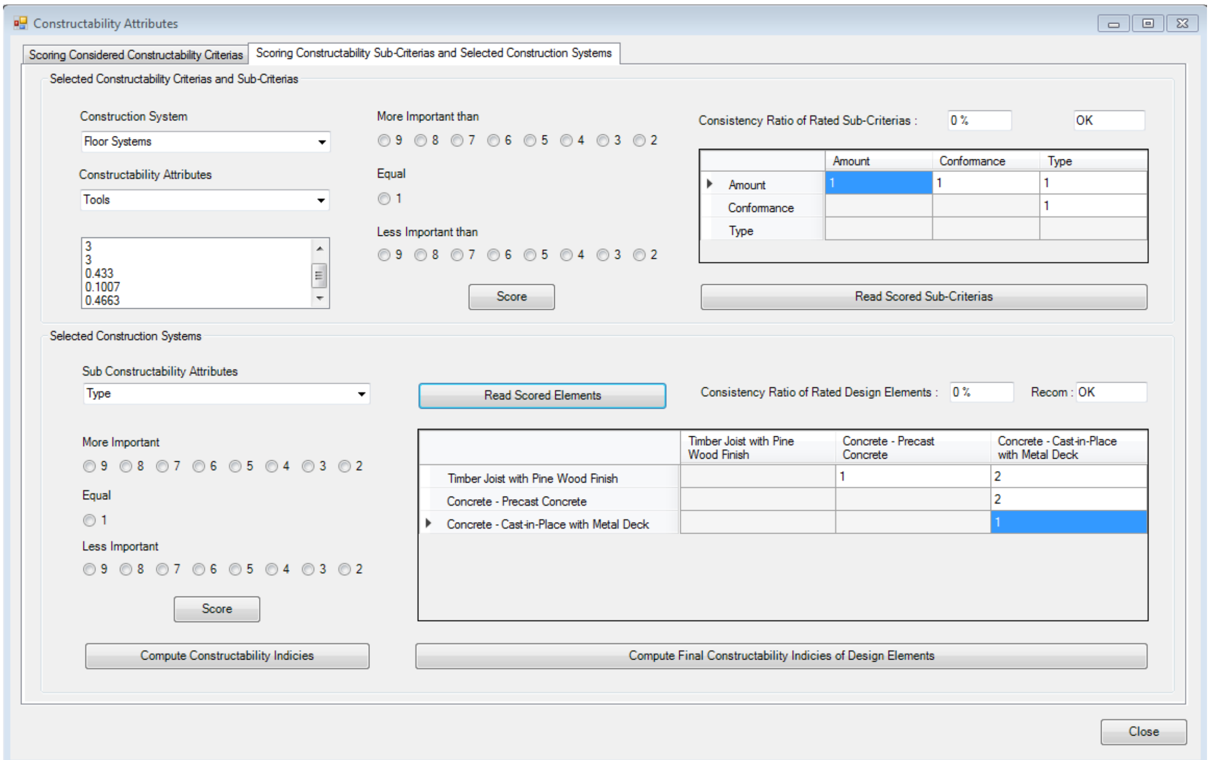


*Figure 6-28: Scoring **Floor options** with respect to **Type** branch sub-criteria clustered under **Tools** criteria*

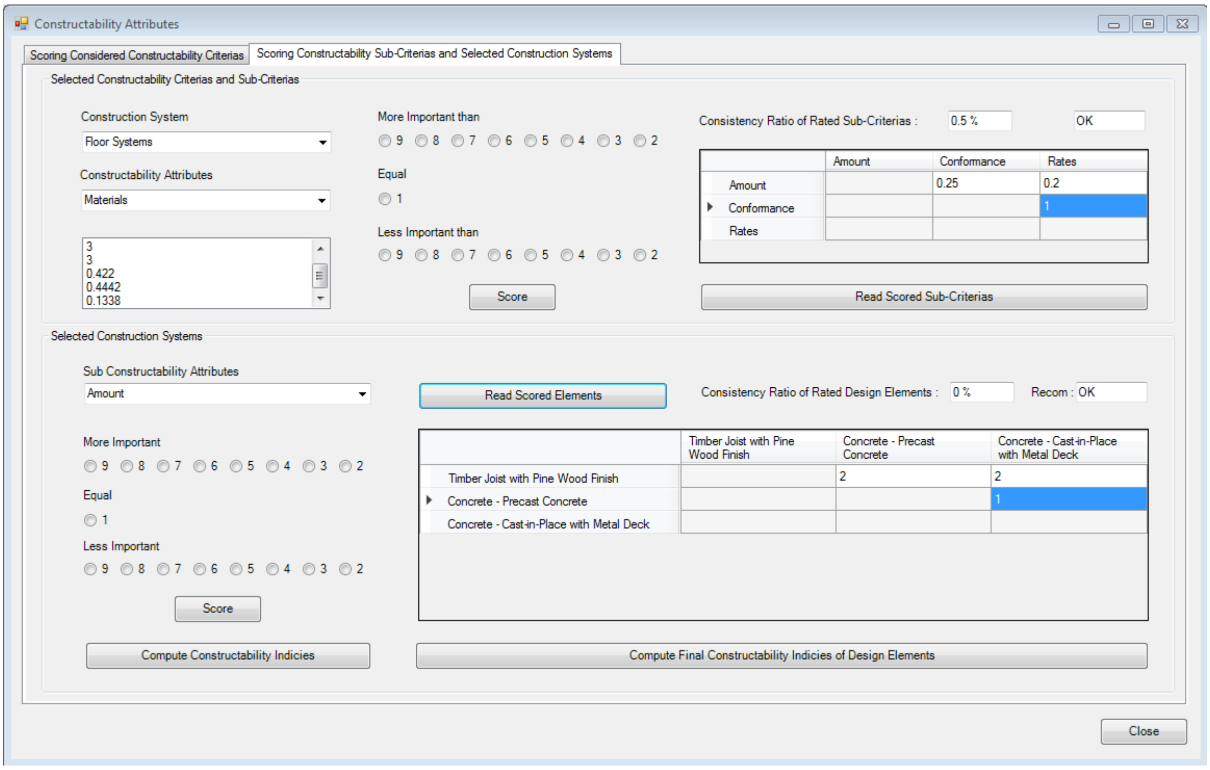


*Figure 6-29: Scoring **Floor options** with respect to **Amount** branch sub-criteria clustered under **Materials** criteria*

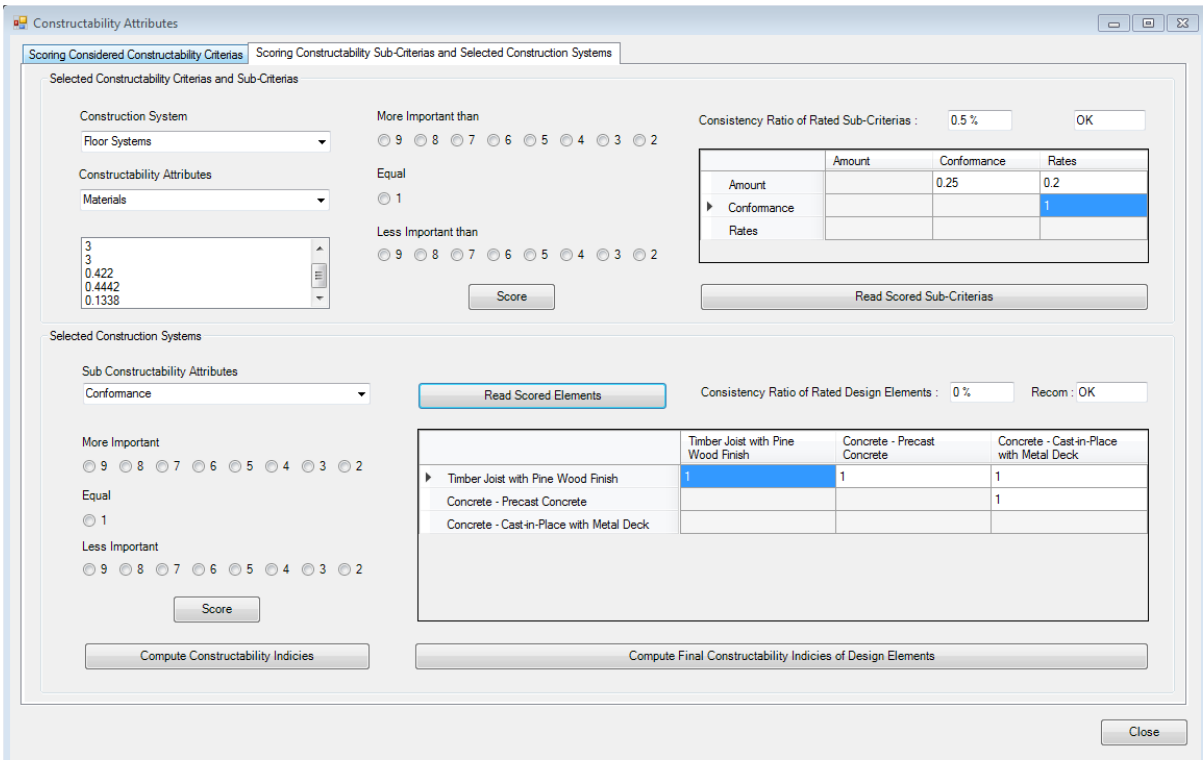


*Figure 6-30: Scoring **Floor options** with respect to **Conformance** branch sub-criteria clustered under **Materials** criteria*

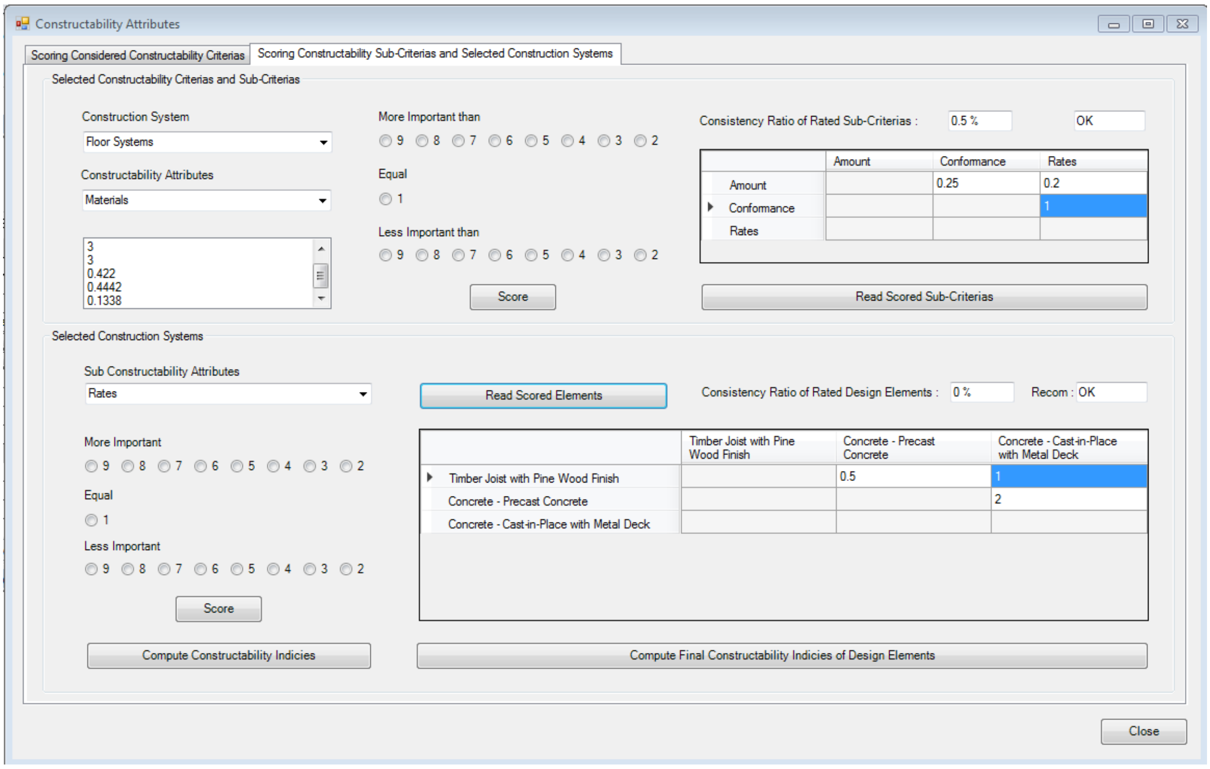


Figure 6-31: Scoring ***Floor options*** *with respect to* ***Rates*** *branch sub-criteria clustered under* ***Materials*** *criteria*

Once all scores are recorded for considered construction systems alternatives, the prototype generates respective constructability indices and deploy them into designated tables in the database. Users are able to preview these indices by navigating through view tabs, as Table 6-6 illustrates. It demonstrates how various options are rated with respect to considered criteria as well as the representative index.

Table 6-6: Scored alternatives of various construction systems

CM								
AEC Systems						Rules of Thumb	Complexity	Location
Weighting Factors	Constructability Indices							
	Slabs	Found.	Envelope	Walls	Str. Frames			

Slab Systems

Roof Systems | Slab Systems | Foundations | Envelope Systems | Walls Systems | Structural Framing Sy

FloorType	Information	Skills	Equipment	Tools	Materials	Priority	Idealised
Timber Joist with Pine Wood	0.6	0.1808	0.6	0.422	0.3113	0.388	1.000
Concrete - Precast Concrete	0.2	0.4113	0.2	0.4442	0.4027	0.340	0.876
Concrete - Cast-in-Place w...	0.2	0.4079	0.2	0.1338	0.2861	0.263	0.678

Foundations

Roof Systems | Slab Systems | Foundations | Envelope Systems | Walls Systems | Structural Framing Sy

FoundationType	Information	Skills	Equipment	Tools	Materials	Priority	Idealised
Concrete - Cast-in-Place Concrete	0.3333	0.2186	0.257	0.2	0.3866	0.280	0.694
Concrete - Precast Concrete	0.3333	0.4646	0.5028	0.4	0.3067	0.404	1.000
Metal - Steel - 345 MPa	0.3333	0.3168	0.2402	0.4	0.3067	0.306	0.756

Envelope Systems

Roof Systems | Slab Systems | Foundations | Envelope Systems | Walls Systems | Structural Framing Sy

EnvelopeType	Information	Skills	Equipment	Tools	Materials	Priority	Idealised
Glass	1	1	1	1	1	0.990	1.000

Walls Systems

Roof Systems | Slab Systems | Foundations | Envelope Systems | Walls Systems | Structural Framing Sy

WallType	Information	Skills	Equipment	Tools	Materials	Priority	Idealised
Brick: Common	0.1179	0.0817	0.1097	0.1111	0.1084	0.102	0.798
Wood	0.1184	0.16	0.1097	0.1111	0.1084	0.121	0.945
Glass: Clear Glazing	0.1114	0.1454	0.097	0.1111	0.0828	0.107	0.833
Concrete Masonry Units	0.1147	0.0845	0.097	0.1111	0.1084	0.100	0.777
Plaster	0.1153	0.0872	0.1236	0.1111	0.1512	0.119	0.926
Gypsum Wall Board	0.1184	0.16	0.1392	0.1111	0.1084	0.128	1.000
Concrete: Cast In Situ	0.0745	0.1454	0.097	0.1111	0.1159	0.113	0.879

Structural Framing Systems

Slab Systems | Foundations | Envelope Systems | Walls Systems | Structural Framing Systems

StructuralFrameType	Information	Skills	Equipment	Tools	Materials	Priority	Idealised
Metal - Steel 43-275	0.2933	0.3867	0.3333	0.3778	0.3933	0.362	1.000
Concrete - Precast Concrete	0.2933	0.3867	0.3333	0.3778	0.2733	0.329	0.907
Concrete - Cast-in-Place Concrete	0.4134	0.2267	0.3333	0.2444	0.3333	0.299	0.826

5. *Customisation of Rules of Thumb Module*

As discussed in section 4.5.5 and presented in Table 4-11, three rules are exemplified in the implemented prototype under the Rules of Thumb module. These are Column Formwork, Room Spacing, and Component Dimensions rules. Users activate them and set their restrictive values at this stage of CM customisation, to be validated against actual values extracted from the examined BIM model at the assessment stage by the AM. For instance, Figure 6-32 illustrates that the CM being customised here is set to check Column Formwork rule. It will identify all columns within the design model that are violating restricted dimensions (i.e. 350 mm for width and 400 mm for depth). Furthermore, depending on the number of violating columns, if exists, it will have implications on the awarded constructability score for this aspect, as explained in section 4.5.5. Similarly, the Room Spacing rule is activated to restrict minimum space within the proposed design solution to 23.22-meter square (Figure 6-33), due to the necessity of a construction activity identified by the user (e.g. movement of specific machinery or personnel).

Under the scope of this module, assessment of the compliance of modelled design features with a specific code of practice or governmental legislation is carried out. However, this aspect is not covered in the implemented prototype. It is only featured to demonstrate how such aspect can be articulated if a full-scale assessment tool is to be developed. An example of legislative rules related to *Notification Requirements for Abnormal Loads Movements,* presented in Appendix 1, is implemented as a part of the CM Location module.

Also, the scoring scheme of this CM module covers the design performance in accomplishing a free-detected clashes design product. While the check of design clashes itself can be carried out by the assessment engine (i.e. AM). However, at the demonstrated level of the prototype implementation, users are encouraged to carry out such task using one of the existing clash detection tools (e.g. Autodesk Navisworks, Solibri, etc.), and then report back the performance (I.e. no clashes are detected/ there are some - even recorded minor issues, or no check has been done at all) to be reflected in the delivered Rule of Thumb score.

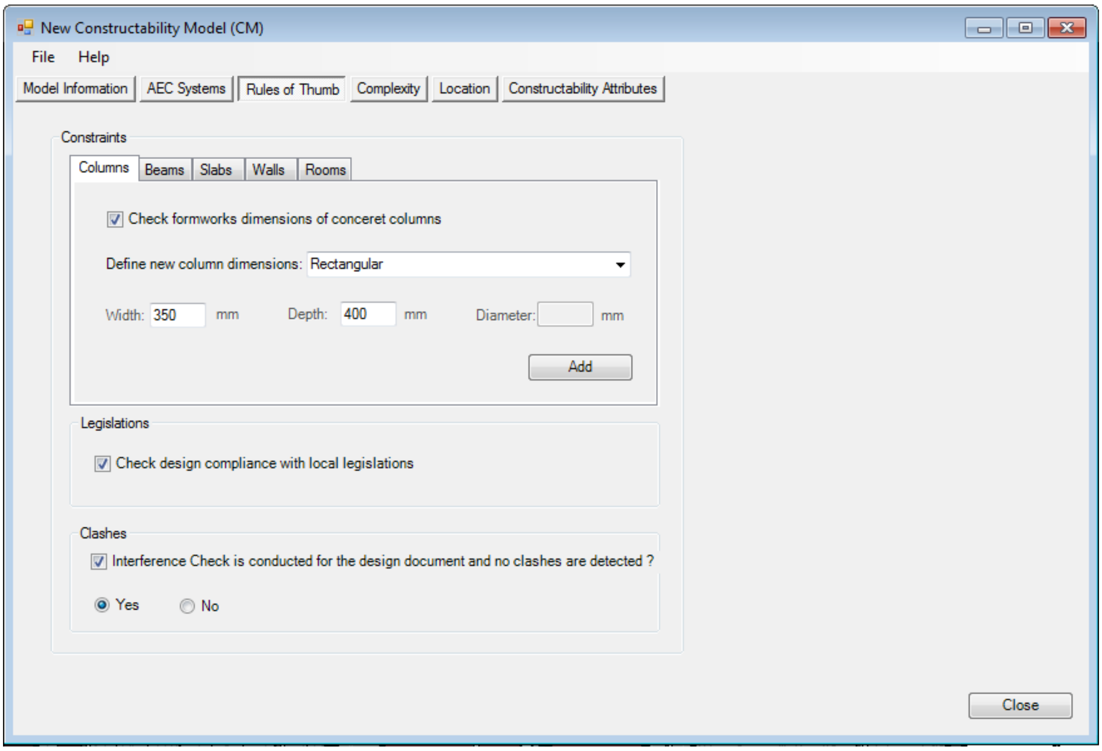


*Figure 6-32: Customisation of the **Column Formwork** rule in the implemented prototype*

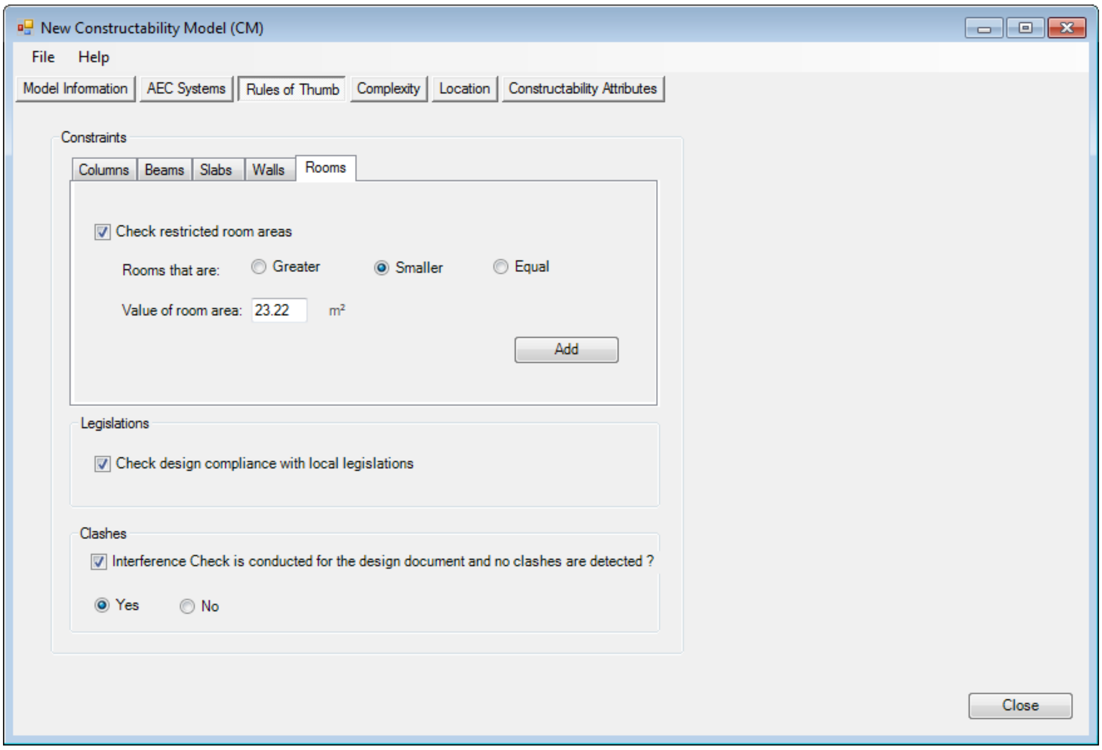


*Figure 6-33: Customisation of the **Room Spacing** rule in the implemented prototype*

6. Customisation of Complexity Module

Implemented aspects within the complexity module included the prototype analysis for design simplicity based on elements connections and wall trades, featured on the digital model being assessed. It also interprets the extent of outlined design product to facilitate the automation of its construction on site. As introduced, produced indicators from these sections are based upon fitness functions that use imported data from examined models. Whilst these formulas are derived logically to describe the behaviour of selected constructability attributes, users can impose any specialities by imputing weighting factors parameters within these functions. Typically, such customisation can be done in the scope of this section for activated attributes set to be assessed, as Figure 6-34 illustrates. They are set at equal weighting factors, but users can carry out pairwise comparisons to generate new weights. Also, they can switch off a specific part of that function, if believed it is not required.

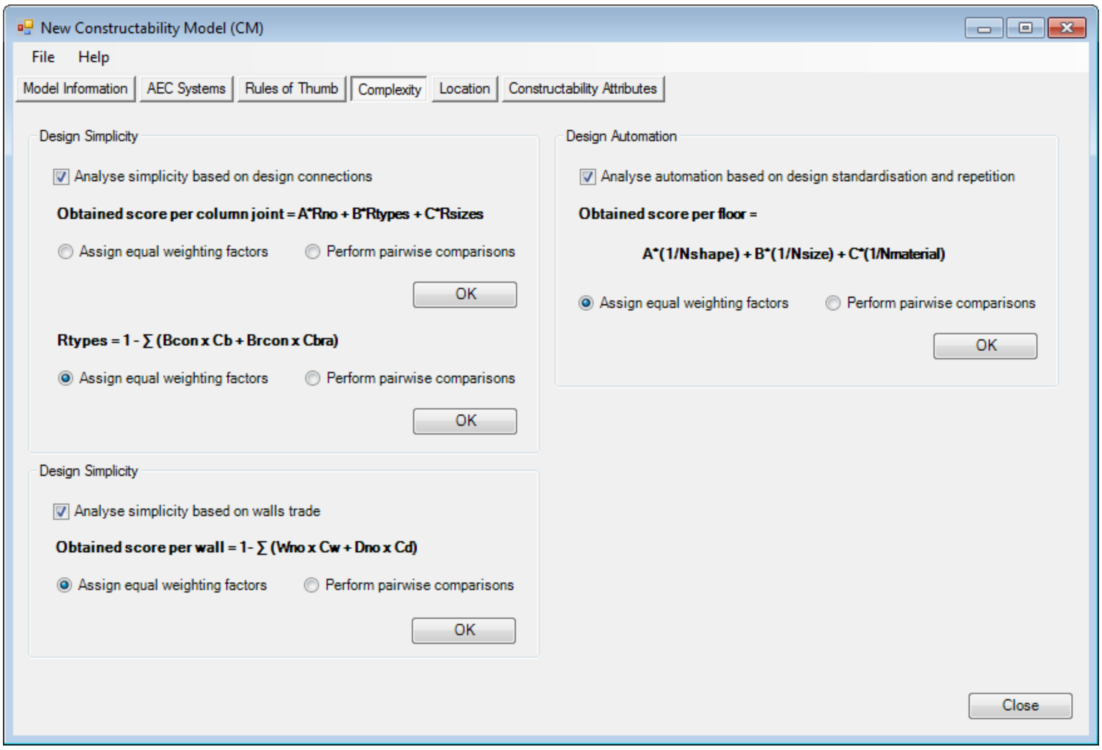


*Figure 6-34: Customisation of **Complexity** components in the implemented prototype*

7. ***Customisation of Location Module***

As introduced in section 4.5.5, customisation of this section is meant to incorporate all restrictions originated from the project location to be observed in the design product. The implemented prototype exemplified the aspects of this module in checking *Notification Requirements for Abnormal Loads Movements,* presented in Appendix 1. It seeks to identify design components that are targeted by this and bring it to the user's attention at the assessment stage. Consequently, they can decide whether to continue with making the necessary preparations, or to modify them if it permits. Figure 6-35 shows that such task is activated within the scope of CM being customised. Though this version of implementation is hardcoding these requirements and their legislative dimensions. It would be more intuitive to provide the facility of overriding these figures if they are amended by local authorities.

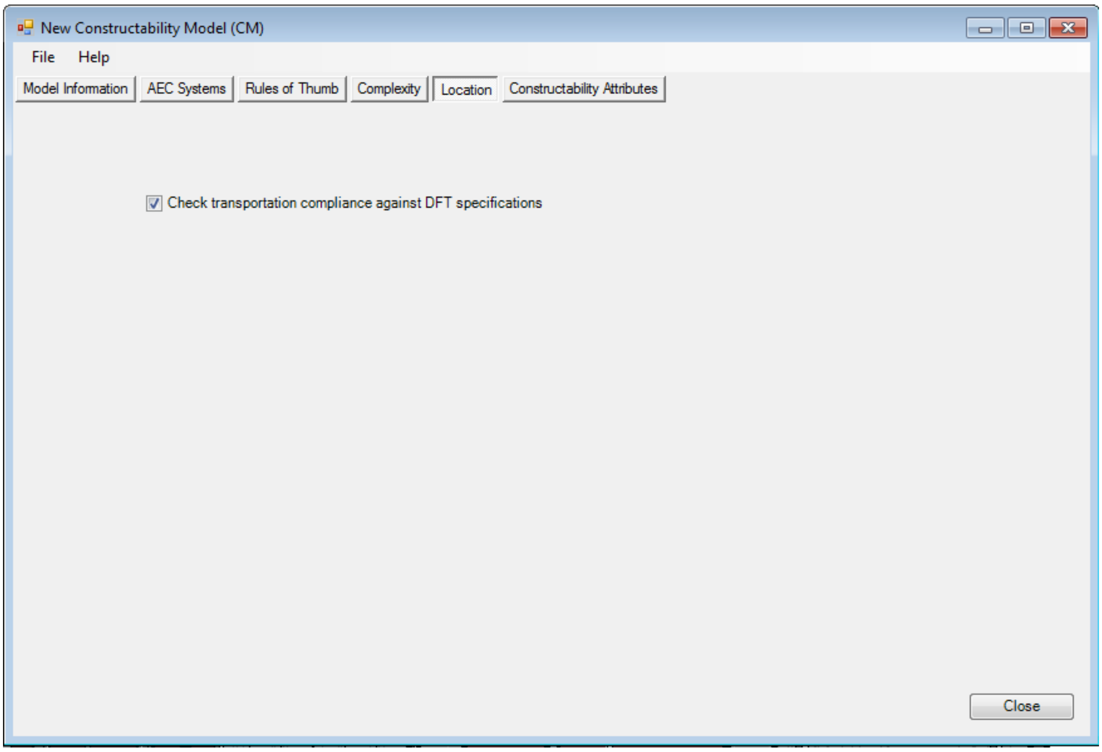


*Figure 6-35: Customisation of the **Location** module in the implemented prototype*

6.5.3. Viewing customised CMs

Once a CM model is configured and saved, users are able to view its contents, enable aspects for assessment, and assign weights and scores for design components during the customisation process. They can also adjust such configurations to clone other CMs if considered cases warrant this, instead of going through the entire customisation process. Figure 6-36, concerning Test 270801 model, shows that all of the model's sections are selected for the assessment, assigning weights to AEC Systems (0.50), Rules of Thumb (0.25), Complexity (0.20), and Location (0.05). It also presents assigned weights for design objectives based on user inputs. For this model, enabled objectives are scored as follows: Construction Cost: (0.39), Production Rate: (0.16), Product Quality: (0.07), and Construction Safety: (0.38). All values are summed to 1.0.

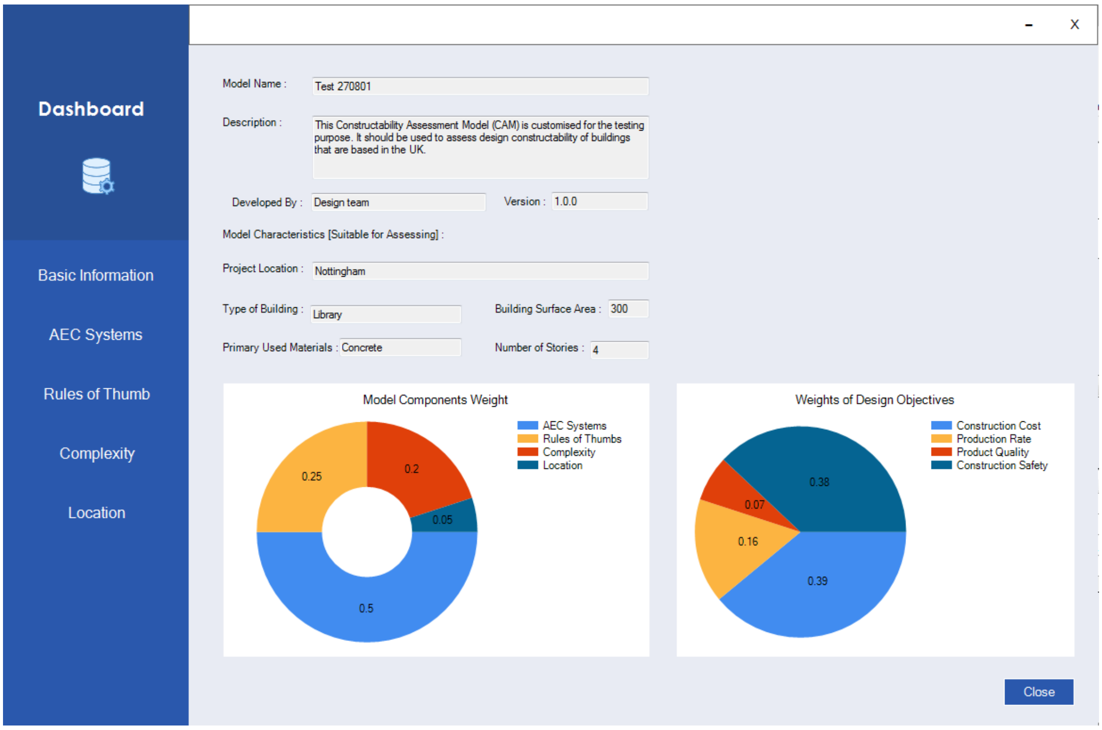


Figure 6-36: Basic information of configured CM and assigned weights for its components

To have a more detailed view of the model, users are able to explore customised model sections, as shows in the case of AEC Systems in Figure 6-37. It presents achieved weights for Roof systems (0.16), Floor systems (0.2), Wall systems (0.09), Foundations (0.14), Envelopes (0.2), and Structural framing systems (0.22) from a user perspective. Also, the contribution of each construction system in accomplishing design objectives is presented, pointing out crucial systems to be optimised in order to improve achieved performance in a specific design objective (e.g. focusing on selecting a fast-fabricated system for the structural framing to speed the process, in contexts where the construction time is the overriding priority among other targeted objectives).

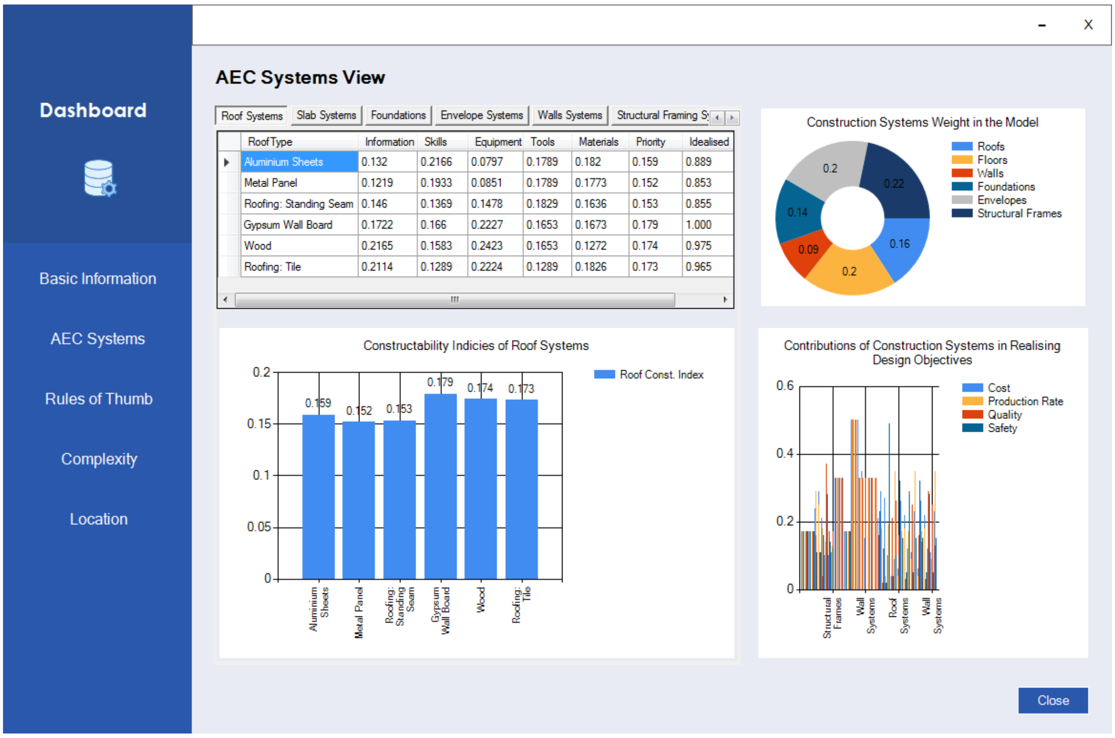


Figure 6-37: Configuration of AEC Systems aspects in the customised CM (Test 270801)

6.6. Constructability assessment results and analysis

This is the critical point when a potential design model is developed and needs to be tested for constructability. It is the targeted end goal for which the previous steps are established. In practical terms, it is essentially the process of reasoning acquired construction knowledge, stored in a CM, to be mapped on extracted features of the design being assessed.

6.6.1. Stage (1):

6.6.1.1. Design Option (1)

For the considered case study, starting by assessing Design Option (1) (steel building, Figure 6-38), the developed plug-in tool integrated with Revit UI is triggered for this purpose (Figure 6-39). From the Dashboard tab, the user can select the suitable CM to act as a benchmark for the assessment process (Test 270801 in this case). This can either be from the user’s library (previous customised CMs) or from a standard package (CMs recommended by others to be used for a specific purpose/region), as Figure 6-39 shows. Assessment outcomes are labelled as per input design option numbers.

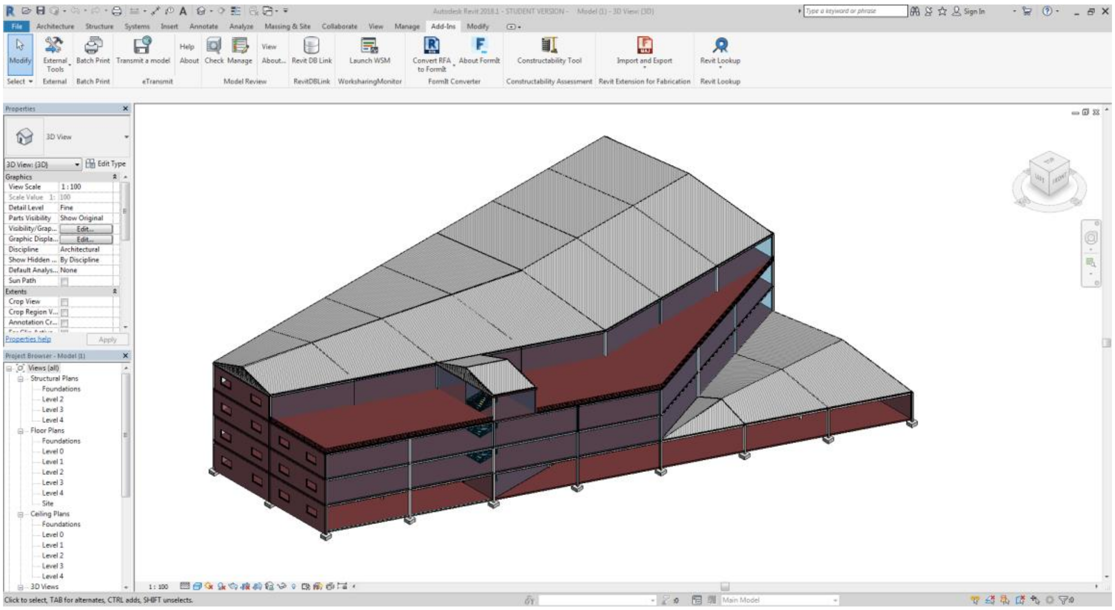


Figure 6-38: Design Option (1): Steel building

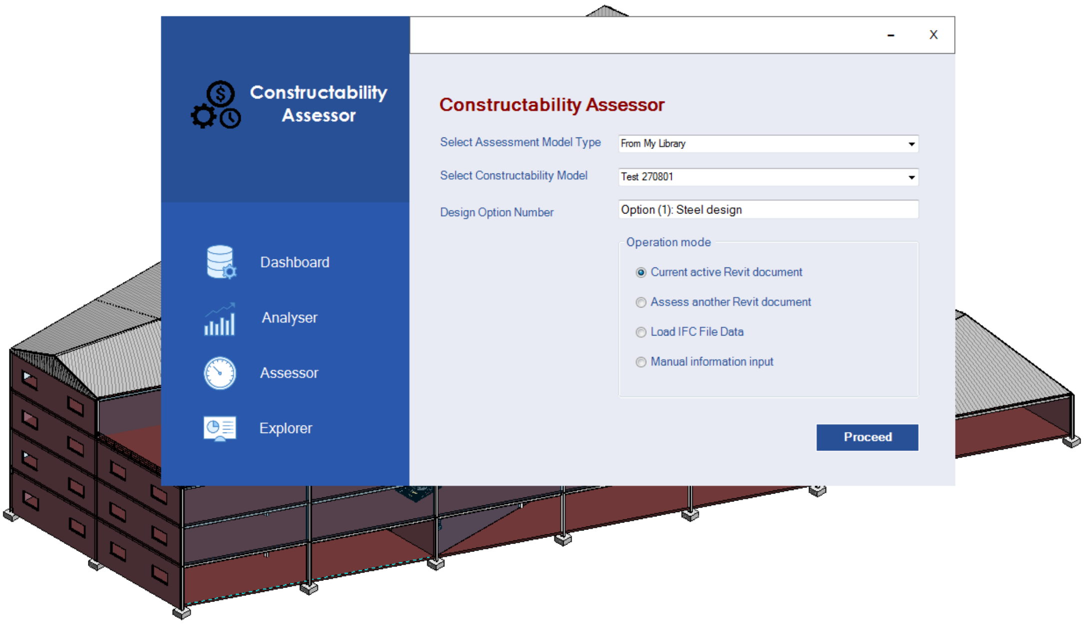
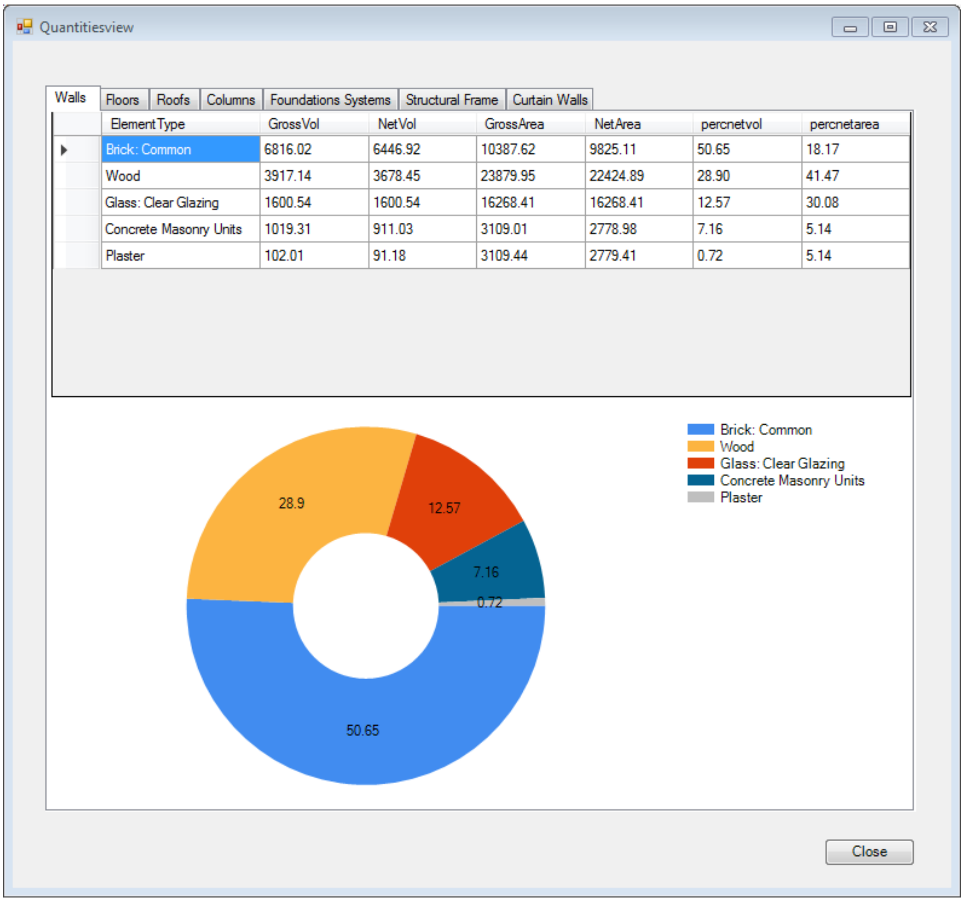


Figure 6-39: Prototype UI to configure and trigger constructability assessment process

The feature of selecting the format of the assessed model (i.e. current active Revit model, IFC file, or manual information input) is to provide more flexibility when carrying out the assessment process. Currently, this is only implemented to work with Revit models, however, as emphasised earlier, the concept is generic and can be implemented on other BIM platforms. The manual input option is included for performing quick assessment tests, if actual BIM models are not currently available. In addition, the prototype provides a feature to present an executive summary of employed construction systems and their quantities for user analysis and observation, as shown in Figure 6-40.

Once the Proceed button is pressed, the first thing to appear to users is warning messages due to non-compliance with rules, as defined in the utilised CM. For this specific case, the implemented rule “Room space” seems unsatisfied in the steel building model (Figure 6-41). Walls affected by this non-workable space (as defined by the user earlier) are presented in Figure 6-42. This might restrict the construction process later when it comes to plastering or painting these walls, due to the movement of personnel or equipment. This can be observed from different views, as shown in Figure 6-43 and Figure 6-44, enabling users to modify the design for a better Constructability score.



ElementType	GrossVol	NetVol	GrossArea	NetArea	percnetvol	percnetarea
Brick: Common	6816.02	6446.92	10387.62	9825.11	50.65	18.17
Wood	3917.14	3678.45	23879.95	22424.89	28.90	41.47
Glass: Clear Glazing	1600.54	1600.54	16268.41	16268.41	12.57	30.08
Concrete Masonry Units	1019.31	911.03	3109.01	2778.98	7.16	5.14
Plaster	102.01	91.18	3109.44	2779.41	0.72	5.14

Figure 6-40: Analysis of design quantities for various construction systems: Design Option (1)

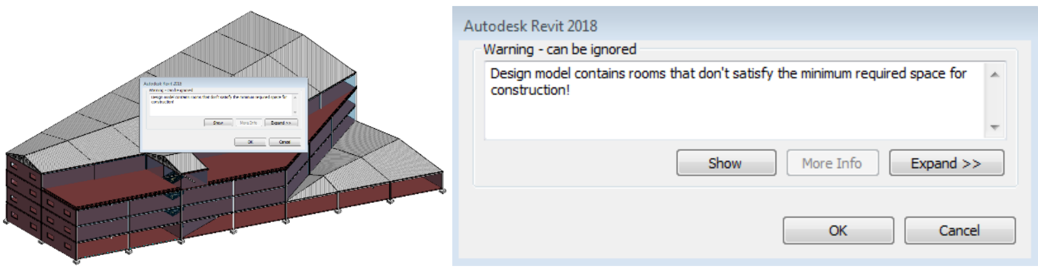


Figure 6-41: Warning message to highlight non-compliant design elements with enabled rules

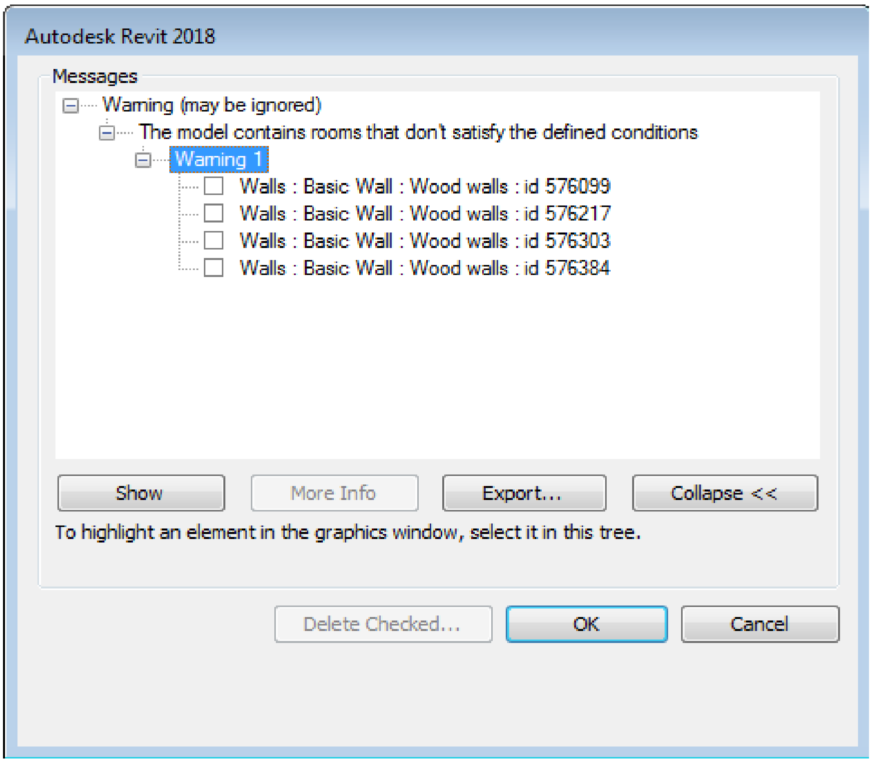


Figure 6-42: Identification of affected walls within the examined design due to non-compliance with Room rule

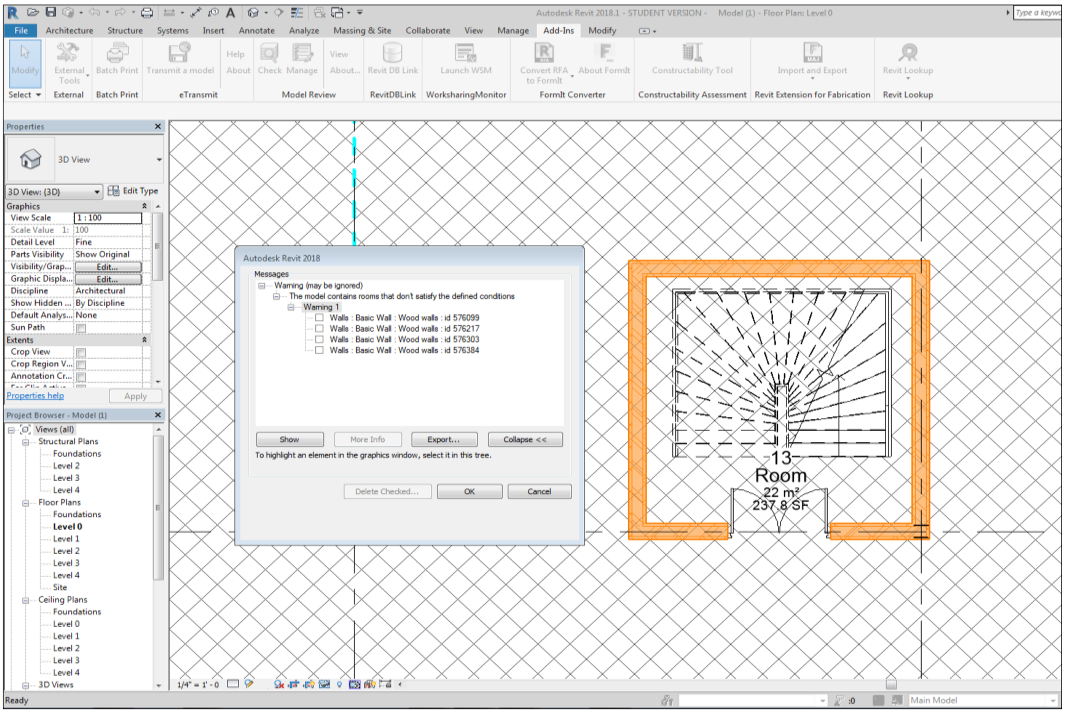


Figure 6-43: Plan view for the affected wall within the examined design model

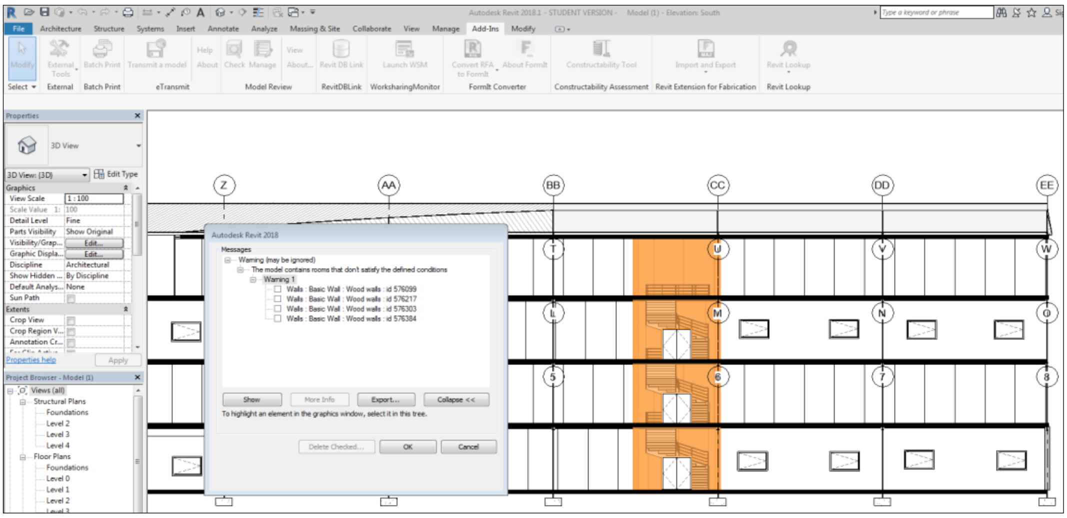


Figure 6-44: Elevation view for the identified rooms within the examined design model

After dealing with warning messages, the main assessment tab presents a summary of obtained results for enabled categories, as well as the overall Constructability score (Figure 6-45). Design Option (1) obtains (0.4691) in AEC Systems, (0.1333) in Rules of Thumb, (0.137) in Complexity, and (0.05) in Location aspect. Details of these scores and their rationales are accessible in individual tabs, as discussed previously. However, the presented figure within this tab is an important one, which reflects how each part performs (Yellow column) against the importance of that part indicated by the assigned weighting factor (blue column). This clearly directs the user to the area of weakness that needs to be addressed. For the current case, the Complexity section seems to be the least performing (0.5479), while the location part attains the full allocated weight (1.00).

Navigating through individual tabs provides more details on calculated scores for individual assessed parts. This is presented in Figure 6-46 for the AEC System section. It shows the performance of each construction system based on assigned importance factors and representative Constructability scores. Such scores are calculated based on actually used elements of the model, as well as their quantities (as explained in chapter 4). The spider figure shows how current considered design contributes towards satisfying defined design objectives: Cost (0.91), Production rate (0.93), Quality (0.94), and Safety

(0.93). They are calculated based on actual system performance, and their scored importance towards satisfying targeted objectives. The other shown chart presents Construction systems' importance versus their performance.

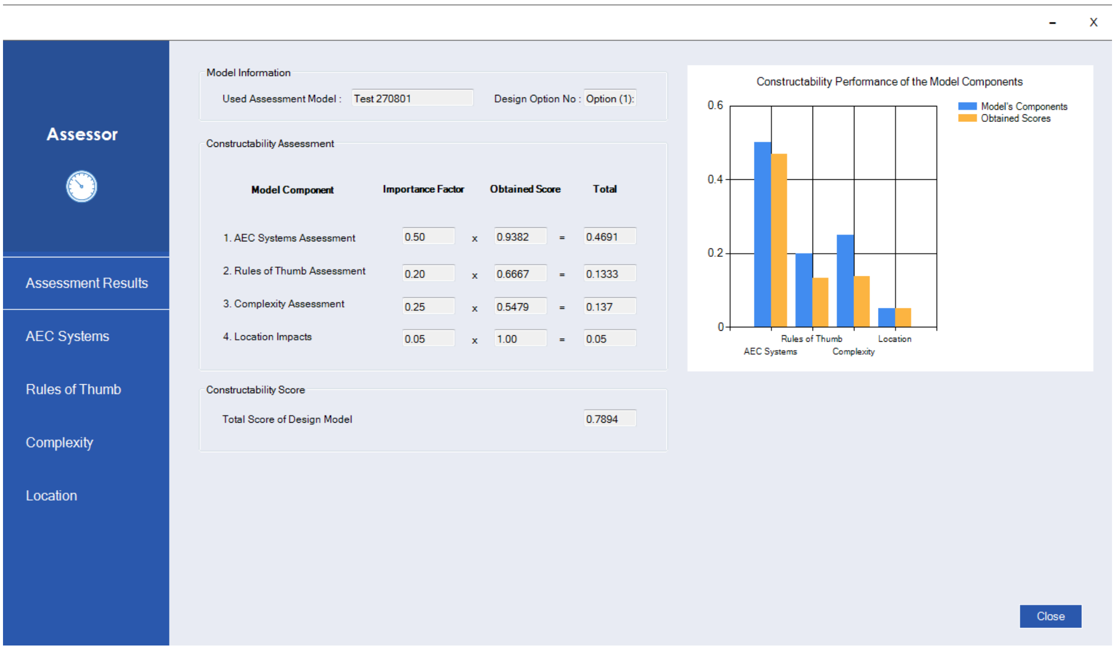


Figure 6-45: Summary of assessment results for various sections and overall achieved score: Design Option (1)

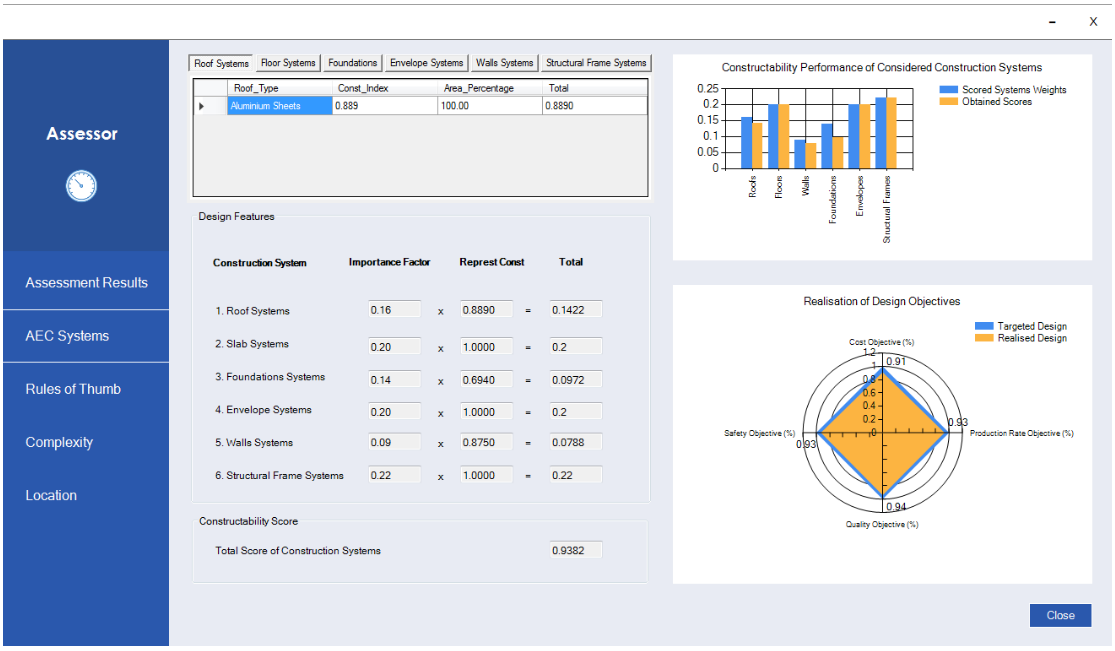


Figure 6-46: Assessment results of the AEC Systems section and its assessed aspects

Figure 6-47 explains the assigned score for Rule of Thumbs section, which is (0.667) based on its assessed sub-sections. The three sections implemented in this part obtained: (0) for Constraints satisfaction, since there is the “Room space” rule that is not satisfied; (1.0) for Clashes check (presumably this has been conducted and addressed); and (1.0) for Legislation, if applicable.

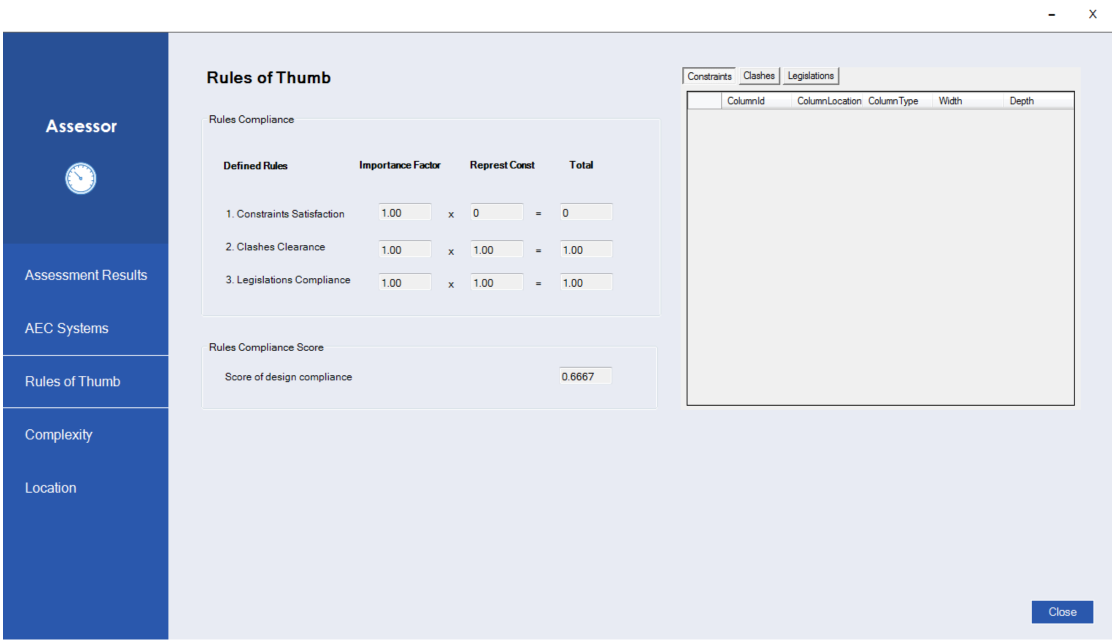


Figure 6-47: Assessment results of Rules of Thumb section and its assessed aspects

For Complexity, as shown in Figure 6-48, a sub-score of (0.5479) is achieved, based on the following scores calculated for its sub-sections: (0.7011) for Hosts and hosted component, (0.6092) for Connections, and (0.333) for Automation. These calculations are performed in accordance with the proposed indicators described in section 4.3. Their results are presented in individual tabs entitled: Host and Hosted Components, Elements Connections, and Automation, as presented in Figure 6-48, Figure 6-49, and Figure 6-50 (respectively). The Location tab is empty in these screens, since no restrictions have been flagged up in the considered design option.

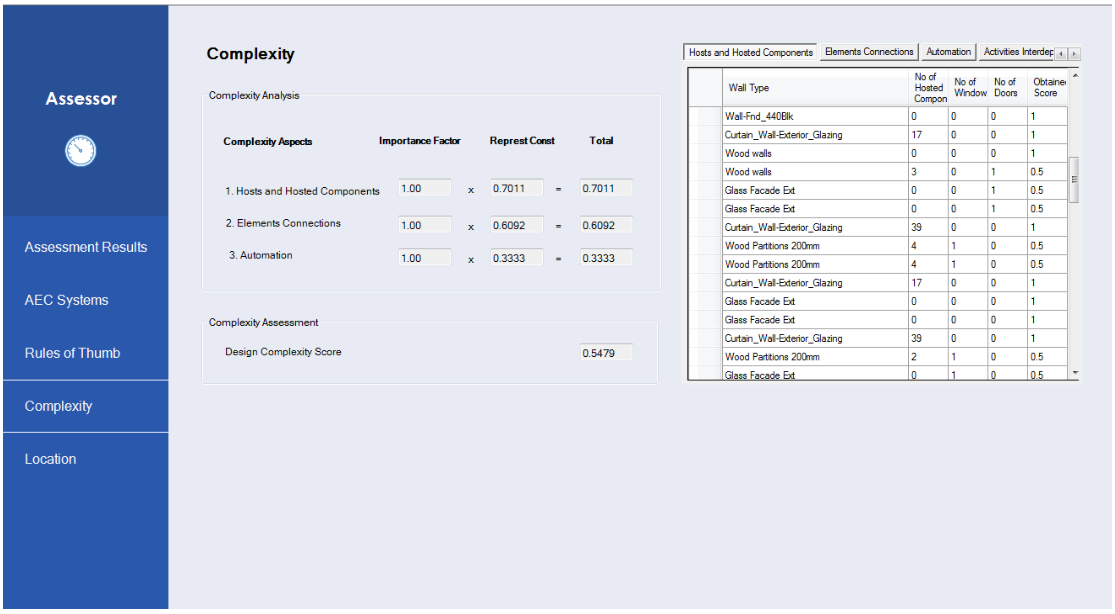


Figure 6-48: Assessment results of Complexity section: Host and Hosted Components

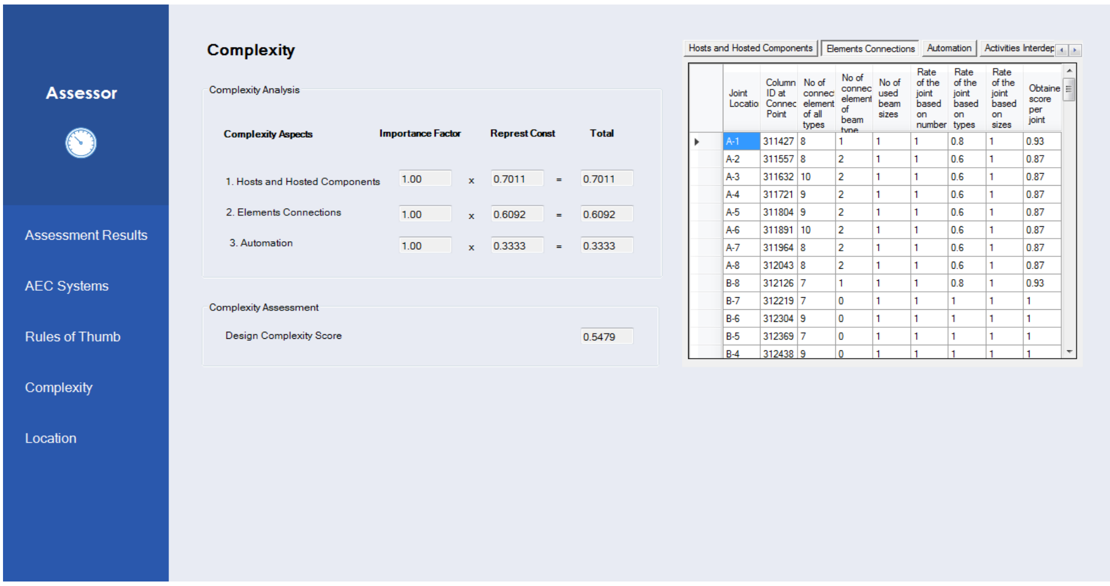


Figure 6-49: Assessment results of Complexity section: Elements Connections

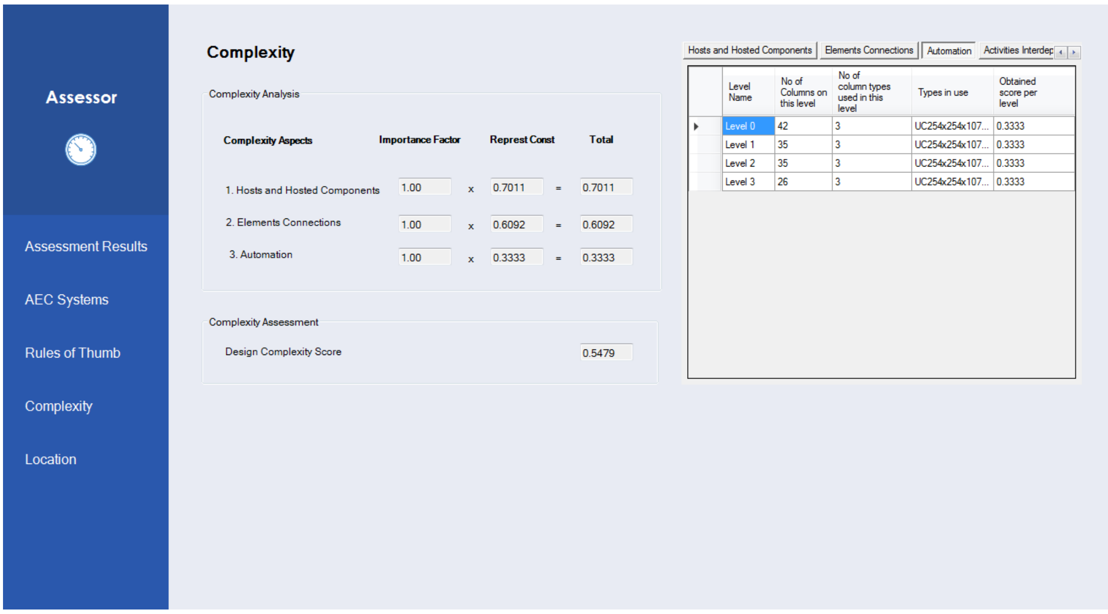


Figure 6-50: Assessment results of Complexity section: Automation assessment

6.6.1.2. Design Option (2)

This same procedure is applied for assessing the constructability of Design Option (2) (Figure 6-51) and Design Option (3). This includes employing the same CM as shown in Figure 6-52. Obtained outcomes are presented and discussed, and interpreted in the same way followed for Design Option (1).

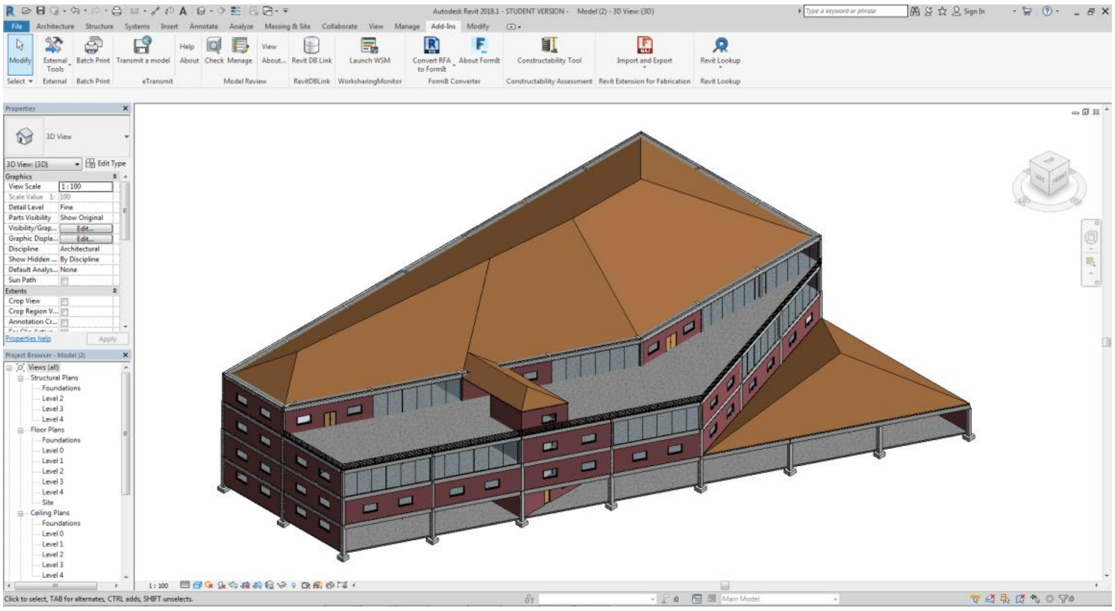


Figure 6-51: Design Option (2): Cast in situ concrete building

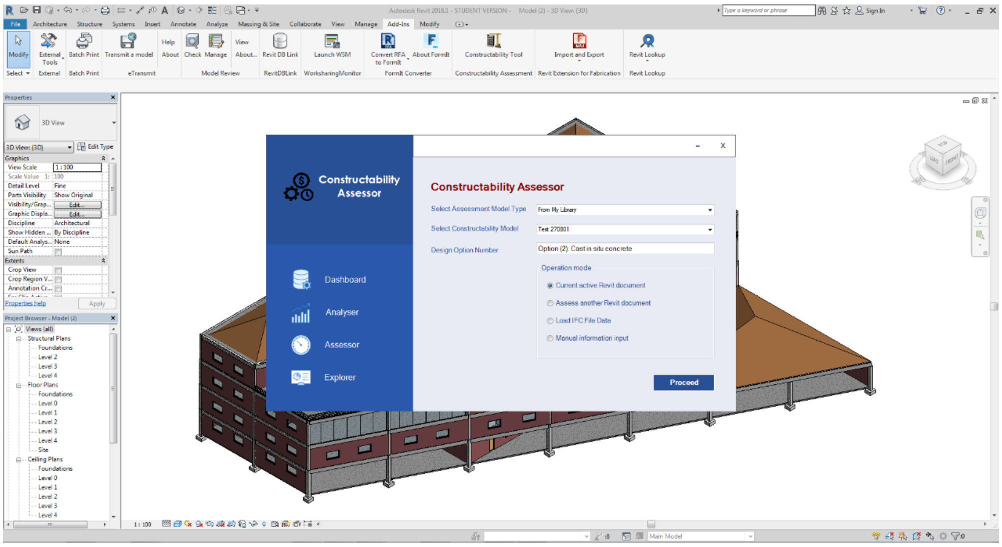
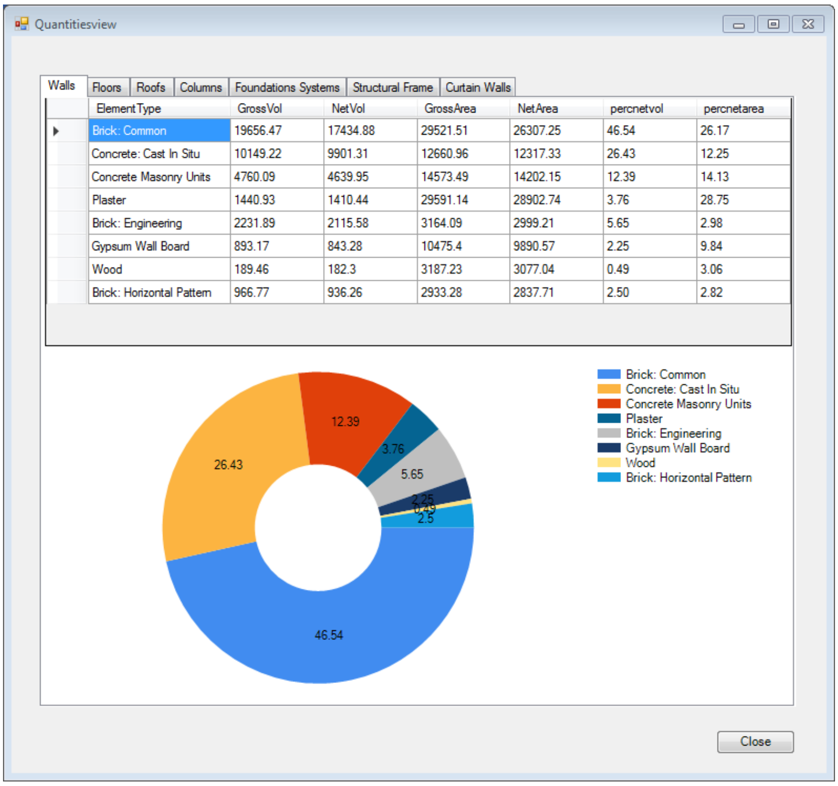


Figure 6-52: Triggering constructability assessment process for Design Option (2)

Figure 6-53 presents a preliminary analysis of the observed model's quantities and its employment of various construction systems. It provides users with an initial impression of where they need to focus their efforts for any sought improvements.



Element Type	GrossVol	NetVol	GrossArea	NetArea	percnetvol	percnetarea
Brick: Common	19656.47	17434.88	29521.51	26307.25	46.54	26.17
Concrete: Cast In Situ	10149.22	9901.31	12660.96	12317.33	26.43	12.25
Concrete Masonry Units	4760.09	4639.95	14573.49	14202.15	12.39	14.13
Plaster	1440.93	1410.44	29591.14	28902.74	3.76	28.75
Brick: Engineering	2231.89	2115.58	3164.09	2999.21	5.65	2.98
Gypsum Wall Board	893.17	843.28	10475.4	9890.57	2.25	9.84
Wood	189.46	182.3	3187.23	3077.04	0.49	3.06
Brick: Horizontal Pattern	966.77	936.26	2933.28	2837.71	2.50	2.82

Figure 6-53: Analysis of design quantities for various construction systems: Design Option (2)

For this design option, the delivered warning message for non-satisfied rules is shown in Figure 6-54. It suggests that the examined solution contains some columns that do not conform to specified formwork dimensions. Non-compliant columns are highlighted and listed in Figure 6-55 with their actual dimensions and IDs. They can be also viewed from various floors plan and sections, as shown in Figure 6-56.

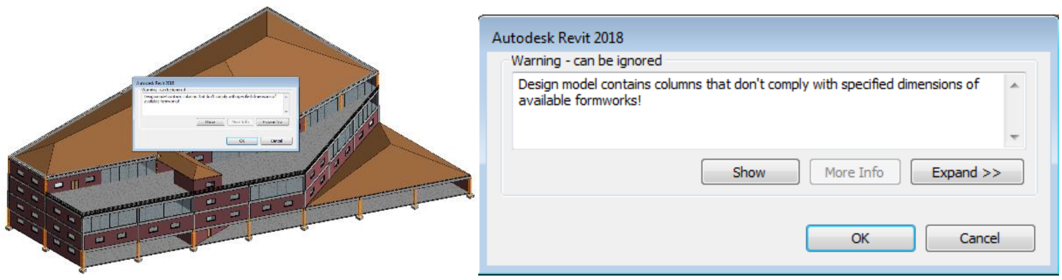


Figure 6-54: Warning message to highlight non-compliant design elements with enabled rules

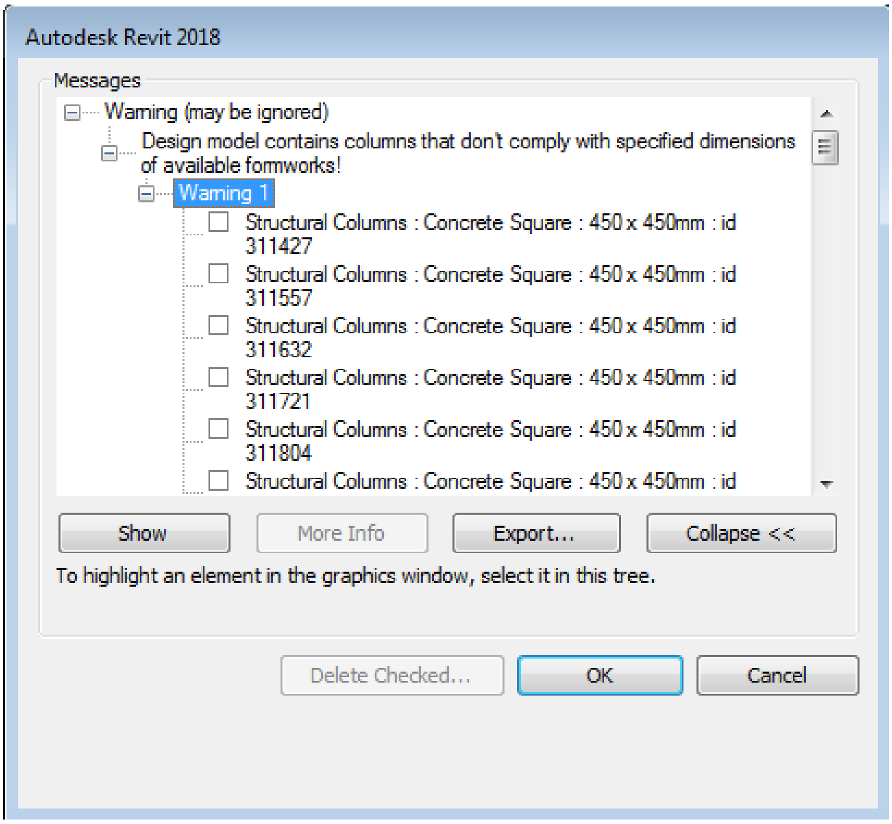


Figure 6-55: Identified non-compliance Columns for their dimensions with Column Formwork rule

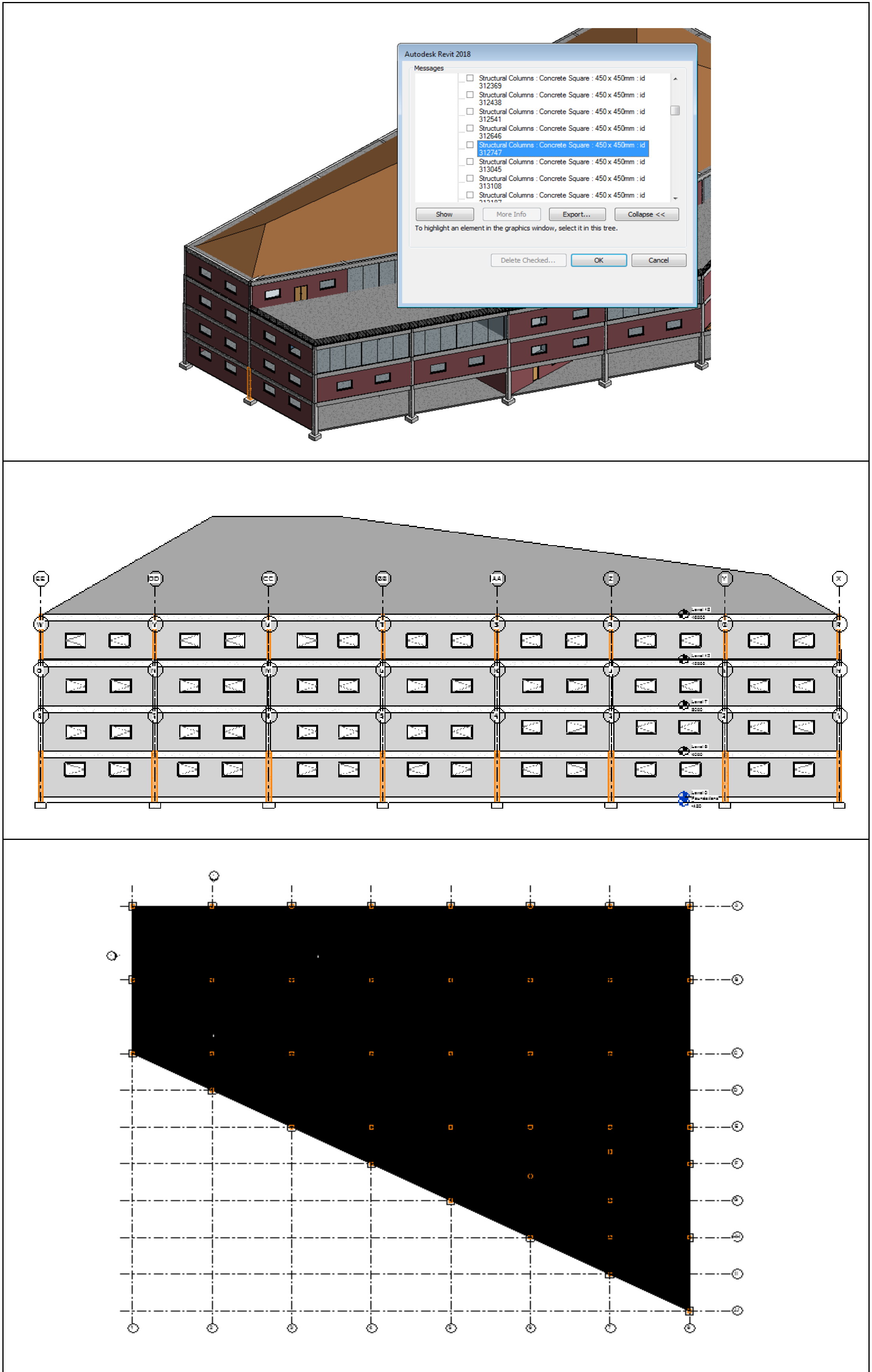


Figure 6-56: Plan, elevation and side view for non-compliant columns

Assessment results for Design Option (2) show that an overall score of (0.8339) is achieved, compared to (0.7894) in Design Option (1) (Figure 6-57). Sub-scores for assessed aspects are (0.4245) for AEC Systems, (0.1662) for Rules of Thumb, (0.1931) for Complexity, and (0.05) for Location. The best performance is recorded in Location section (1), with quite similar performance for other parts, while the worst is Complexity (0.7723).

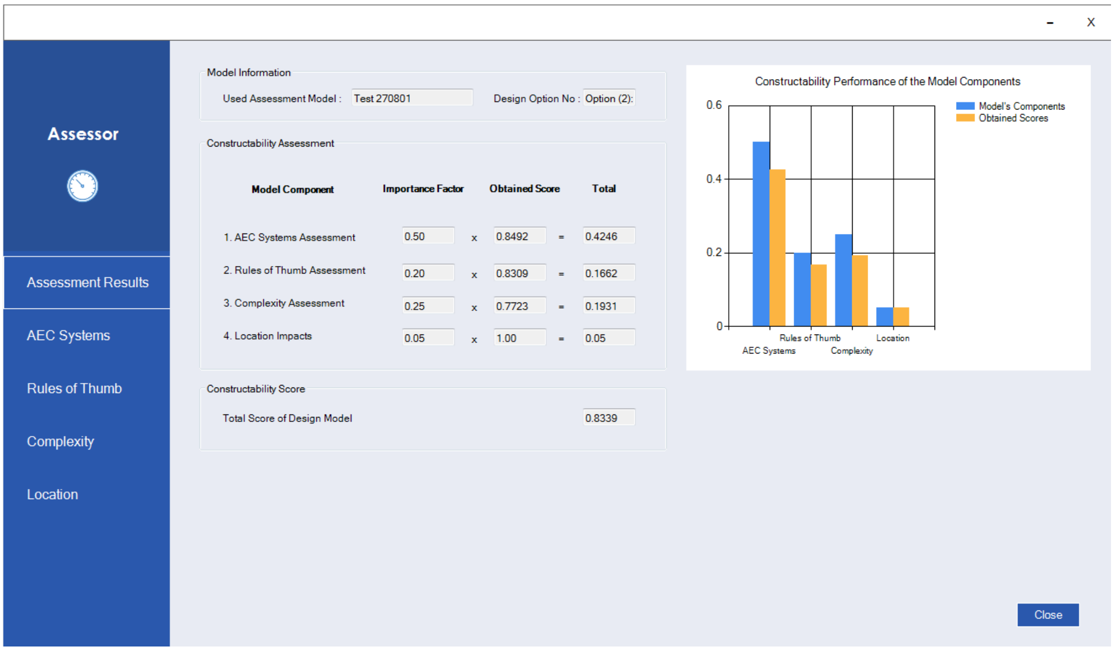


Figure 6-57: Summary of assessment results for various sections: Design Option (2)

Looking closely at the AEC System through its detailed tab (Figure 6-58), used construction systems performed as follows: (0.9788) for Roofs, (0.6780) for Slabs, (0.6940) for Foundations, (1.0) for Envelopes, (0.8649) for Walls and (0.8271) for Structural framings. This indicates that focus should be directed to improve Slab and foundation systems if a better Constructability score is sought. In terms of objectives realisation, the current design contributes by (0.79) towards satisfying Cost, (0.82) for Production Rate, (0.92) for Quality and (0.88) for Safety objectives. Though the overall score obtained for Design Option (2) is slightly higher for Design Option (1), however, the realisation of design objectives does not agree with this. This suggests that both slabs and foundation systems affect significantly the satisfaction of such objectives, and hence lower performance leads to lower realisation rate.

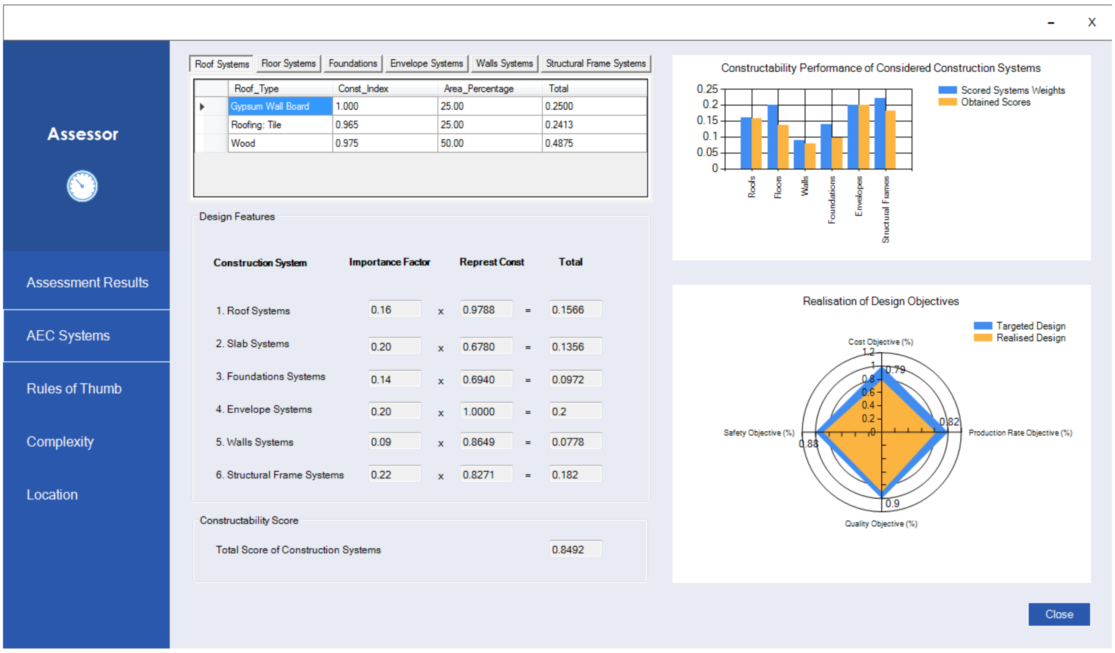


Figure 6-58: Assessment results of the AEC Systems section and its assessed aspects

Rules of Thumb score is (0.8309) (Figure 6-59), based on (0.4928) achieved in the Constraints satisfaction and (1.0) for both Clashes and Legislation requirements (as previously explained). The severity of the assigned score due to non-compliant rules (0.4928) is less than assigned in Design Option (1) when a value of (0) was awarded. This is because that number of non-compliant elements here (i.e. the number of columns having different dimensions than specified) are quantified, and the percentage of non-compliance can be calculated as a better indication of constructability status. However, it may be considered that the existence of any non-constructible item will affect the construction process regardless of amount, thus zeroes should be assigned to highlight these values and direct attention to troubleshooting issues with these items.

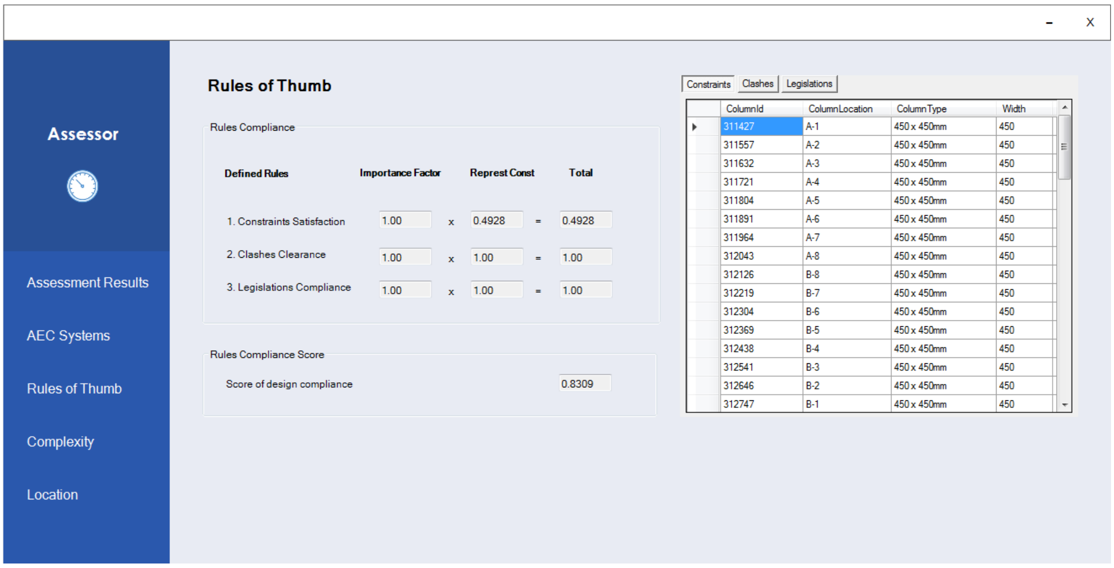


Figure 6-59: Assessment results of Rules of Thumb section and its assessed aspects

Complexity achieved (0.7723), explained as follows: (0.6918) for Hosts and hosted components, (1.0) for Elements Connections, and (0.625) for Automation, as presented in Figure 6-60, Figure 6-61, and Figure 6-62. The value of (1.0) is awarded for connections, since this a concrete building, which therefore has no connections to be assessed using introduced indicators (i.e. the View tab is empty). This is one of the prototype benefits when adjusting itself to assess what can be assessed in the actual design.

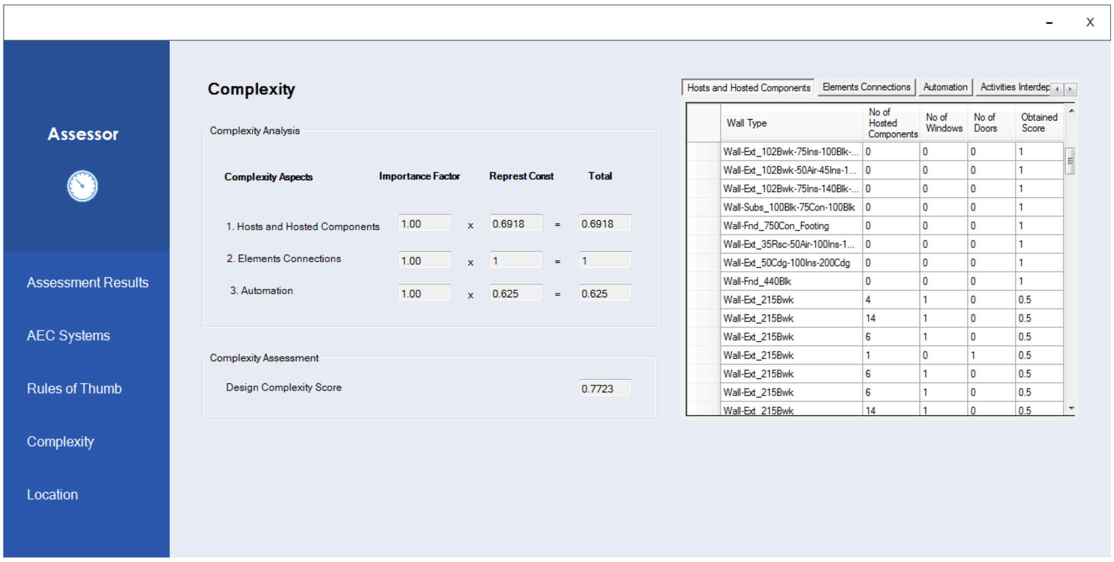


Figure 6-60: Assessment results of Complexity section: Host and Hosted Components

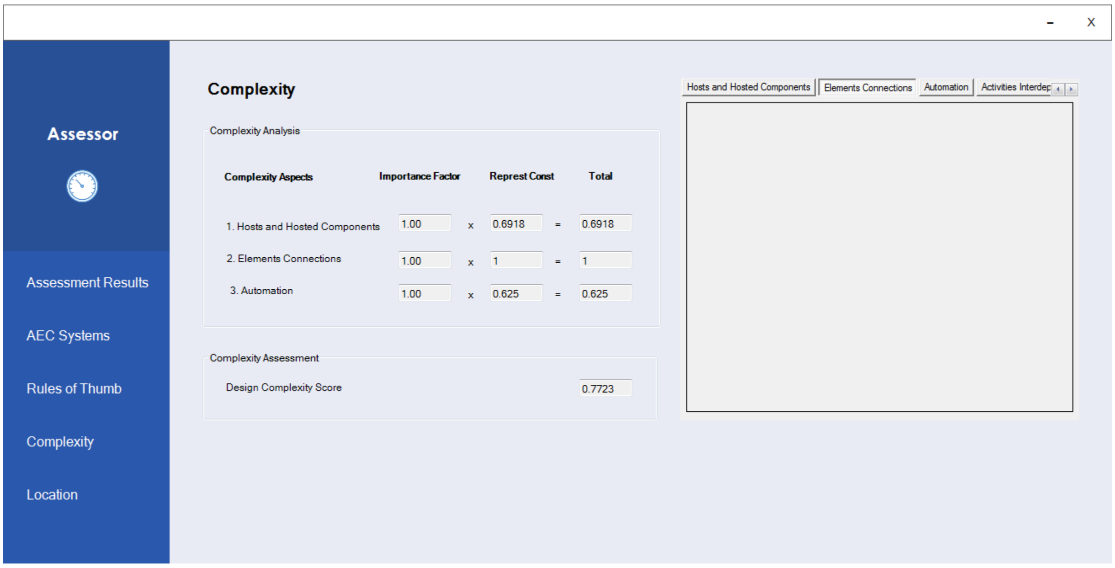


Figure 6-61: Assessment results of Complexity section: Elements Connections

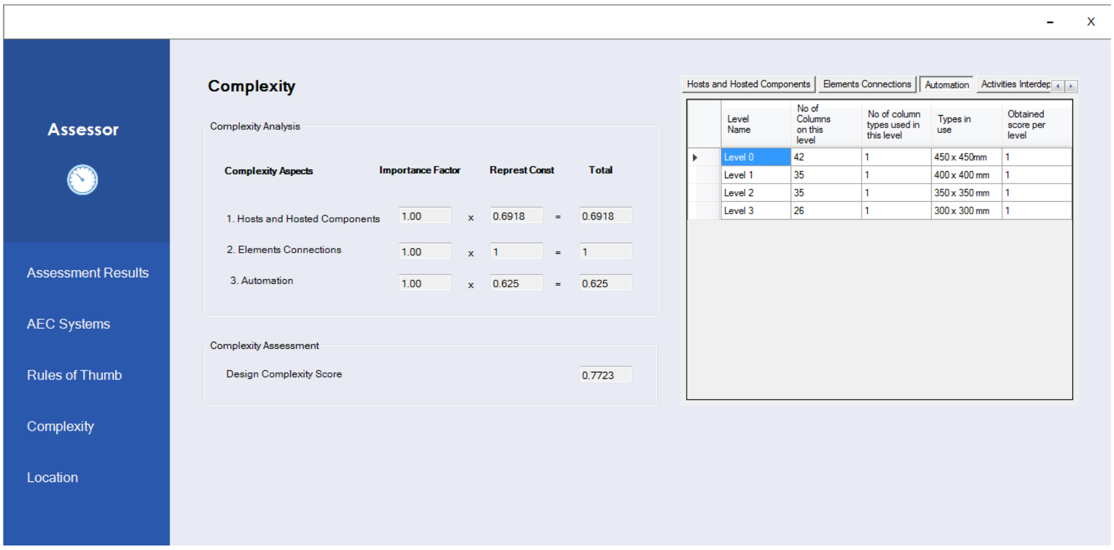


Figure 6-62: Assessment results of Complexity section: Automation

6.6.1.3. Design Option (3)

Following the same procedure, constructability assessment outcomes for Design Option (3) (Figure 6-63) using Test 270801 CM (Figure 6-64) are presented.

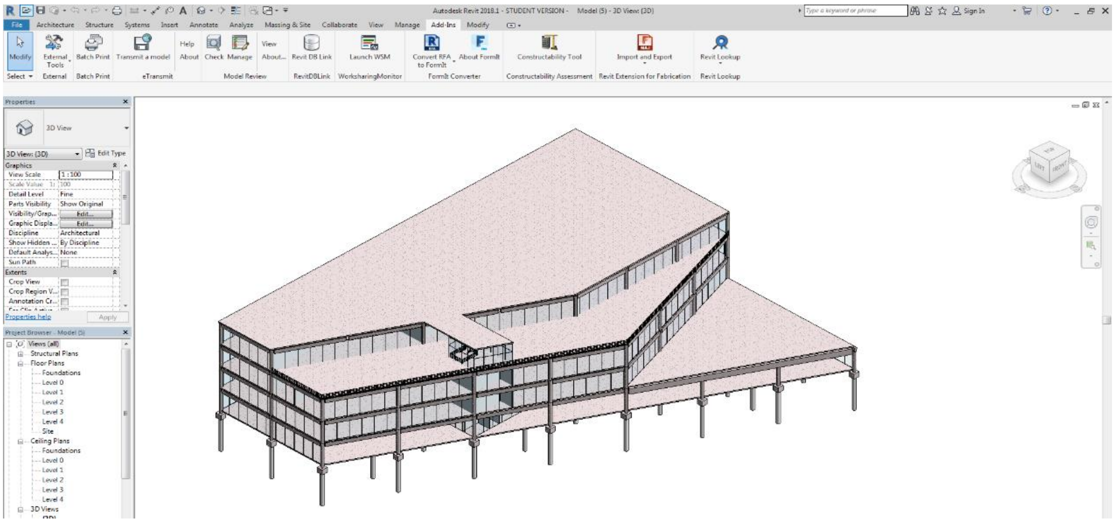


Figure 6-63: Design Option (3): Pre-cast building

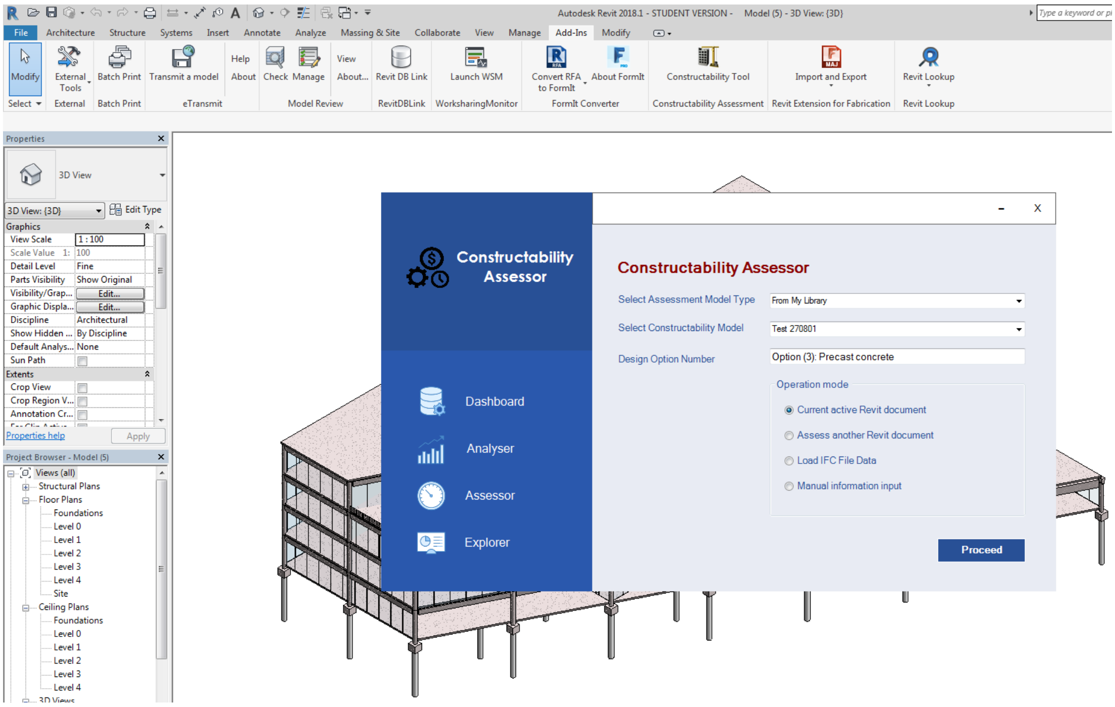


Figure 6-64: Triggering constructability assessment process for Design Option (3)

For Design Option (3), as shown in the message in Figure 6-65, the design solution contains a component that needs special arrangements in advance (an abnormal girder to be transported to the site). This is based on specifications provided by the Department of Transport (as described in section 4.5.). Such a warning will bring the attention of designers and engineers to address it by exploring all available options at the time of assessment. This includes changing the design by splitting the girder into small pieces. Alternatively, keeping the current solution as it is while arranging for the requested procedure is an option the design team can consider.

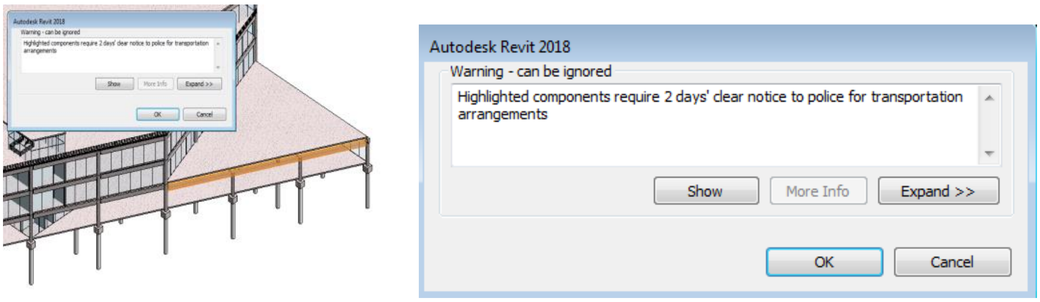


Figure 6-65: Warning message to highlight non-compliant design elements with Transportation specifications

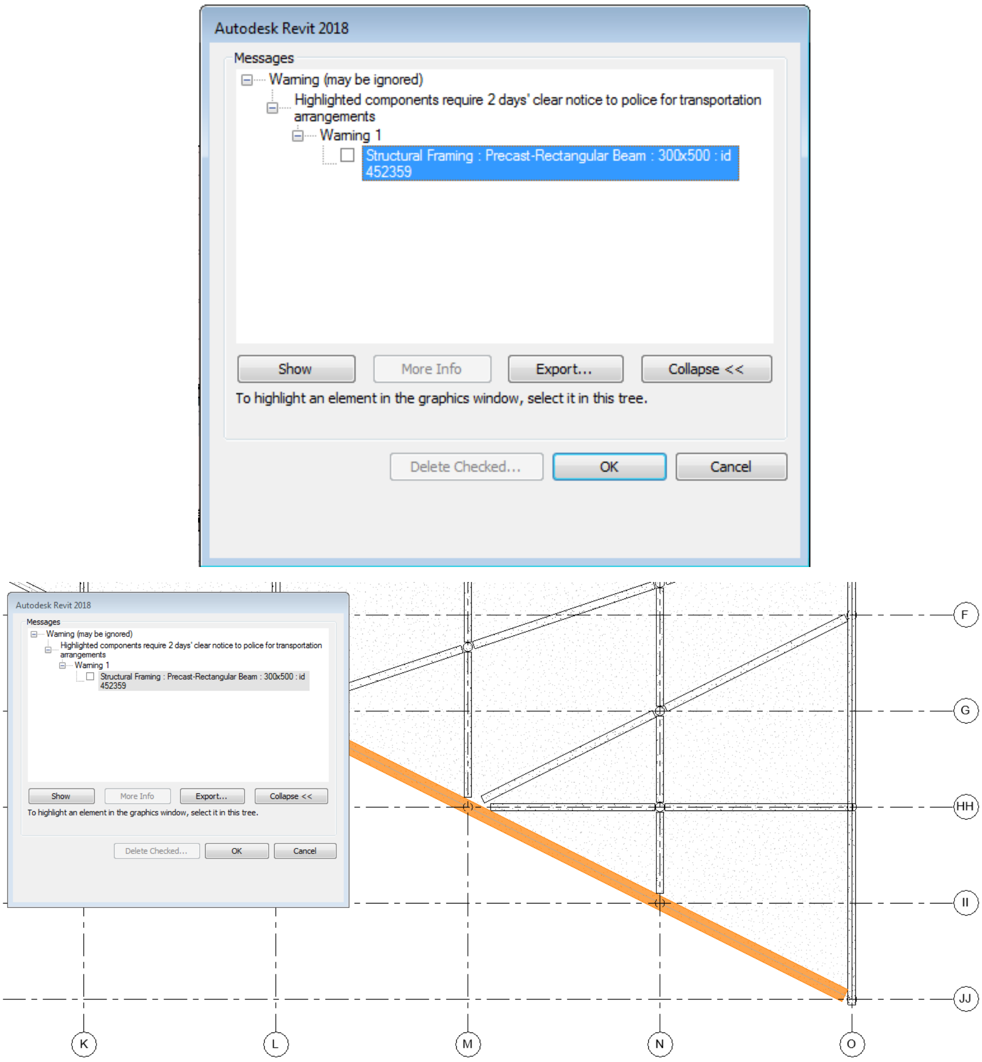


Figure 6-66: Identified non-compliant girder with Transportation specifications on a Plan view

Figure 6-67 shows that an overall score of (0.8916) is accomplished for this design with full satisfaction for Rules of Thumb (1.0), and a value of (0.0) for Location, due to the recorded abnormal transportation requirement. This is expressed in assigned scores as follows: (0.45905) for AEC Systems, (0.2) for Rules of Thumb, (0.2326) for Complexity, and (0.0) for Location, as mentioned.

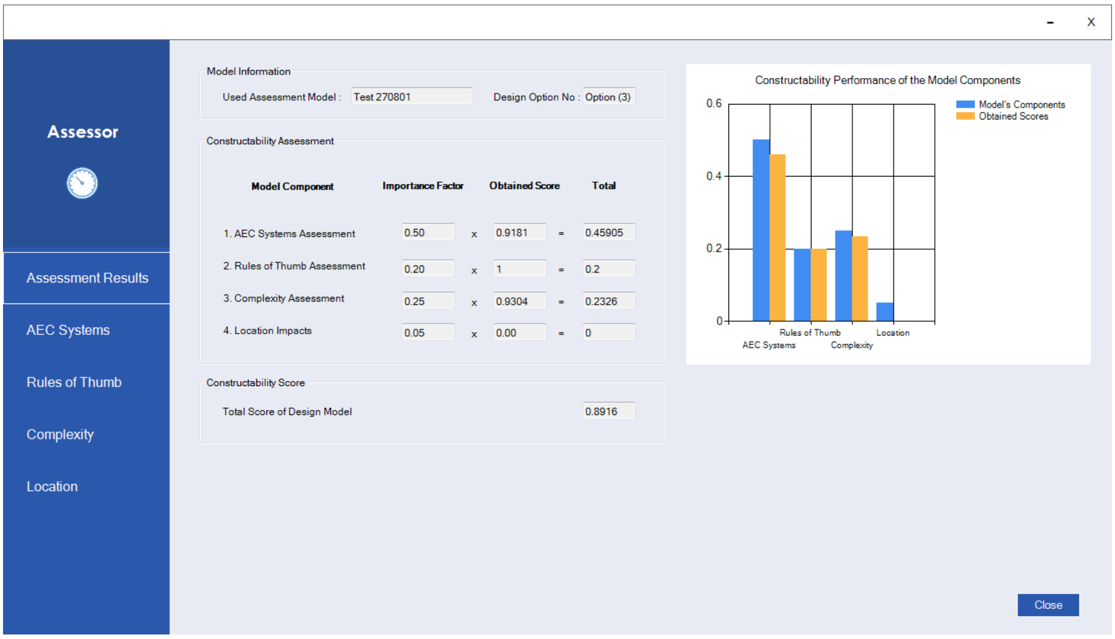


Figure 6-67: Summary of assessment results for various sections: Design Option (3)

Assessment of AEC Systems recorded (0.9181) due to calculated scores of used construction systems (Figure 6-68) as follows: (0.1366) for Roofs, (0.1752) for Slabs, (0.1168) for Foundations, (0.2) for Envelopes, (0.09) for walls, and (0.1995) for Structural framings. The realisation of defined objectives is in better shape than the Design Option (2), recording (0.9) in Cost, (0.91) in Production rate, (0.94) in Quality and (0.91) in Safety.

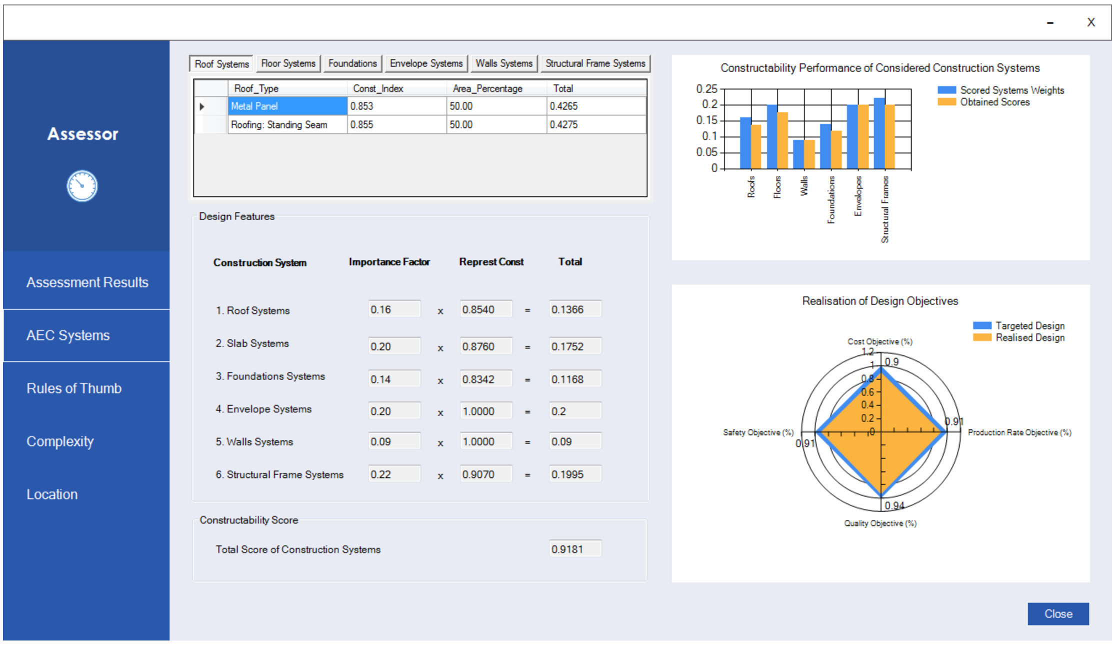


Figure 6-68: Assessment results of the AEC Systems section and its assessed aspects

Rules of Thumb for this design solution achieved full score (1.0), as no design elements are identified as non-complaints for enabled rules (Figure 6-69). An overall score of Complexity recorded (0.9304), resulting from (0.791) for Hosts and hosted components, (1.0) for elements connections (Concrete building) and (1.0) for Automation (using typical column size overall the building), as presented in Figure 6-70, Figure 6-71, and Figure 6-72 (respectively). However, the Location section scored (0) due to non-compliance with transportation requirements, given that the project is in the UK.

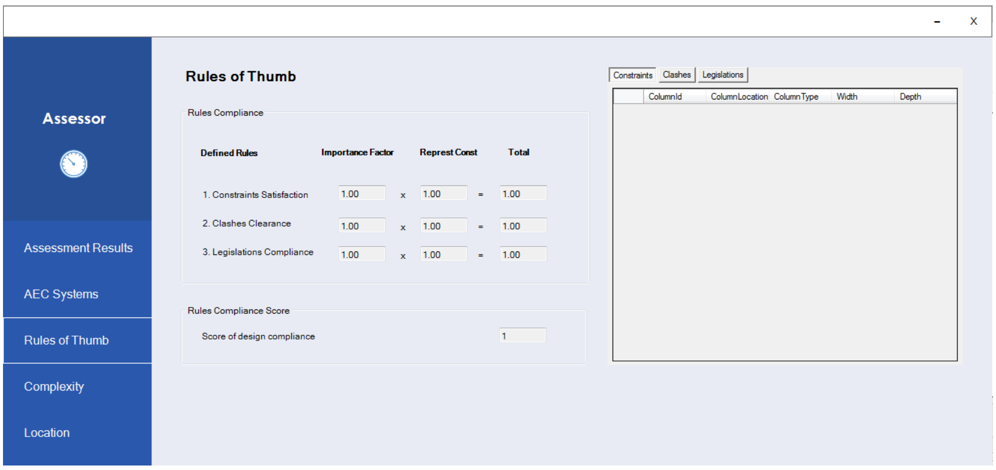


Figure 6-69: Assessment results of Rules of Thumb section and its assessed aspects

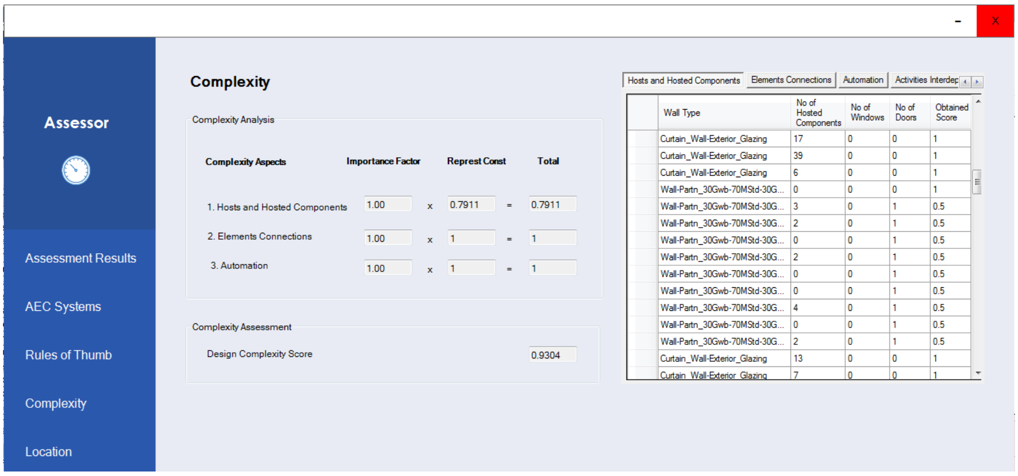


Figure 6-70: Assessment results of Complexity section: Host and Hosted Components

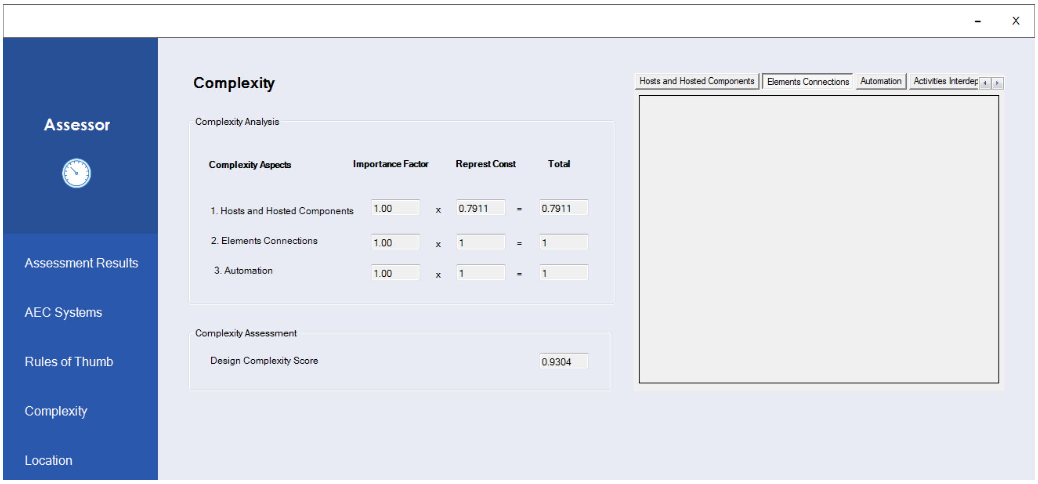


Figure 6-71: Assessment results of Complexity section: Elements Connections

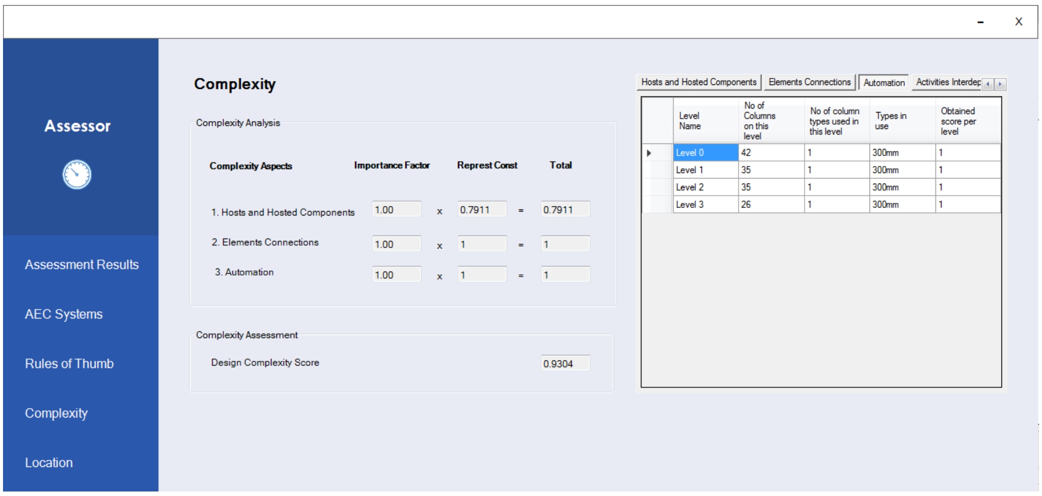


Figure 6-72: Assessment results of Complexity section: Automation

6.6.2. Stage (2): Design Option (4)

Based on obtained assessment results for design alternatives examined in stage (1), Design Option (3) is the best-performing solution among the models assessed for constructability, suggesting that any optimisation should be start from this option. As explained earlier, stage (2) investigates the impact of design quantities and shape, rather than used construction systems. This is carried out using Design Option (4) (Figure 6-73), which utilises the same families as Design Option (3), but which has a different shape and quantities.

The model was built to avoid the shortcomings inherent in previous models, to achieve enhanced constructability performance. This was in-line with the objective of improving design quantities for the AEC Systems section to test sensitivity. Obtained assessment results and their analysis are presented using Test 270801 CM (Figure 6-74).

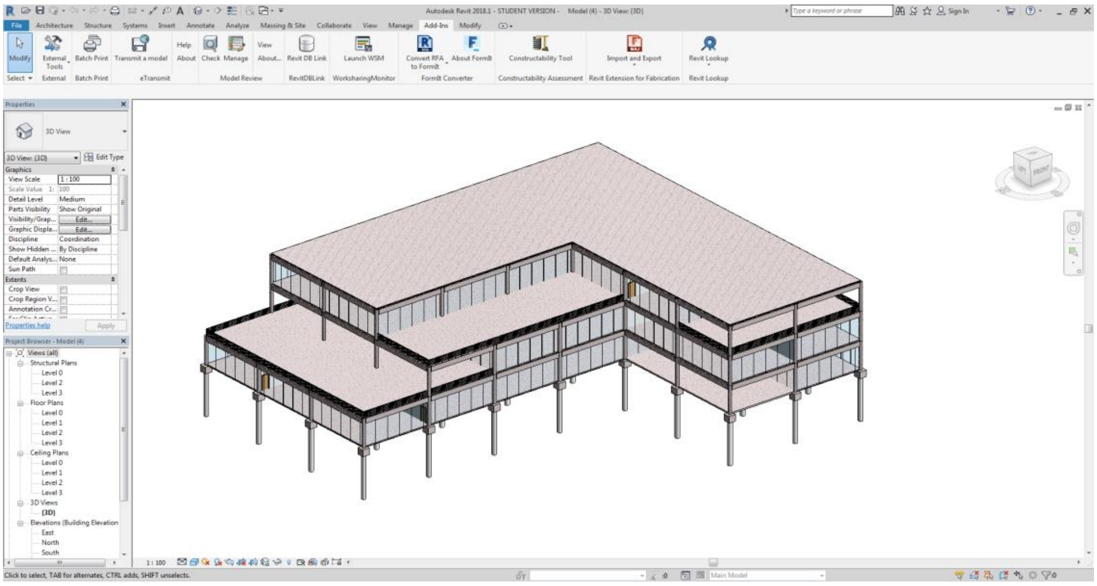


Figure 6-73: Design Option (4): Pre-cast building-Stage (2)

Demonstrated outputs for the assessment of this model (Figure 6-75) achieved an overall Constructability score of (0.935), recording the highest score among all suggested models, which is clearly attributable to addressing the previously identified issues in other models . However, room of improvement is always available if there is a need (e.g. compliance with any required score or legislated policies). Sub-scores performed as follows: (0.9181) for AEC

Systems, (0.2) for Rules of Thumb, (0.9041) for Complexity, and (0.05) for Location.

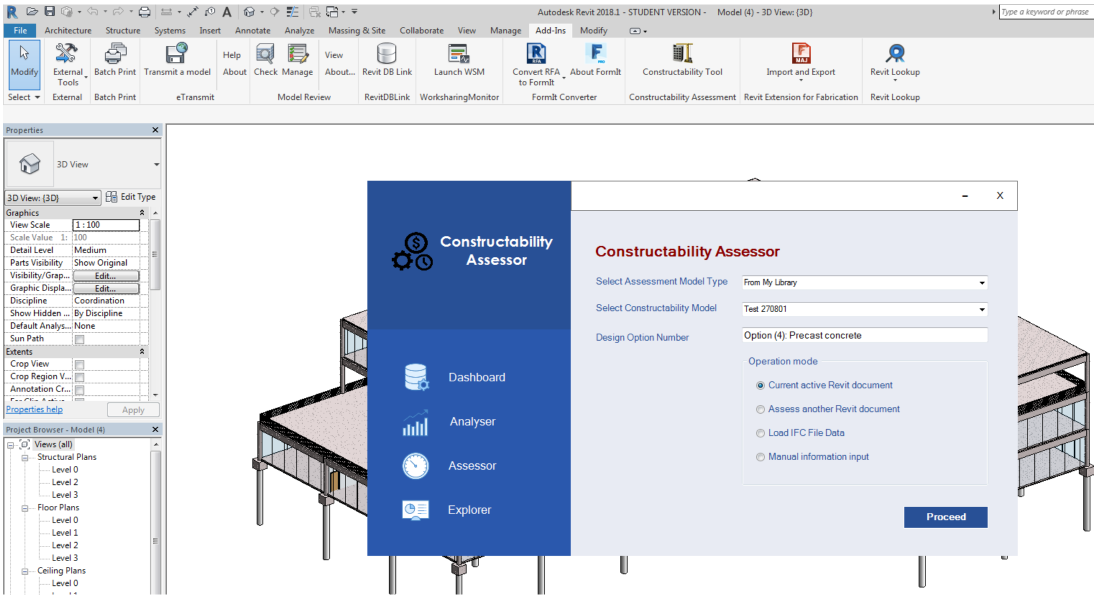


Figure 6-74: Triggering constructability assessment process for Option (4)

Figure 6-75: Summary of assessment results for various sections: Design Option (4)

Figure 6-76 presents sub-scores for AEC Systems that comprise the achieved score for this category (0.981): (0.1366) for Roofs, (0.1752) for Slabs, (0.1168) for Foundations, (0.2) for envelopes, (0.09) for walls, and (0.1995) for Structural framings. Design Option (4) realises (0.9) for allocated cost, (0.91) for the scheduled time, and (0.94) for targeted quality, while maintaining (0.91) of the project safety during the construction process.

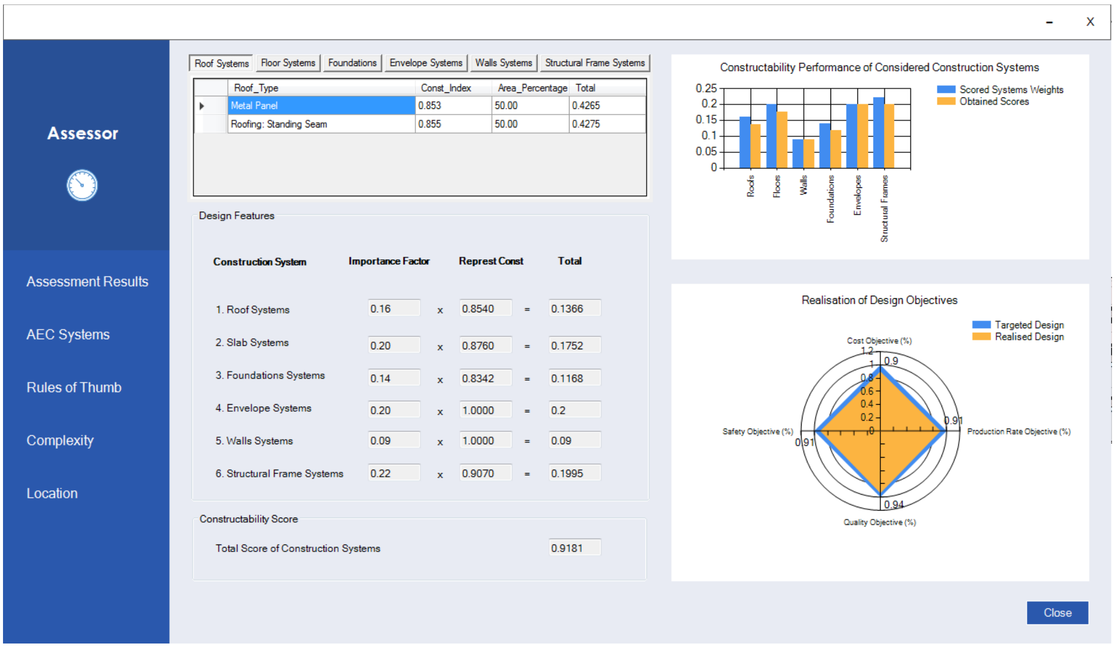


Figure 6-76: Assessment results of the AEC Systems section and its assessed aspects

Rules of Thumb for Design Option (4) Figure 6-77 recorded a full score, as for Design Option (3), ensuring the elimination of any potential issues for the current Rules of Thumb in the implemented case study.

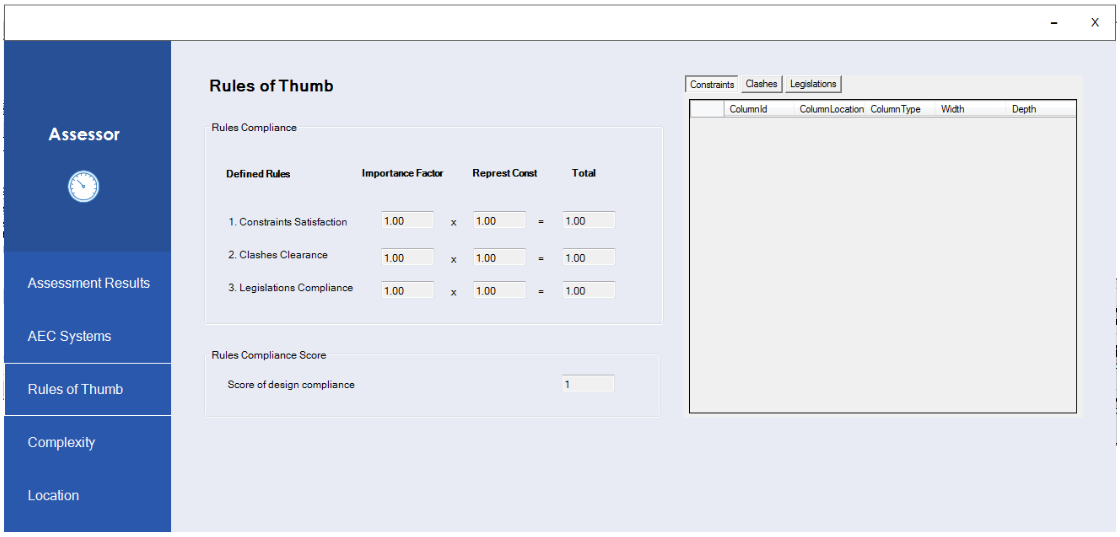


Figure 6-77: Assessment results of Rules of Thumb section and its assessed aspects

For Complexity, the calculated score of (0.9041) is due to: (0.7123) in Host and hosted components; (1) for Elements Connection, since it is a pre-cast building with no steel connections; and (1.0) for Automation, using the same column size for all floors in this implemented case. These sub-divisions of Complexity are shown in Figure 6-78, Figure 6-79, and Figure 6-80, respectively.

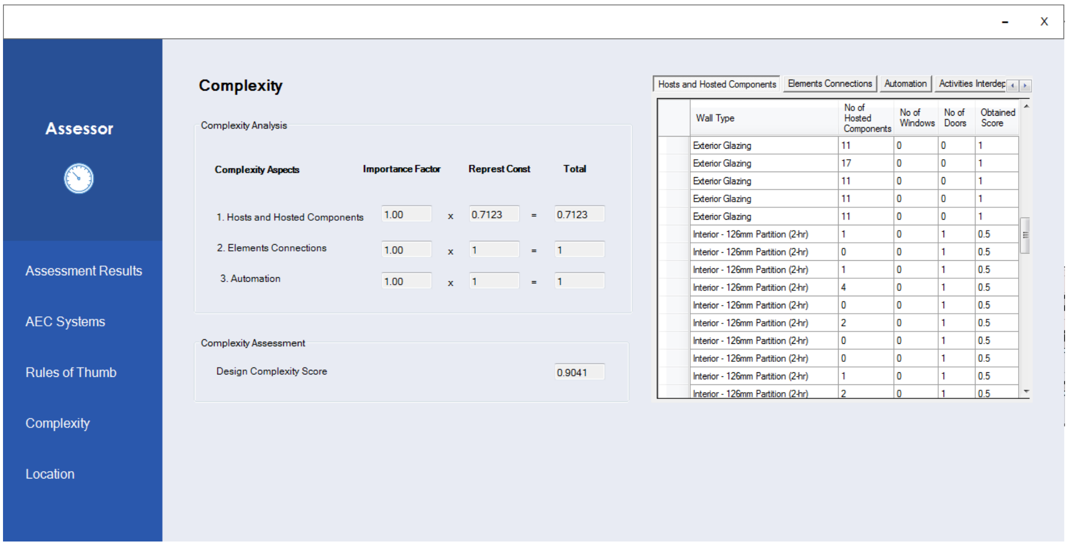


Figure 6-78: Assessment results of Complexity section: Host and Hosted Components

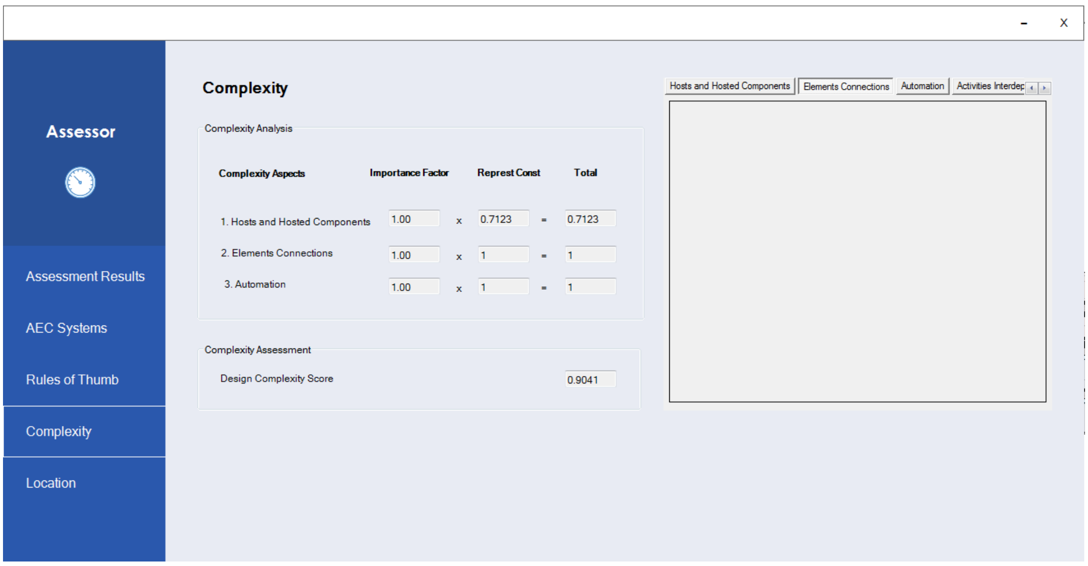


Figure 6-79: Assessment results of Complexity section: Elements Connections

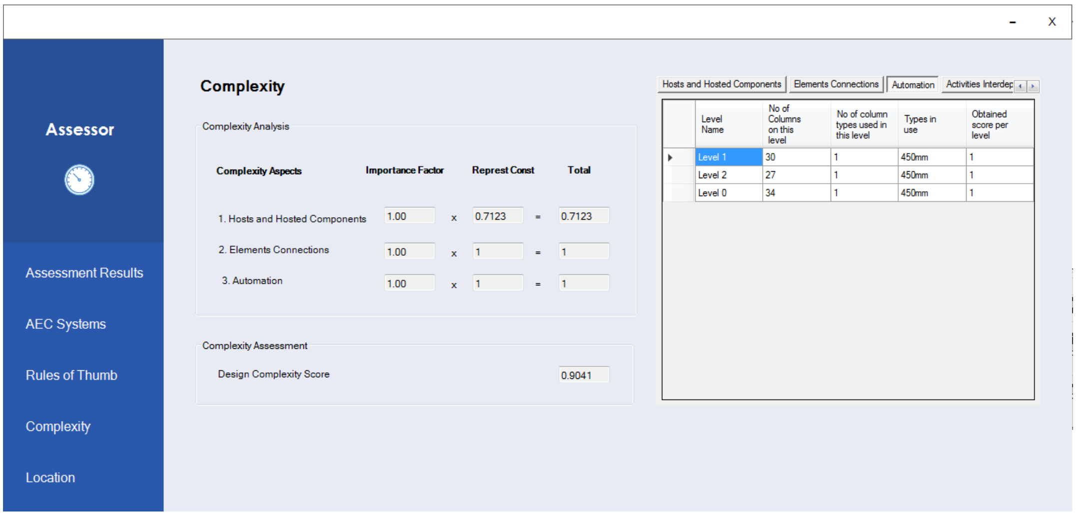


Figure 6-80: Assessment results of Complexity section: Automation

6.7. Remarks on sensitivity analysis

The discussed case study did not attempt to draw generic conclusions from obtained results that favour the constructability of one system over another. The rationale behind this is that every design case is unique, and any consideration for constructability should account for the project conditions, location, and the capabilities and resources of potential builders. The implemented process enabled comparison between the assessed models in terms of their constructability performance. General feasibility can be observed from Figure 6-81 and Figure 6-82. They demonstrate obtained scores of different components for various model options at stage (1) and (2). This is useful to decide on the overall score summed from individual constructability aspects, and to analyse, compare, and optimise (Table 6-7).

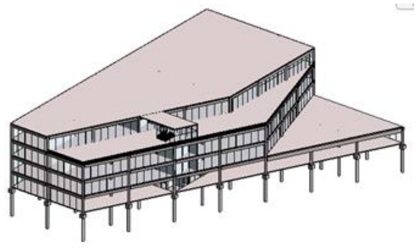
Table 6-7: Constructability performance of design options at Stage (1)

Constructability Aspect	Weighting Factor	Design Option (1): Steel Structure	Design Option (2): Cast *In Situ* Concrete	Design Option (3): Precast Concrete
AEC Systems	0.50	0.4691	0.4246	0.45905
Rules of Thumb	0.20	0.1333	0.1662	0.2000
Complexity	0.25	0.137	0.1931	0.2326
Location	0.05	0.05	0.05	0.00
Obtained Constructability Score	1.00	0.7894	0.8339	0.8916

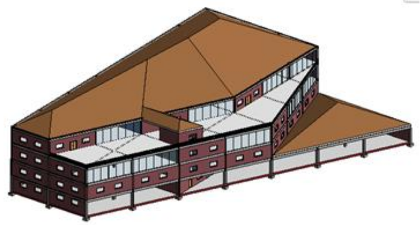
The overall score is improved in Design Option (4) from Design Option (3), given that they employ the same construction system but different shapes. However, this was mainly due to improvement in the Location (from 0 to 0.05) and (to some extent) Complexity (from 0.226 to 0.2326) sections (Table 6-8). Contrary to expectations, achieved scores did not indicate sensitivity to the change in design quantities. A possible explanation for this might be that considered models are not using multiple types in the same construction systems (slabs, floors etc.). For instance, using the same type of envelopes for both models will not be affected by changes in quantities. This would make a difference when two or more types are used within the same design, while changing in their used ratios. While this does not contribute to the target of gauging the sensitivity of obtained scores towards designs shape, it confirms the effectiveness of system scalability when dealing with various design sizes, to assess their constructability performances.

Table 6-8: Constructability performance of design options at Stage (2)

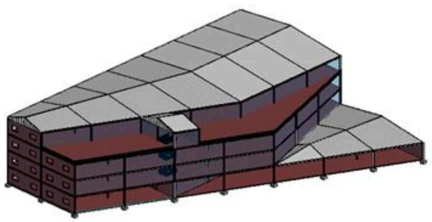
Constructability Aspect	Weighting Factor	Design Option (3): Precast Concrete	Design Option (4): Precast Concrete
AEC Systems	0.50	0.45905	0.45905
Rules of Thumb	0.20	0.20	0.20
Complexity	0.25	0.226	0.2326
Location	0.05	0.00	0.05
Overall Constructability Score	1.00	0.8916	0.935



Option (3): Pre-cast concrete building



Option (2): Cast in situ concrete building



Option (1): Steel building

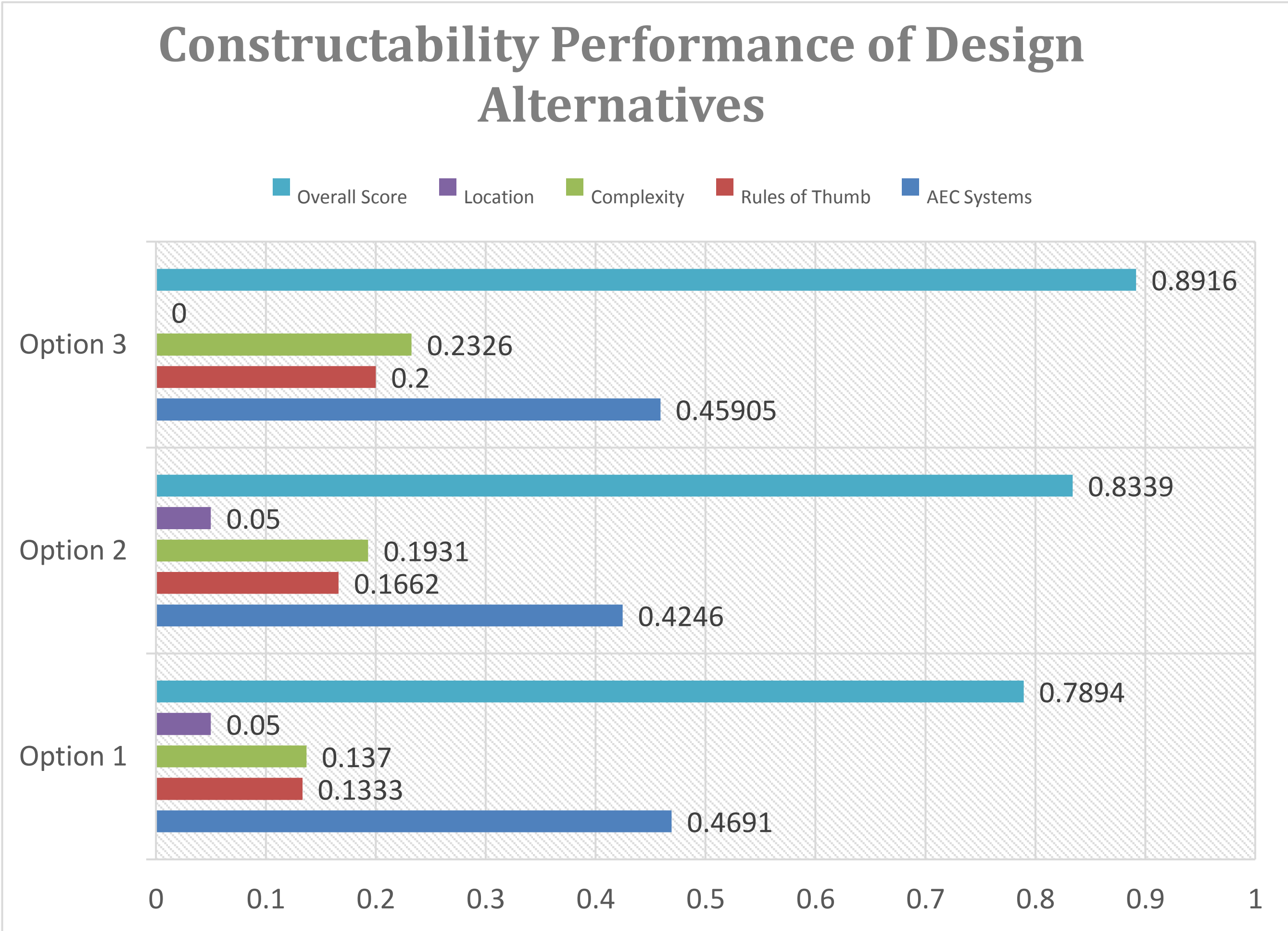


Figure 6-81 Constructability assessment scores (Option 1, Option 2, and Option 3): Stage (1)

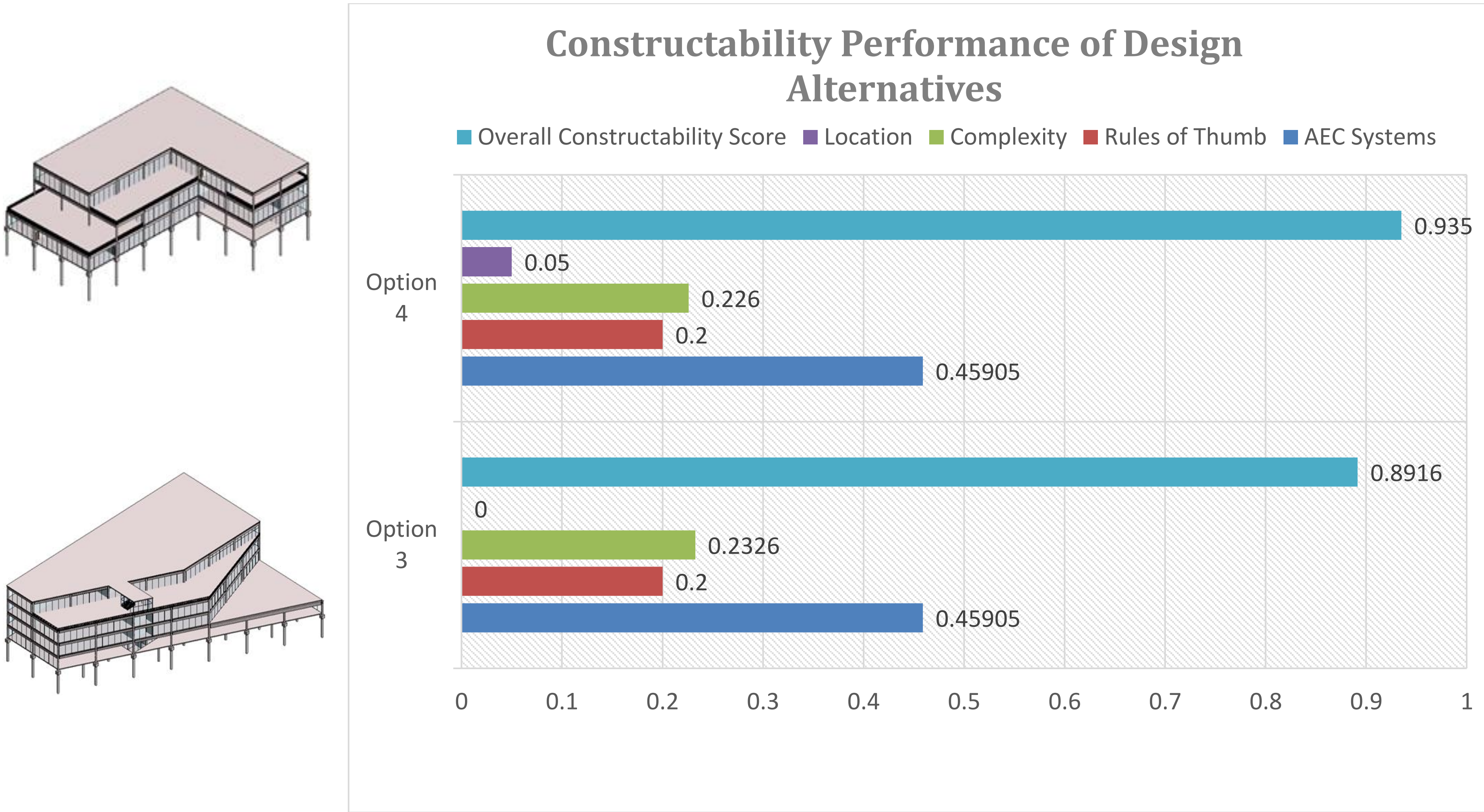


Figure 6-82: Constructability assessment scores (Option 3 Vs Option 4): Stage (2)

6.8. Constructability improvement strategy

The proposed system and its implementations are designed to direct its users to potential areas for improvements. This can be observed through the discussed assessment results of the considered case study. Based on the testing presented, the resultant strategy can be iterated as follows:

- The main tab presents a summary of the constructability assessment performance achieved by each section of the model as well as the overall factored score. This clearly indicates the importance of each section towards the sought score represented in assigned weighting factors. It also presents how they actually performed, which enables comparison with what was originally expected.
- Based on this, lower performing parts are identified and considered carefully, given that their improvements can contribute significantly to the entire system's improvements. As an example, focusing on the AEC Systems category within the examined case study was highly effective, as it carries the highest weighting factor.
- Users can then work on improving the performance of the identified category using achieved results of their assessed aspects provided in separate tabs accordingly:
    - *AEC Systems*. Interpreting the actual performance of the used construction system indicates the area of improvement by recognising assigned importance and actual performance. To improve scores, each system shows constructability indices of used design components as well as quantities extracted from the design solution. This allows deciding whether to change types of used construction systems or reduce their quantities if deemed to make a difference.
    - *Rules of Thumb*. Addressing issues with flagged design elements due to non-compliance with any defined rules improves the Constructability score of this section.
    - *Complexity.* This score can be improved by investigating poorly assessed aspects based on their obtained scores, through

understanding employed assessment formulas and their inputs from design models. Users should react accordingly, to amend their designs and accomplish higher scores.

- *Location*. Again, the obtained scores, as well as highlighted aspects presented in the show tabs, provide guidance on how to enhance their performance.

It should be noted that it is important to emphasise that the accuracy of any performed appraisal for constructability, critically relies on using the right CM in examining the assessed design model, at the right time of the design process.

6.9. Discussion and remarks

Constructability score is subjective, and may vary significantly from one case to another, relative to project conditions and potential constructors' capabilities. Therefore, there is no standard reference or benchmark point to decide on the accuracy or correctness of obtained assessment results. Only actual builders of designs can decide on the optimum choices, based on their contextual requirements and professional perspectives and experience. By customising their CMs, they have already reflected their own construction capabilities, as well as expressing preferences among various construction systems. This underscores the integrity of the obtained assessment results and provides information on constructability performance.

The employed assessment method represented in the implemented prototype is only a decision-support tool, assisting designers in attaining such assessment outcomes. It has no inputs on the assessment results; the user is responsible for customising the model or applying information provided from the BIM model. The fieldwork clearly presents the ranked preference of various construction systems scored by the users under AEC Systems. On the Rules of Thumb section, it seeks to identify non-compliant design elements against what the user defined as imposed constraints. For the Location part, it also enforces user limitations introduced to the project due to its location.

However, only the complexity part might be considered as a section whose assessment needs verification, because of the formulas it employs to obtain the assessment scores of its sub-sections. These formulas are the only implementation of generic constructability guidelines provided by construction experts in previous studies. They are described as a good practice to approach the constructability concept, but with no means to impose them on design solutions given their generic attributes. Therefore, the integrity of their achieved indicators should be trusted, although there is doubt about the sensitivity of their impacts and assigned weights. Nevertheless, these are useful and expedient, given the lack of available data to derive exact implications. Also, the system is designed to provide users with the flexibility to override and impose their own views. It aims to act as a starting point, guiding users to identify impacts on their design performance.

Ideally, the implemented prototype should be tested on a real case study that has experienced clear construction challenges due to design decisions, and which could have been avoided if constructability was considered from the design inceptions. However, the proposed prototype has not been implemented in its full scale, hence its real impacts might not be observed for greater volumes of design complexity in real projects. However, the implemented prototype has been successful in examining the feasibility of the method, highlighting its potential impact if fully implemented.

6.10. Summary

The chapter presented an applied case study utilising the proposed framework and its implemented prototype for assessing design constructability. A benchmarking CM was customised to be used for modelling constructability in building designs. Various design options were considered for examining constructability performance. An analysis of the constructability performance of design alternatives was carried out and discussed. In addition, their sensitivity for the assessment process was observed, to understand the impacts of design variables, and the behaviour of the prototype in capturing this. Based on the results, the model was optimised, and a strategy to improve designs' performances using obtained results was formulated. The intention of this aspect is to examine the feasibility of using the proposed prototype on a studied case for further verification through a validation process. This is covered within the scope of the next chapter.

7. Validation

7.1. Introduction

A developed BIM-based constructability assessment model is to be validated through different approaches, including interviews with experienced practitioners and a focus group comprising experts from industry and academia. The implemented case studies reported in Chapter 6 paved the way for the validation process through courses of discussion with experts or by comparing their outcomes to results of typical assessment methods.

7.2. Validation objectives

The goals of the validation comprise the following:

- Validate that the proposed system can extract constructability knowledge to formulate a persona-based knowledgebase.
- Validate that the system can capture its users' requirements within the formulated model.
- Validate that the implemented system can reason about constructability using formulated knowledge and extracted BIM features.
- Validate that the system is able to inform design decisions on the constructability of alternative design solutions, using the proposed scoring system.
- Identify potential barriers that may face the adoption of the proposed system in the construction industry.
- Collect suggestions and recommendations for system expansion to achieve further improvements.

7.3. Validation procedure

The validation procedure can be summarised as follows:

- The prototype concept and its implementation were presented to a group of people. This covered aspects such as the necessity for the prototype, the theoretical framework, how the scoring system functions, the implementation, and its integration with a current BIM platform (i.e., Revit).

- A case study was demonstrated before the group, using the implemented prototype.
- An extensive discussion took place afterwards, with some questions set to stimulate ideas, as listed below:
    - How can constructability knowledge be identified and captured?
    - How to accommodate the subjectivity of constructability knowledge from one person to another, and from one project to another?
    - Is it feasible to capture constructability knowledge and reason with it using the proposed system in conjunction with BIM?
    - How can the model be improved?
    - Could the model be used in the construction industry?
    - What are the challenges in using the proposed model?
- Additionally, participants were encouraged to express any opinions or views on the BIM-based constructability assessment model that were outside the scope of the above questions.

7.4. Participants Profile

7.4.1. Profile of the participants at the focus group meeting

Five participants attended the meeting, comprising practitioners from industry and academia (i.e., industrial tutor (More than 20 years of practical experience), two academics and two researchers).

7.4.2. Profile of the participants in the interviewees

Interview No	Participant's current role	Years of experience
1	Head of Digital Engineering and BIM	14
2	Project Control Department Manager	25
3	Senior Professional Architect	17
4	Resident Engineer	9
5	Senior Civil and Structural Engineering Advisor	20

7.5. Data Analysis Method and Process

It is essential to properly analyse the data collected through the focus group and interviews to yield meaningful and useful results (Terry, 2017). A methodical analysis approach ensures that the collected data are systematically reviewed and examined, without overlooking information that might not fit with preconceived assumptions of what people were going to say and do. However, there is no single right way to carry out qualitative data analysis, and it mainly depends on the study objectives. One common method of analysing semi-structured, open-ended interviews and focus groups is thematic analysis (Lorelli S. Nowell, 2017). This method helps to identify common themes, topics, ideas and patterns in the examined data. This is particularly useful when researchers are trying to find out something about people's views, opinions, knowledge, experiences or values from a set of qualitative data (Caulfield, 2020).

This study, therefore, adopts the thematic analysis method to analyse the collected data through the focus group and interviews. This includes the answers of participants to the pre-set research questions highlighted in section 7.3. One of the advantages of thematic analysis is its flexibility for adaptation for explorative studies, where there is no clear idea of targeted patterns, as well as for deductive studies, where we know exactly what we are interested in (Lorelli S. Nowell, 2017). The latter describes our situation here, as we aim to deductively validate the proposed BIM-based constructability model. As discussed in chapter 1, the deductive research strategy was found to best suit the model validation at this stage, by examining the behaviour of the implemented prototype and the extent to which it satisfies established requirements when presented to experts.

The analysis process itself involves a constant moving back and forward through the entire data set. Through an iterative process, moving from direct answers to research questions to extensive discussions to identify important themes in the data, credible answers can be established to achieve the identified validation objectives stated in section 7.2.

The process started with the familiarization stage, where recorded meetings were listened to repeatedly and transcribed to capture all aspects of the conversations and not overlook minor details that might not be detected initially. Using Microsoft Teams for conducting the interviews and focus group provided a record of the meetings as well as facilitating transcription of their contents. Following this, the next steps involved generating codes and searching for themes, with descriptive codes assigned to participants' answers and phrases within them, and then interpreted into broader themes. Such steps enabled the categorization, grouping and naming of themes, with the set questions again helped in this process. This covered validation aspects such as the model's ability to capture and represent construction knowledge and experience, its accommodation for users' requirements, its practicality for use, potential challenges for its adoption, strategies to overcome identified challenges, and possibilities for improvements of the model. The themes resulting from this validation process are presented in the Results section of this report. Issues that were raised by participants but not relevant to the identified themes are, nevertheless, included in appendix 3 with their responses.

7.6. Validation Results

7.6.1. Focus Group Meeting

The focus group allowed the researcher to gauge participants' opinion on the developed assessment system and the feasibility of its adoption in the construction industry. It also provided a venue to collect feedback from the participants on how the developed model could be improved. The interactive discussion between participants encouraged them to express their views on the topic and stimulate the generation of creative thoughts. More details about the meeting are given in Appendix 3.

Merits of the proposed BIM-based assessment model:

Overall, there was a consensus among all participants that the constructability model is able to capture and represent the constructability knowledge of its users. The model provides a framework around the knowledgebase, which is currently subjective to quantify, but with the use of the proposed model could evolve into something more objective. It enables its users to articulate their views on constructability, formalising an output for reporting to clients and backing up their subjective opinions. The power of the framework was seen to lie in its ability to generate new knowledge and the flexibility it provides within the design team by being open-ended to add/amend their constructability considerations.

The participants were satisfied with the set objective, which is the development of the tool as a framework to assess constructability, and the demonstration has shown that the objective is met. With that in mind, they confirmed that the tool is very robust.

Use of the model in the industry

Participants agreed that the model can be adopted in the construction industry to enable designing for constructability. It is particularly applicable to large projects, where it can help with their complex nature, as opposed to small projects, especially if the model is to be used only once.

It was also suggested that the model can help companies in formalising their practice, especially when dealing with projects which have a degree of similarity. They can use the model to establish internal company values and priorities, which could be used for comparison in future projects. This can be helpful in backing up some decisions or justifying choices when reporting to non-technical people.

One participant, who has more than 20 years of experience in industry, explained that the system should be seen in the same way as designers use other structural analysis tools, where it should assist them in making decisions, formalising their knowledge and experience, and flagging issues and conflicts. Similar to such tools, however, he also pointed out that the quality of the output will also depends on the input to the CM (rubbish-in rubbish-out), which is acceptable as it puts the responsibility back on the engineer and not the tool. He advises that the benefits of the model can be clearly seen during the design stage, where designers can build a quality model. However, to maximise the benefits and extend them to other project phases, his thoughts that the CM developed by the design team, being at a high level of detail due to efforts invested by the team, can then be inherited by constructors in design-bid-build cases, where they can amend and build upon it as they see appropriate. In such a manner, there could be only one CM at the early design stages that conforms to typical design team requirements and preferences, to be used for assessing design alternatives and to enable selection. At the later stages, when contractors have inherited the model and developed their own versions to suit their requirements, there will be more CMs, but only one detailed design model ready for construction.

Challenges and potential barriers

Potential challenges when using the model included its accommodation for capturing multi-perspectives from the project team, especially if these include conflicting elements. The subjectivity of the concept can lead to different interpretations when transformed into scores and priorities by various users. As such, the team might struggle to come up with a unified CM that represents their knowledge collectively.

Another identified challenge is that the quality of developed constructability models mainly relies on the quality of information input by the user, and whether they have given the right level of details to enable the decision making.

Strategies for overcoming arising challenges

One common suggestion among participants is that companies will need to establish a practice around how to deal with conflicting views when using the model. This could take the form of developing a separate document or template to be used by the design team and the client as an initial way of gathering the information to populate the data that goes into the model. It will help the team in structuring their data and standardising their assessment for various values and attributes, which will make the tool more useful.

Suggestions for improving the system:

It was suggested that the model could be improved by establishing the means to capture multiple perspectives or preferences. This might include the consideration of employing other decision-making techniques when the AHP technique falls short.

Another participant added that the implemented tool could provide more detailed reporting in addition to showing obtained constructability resources that will enable the improvement. However, he was satisfied by the reporting features within the implemented prototype when mores details were presented with regard to this aspect.

7.6.2. Interviews with Industry Practitioners

Through a series of interviews with experienced practitioners, the collected views on the model's validity reflected a picture of various parties in the construction industry. The interview approach provided practitioners with room to fully understand the proposed assessment model, discuss its various aspects, and express their opinions and concerns. Below are the series of conducted interviews:

7.6.2.1. Interview (1):

Table 7-1: Interviewee (1) Profile

Participant's current role	Head of Digital Engineering and BIM
Years of experience	14

The respondent believed that the model will be useful in assessing design constructability, especially at the early design stages. From a design lead perspective, he suggested that the adoption of the system will reduce the necessity for buildability workshops with contractors. Instead, such information can be exchanged directly through the model, where the design team performs its evaluation and shares it with the contractor. Subsequently, the contractor will give feedback on the accuracy and appropriateness of results achieved, and amend where they see necessary to reflect its capabilities. For example, if the design team identified that the fabrication of a specific part of the building presents a challenge, they share such information with the contractor, who could come back to inform them if they have the capability to deal with it or to request a change in the design.

The respondent believes that the system is greatly needed in the industry and provides a solution for constructability analysis problems. He thinks the emphasis should be now about how it is implemented in workflow practice, given different scenarios in the relationships between designers and contractors (e.g., design and build, design-bid-build) To get the real benefit of the model, he encourages embedding the tool within the design process at the option stage to perform a thorough assessment as the design develops and increases in detail. Then, the output of this goes to contractors to feed back into the design teams to make changes. He imagines it as a connected loop process, where the tool reduces inefficiency in existing processes by establishing what is intended and how it should be implemented. It also helps to validate the contractor’s decisions regarding changes in materials, where the client can approve, reducing the required amount of paperwork in such a process.

The respondent is keen to see that the constructability analysis remit is mandated upon the client, the designers, and the contractors by a specific clause in the contract stating that they must follow this constructability model. If the client wants to delegate their responsibilities to a third party, they can do so by including another clause to allow for this. In such a way, the team are able to overcome problem situations by using the tool to help in defining complexity into standardisation and into a formal process. The model will get contractors, clients and designers thinking more about how the thing could and should be built. A 4D model with time simulations would be useful in the analysis, but the current model is beneficial in terms of constructability and phasing.

When asked about possibilities for improvement in the developed system, the expert indicated that he would like to see fewer manual inputs from the design end, though this will be challenging to implement given that it is all about representing that element of knowledge and experience at this stage. This is the foundation, and the suggestion is to automate complexity models using the analogy of digital twins, where the data is fed back to update the model and escalate any actions that need to be done. Other elements of inputs should be done by the contractor, because contractors know the staff, while the design team, at this stage, are only guessing the competence and skills of the workforce.

The respondent also added that such a model can inspire the development of a similar model for maintainability, where considerations for building operation and maintenance are brought up at the design stage.

7.6.2.2. Interview (2)

Table 7-2: Interviewee (2) Profile

Participant’s current role	Project Control Department Manager
Years of experience	25

When asked about the model’s ability to represent construction knowledge, the expert agreed that the model has the ability to do so. The proposed system provides a platform where they can systematically input their knowledge, comprising their experiences, rules, constraints and preferences to produce representative models.

The expert also commended the concept of establishing a database to document customised CMs, allowing them to go back and tune their parameters for use in different projects. As an example, he mentioned that one of their clients is a bank who is interested in having the same design built in different locations to maintain the bank’s corporate image. Though these designs are similar, when the location of the project is changed, this has implications for the entire project that should be catered for.

The expert indicated that they adopt a similar scoring approach in their current company when deciding on a contractor to build a design. They score all potential contractors based on their financial and technical capabilities. Financially, this includes aspects such as the overall price, which carries the major weight, as well as other financial indicators, all of which meant it was important to assess the risks of delays in the project due to financial issues. Technically, it was important to assess the contractor's capabilities in different areas, including their equipment, staff, workload, previous projects, etc. He advised, based on his company's experience, that such a system is very effective in reflecting contractors' construction capabilities, and has enabled the decision-making process on many occasions. Hence, he believes that the assessment framework with the adopted scoring system can facilitate their day to day tasks.

When asked about the practicality of using a descriptive equation to decide on the extent of the complexity of a particular design, the expert agreed that such indicators can steer the design process. However, he suggested that this shouldn't be confused with the minimum requirements within the design specifications. For instance, he mentioned that, sometimes, it is required to use more than one finishing material in a specific part of the building, so this shouldn't be considered as a complex design aspect. When it was clarified that they will have the facility to override such formulas or develop their own, he accepted that this could resolve the issue.

For the rules of thumb part, the expert suggested that the feature could be very useful in capturing minor details that might prompt the need for major design changes. For example, he mentioned that a requirement for a clear span of particular length could lead to changing the slab system from cast-in-situ to steel or precast, and again involved accounting for availability in the local market, which could leave them with only the steel option. Thus, having a feature that flags such details is an asset to the design team, enabling them to put the focus on more important aspects, whilst being confident that such details will be captured when they exist.

When asked about the reliability of the model in its delivered assessment results, the respondent was of the opinion that the model can be relied on, given that the right level of information is fed into the model during the customisation stage. He added that the model prompts discussion between the heads of design disciplines, and by enabling the documentation of recorded factors, the team will be able to revisit and correct as they see appropriate. Additionally, it enables the team to develop a consistent approach to expressing their views, which will eliminate personal and biased views.

7.6.2.3. Interview (3)

Table 7-3: Interviewee (3) Profile

Participant's current role	Senior Professional Architect
Years of experience	17

The expert was affirmative that the established system can be very beneficial for use during buildability and constructability workshops, where they usually have the input of the contractors and sub-contractors simultaneously. In such workshops, the model can articulate the participants' knowledge to formulate a solid base that the project team can rely on, saving much time and many conversations during such a brainstorming process. Additionally, he suggested that the model needs to be used by highly experienced people to produce reliable outputs. Given his experience in working as an owner's representative, general contractor, site supervisor and currently as senior professional architect, the respondent suggested that designers usually lack such elements of knowledge, which could be better obtained from contractors, as they are usually the people who suffer from designs lacking constructability considerations.

The participant also added that using 4D BIM to animate the construction process can contribute towards visualising constructability issues which may arise during the construction process. This aspect doesn't involve the utilisation of construction knowledge elements, but it could facilitate the scoring process performed by the user.

When asked about the applicability of the tool in the industry, the expert affirmed the feasibility of its use within construction firms, providing that they have a reliable database of information to support the input process. He also suggested that, if a company has adopted the use of the model, they will be able to build good practice in its implementation within 2 to 5 years that could save them time in the future.

For challenges in using the model, the expert pointed out that, as the accuracy of the model outputs relies mainly on its user input, a careful approach should be taken when interpreting the outcomes. As a way of improvement, he wanted to see the model become less reliant on the user input, upgrading its behaviour from a decision-support tool to be a decision-making tool, though he doesn't know how this could be achieved at the moment. Also, adding a space for the user to leave notes during the customisation process to justify their decisions would be beneficial when revising the contents of the model, or if another individual wants to use it.

7.6.2.4. Interview (4)

Table 7-4: Interviewee (4) Profile

Participant's current role	Resident Engineer
Years of experience	9

In general, the respondent was satisfied with the model's concept and what it seeks to address within the construction industry; it could be a great solution for issues that they struggle with daily onsite.

When asked about the system's ability to capturing and represent construction knowledge, he believed that the system is able to objectify subjective concepts and produce representative knowledge that can inform decisions. By covering both quantitative and qualitative constructability aspects in both the design and construction processes, he trusts that the system hierarchy enables a systematic review of major constructability issues in design solutions without losing sight of minor details.

When asked about the practicality of the model for adoption in industry practice, he advised that the system is highly applicable and will standardise the practice of designing for constructability. He mentioned that common issues and mistakes are repeated in many construction projects, and their feedback is often overlooked because of the fragmentation of the process. However, the system can improve this situation by giving the means to impose such feedback and ensure that issues are addressed before moving onsite. He also added that the system can help to resolve the typical blame war between the design office and contractors when issues arise on site. Contractors always think it is designers' mistake to bring a design that does not account for construction challenges, while designers tend to blame contractors for not being qualified enough to build the design solutions they have developed. By clarifying responsibilities in addressing potential construction issues, and documenting the process and challenges, productivity will witness a significant improvement.

He also mentioned that, sometimes, the client asks for a specific contractor to be awarded the job, while they believe this contractor is not qualified to build the design. By using the model to justify their decision, this can become a quietly efficient and professional process.

One of the issues clarified in this interview was the distinction between the scope of the model and construction risk assessment exercises. It was noted that, while both schemes aim to flag potential construction issues onsite, using someone's experience at an early stage, the proposed system meant that this would be fed back into the design solution to improve things. In contrast, risk assessment will help in setting out proper actions and contingency plans for identified risks without the need to amend the design.

When asked about potential challenges and barriers in using the system, he advised that project stakeholders will need to be trained on using the system to achieve the targeted benefits. Additionally, he thinks the system might not be implementable for those who have not adopted BIM technology or mastered the use of 3D models. He added that this should soon cease to be a problem, given that more people are converting to the use of BIM.

For possibilities of improving the model, he asks about the feasibility of establishing a database where users can input a contractor's construction resources in terms of labourer numbers and machines, and then be advised on that contractor's capability of constructing a specific design. The response was that it is possible to implement such a feature, given that the system is connected to the construction programme, whereby the productivity of the contractor per time unit can be estimated. However, there might also be other factors to be considered, arising from the interdependence of construction activities and identification of the critical path, where qualified contractors can be determined when planning the construction schedule and implementing it onsite. This will also restrict the use of the tool at the procurement stage and convert its scope from assessing a user's own capabilities to assess another individual's capabilities, which will involve making some assumptions at the input stage.

7.6.2.5. Interview (5)

Table 7-5: Interviewee (5) Profile

Participant's current role	Senior Civil and Structural Engineering Advisor
Years of experience	20
Duties and responsibilities	The expert is currently working as a senior adviser for a major governmental department. His duties and responsibilities include developing, revising and overseeing all design activities for major infrastructure projects in the country. The country is preparing for hosting an international sporting event and, as such, is currently witnessing the construction of megastructures. With respect to constructability assessment, the expert's profile included the assessment of bridges, tunnels, and high-rise buildings.

7.6.2.6. Demonstration of the CM customisation process

After providing an overview of the proposed model, its components and how it operates, the implemented case studies were demonstrated in detail to the expert for a full understanding of the process. As a result, he was able to discuss minor details and ask about very technical aspects that might have been overlooked when observing the model's behaviour from the big picture.

The discussion with the expert included the following:

- For the AEC System, the expert is of the opinion that the slab system is the governing aspect when carrying out constructability assessment. However, it is a great addition to include the assessment of other systems, giving the user the option to impose importance factors from their own perspectives.
- By computing a consistency ratio, the integrity of priorities and weights obtained during the scoring process can be verified and confirmed.

- For the rules of thumb, the expert was of the opinion that it can facilitate checks of minor details that they are required to comply with, but he would like to see this implementable for non-programmers to add and execute their own rules within the model.
- For the complexity part, he suggested that the implemented model should include the shape of slabs as an important factor in informing the extent of a design's complexity. Through conducting a geometry analysis for slab profiles based on the BIM model, he believes this important aspect can be covered.

7.6.2.7. Comparison of the model outcomes to the delivery of typical appraisal methods

The expert advised that the model adopts many principles that are manually implemented in current practice, but in a more structured, concise and comprehensive way. He affirmed that following the demonstrated process delivers assessment results that would have been achieved using typical assessment methods, but saving 70 – 75% of the effort.

7.7. Summary

The validation process through different approaches has been reported within this section. As a result, the BIM-based model has been found to provide the capability to represent constructability assessment knowledge within its Constructability Model. In addition, it demonstrated capabilities to employ produced knowledge-bases to reason about the constructability of alternative designs. Furthermore, practitioners have confirmed that the model is highly applicable in the industry and greatly needed to improve the practice of designing for constructability. The main issue that practitioners need to be aware of is that the quality of the output depends on the quality of the input (CM) and should not treat the output as the absolute answer. The users also seen a potential in the system in being extended to include sustainability assessment.

8. Evaluation

8.1. Introduction

This chapter evaluates the proposed system for assessing design constructability in conjunction with BIM technologies. The intention is to assess the feasibility of the implemented prototype to accommodate the abstract concept based on its performance on the applied case study. The evaluation methodology is explained, and its results are critically discussed. Aspects of discussion include the prototype concept, implementation, operation, and delivered assessment outcomes. Suggestions are also made for additional features to further improve the design.

8.2. Evaluation goal and objectives

This evaluation was performed as a part of the research methodology to accomplish one of its objectives: to collect feedback on the proposed system in regard to its effectiveness, applicably, and ease of use. The goals of this evaluation therefore comprise the following:

- To gauge expert opinion on the proposed system in terms of required efforts and time to implement the concept in typical design cases (to determine perceived and actual ease of use among practitioners).
- To assess the prototype contribution in informing design decisions on the constructability of design alternatives solutions.
- To assess the fulfilment of the proposed system for identified requirements of desired constructability assessment systems (i.e. being a generic, scalable, flexible, comprehensive, simple, accurate, and effective constructability assessment system).
- To ascertain the impact of the introduced assessment system on current design practice, and to comprehend long-term performance in the construction industry.
- To identify potential challenges that may face the adoption of the proposed system in current design practice.

- To offer suggestions and recommendations for system expansion to achieve further improvements.

8.3. Evaluation procedure

The implemented prototype was demonstrated to a group of civil and architectural engineers currently working in academia and the construction industry. Their feedback was obtained via a questionnaire to evaluate the prototype implementation and its effectiveness in design constructability decision making. Peer and group reviews were obtained with practical expediency to gather data, and questionnaires were also used to encourage participants to express their anonymous, objective views. However, the potential lack of respondents' engagement with the questions is the major downside of this method. To minimise the impacts of this, the questionnaire was designed to stimulate respondents to cognitively engage with the subject before answering questions. While this affected the response rate, it ensured the quality of obtained answers.

The evaluation procedure can be summarised as follows:

- The prototype concept and its implementation were presented for the evaluators. This covered aspects such as the necessity for the prototype, the theoretical framework, how the scoring system functions, the implementation, and its integration with current BIM platforms (i.e. Revit).
- A case study was demonstrated before the evaluators, employing the implemented prototype. This was carried out on a typical design problem, to assess its design constructability. Aspects of using the prototype to explore alternatives to inform the decision making with regards to their constructability performances were also presented.
- An elaborated discussion took place afterwards, ensuring that all participants' questions and comments are addressed.
- Questionnaires were distributed to evaluators to provide their feedback on the system (Appendix 4). It contains four quantitative and six qualitative questions. The quantitative questions aimed at measuring

the evaluator’s opinions on the system as one group, using Likert-type numerical responses. The qualitative questions seek to capture aspects that cannot be quantified, concerning expertise in construction techniques, offering a space for the evaluators to identify any shortcomings or suggest improvements to the prototype.

8.4. Questionnaire evaluation: Results and analysis

This section presents and analyses the responses received from the system evaluators.

Q1. Your role

Figure 8-1 shows the statistics of the questionnaire respondents on their roles; this was asked to ascertain the evaluation involved various roles related to the subject with diverse perspectives. Academics and Researchers are the predominant group (62.5%), with their research areas are mainly in Engineering. Representatives from industry, such as Architect, Technical Manager, and Designer, were present in lower proportions (12.5% each). The figure demonstrates that no other responses were received outside the targeted groups, which indicates that the respondents are the most suitable people to obtain their feedback on the proposed solution.

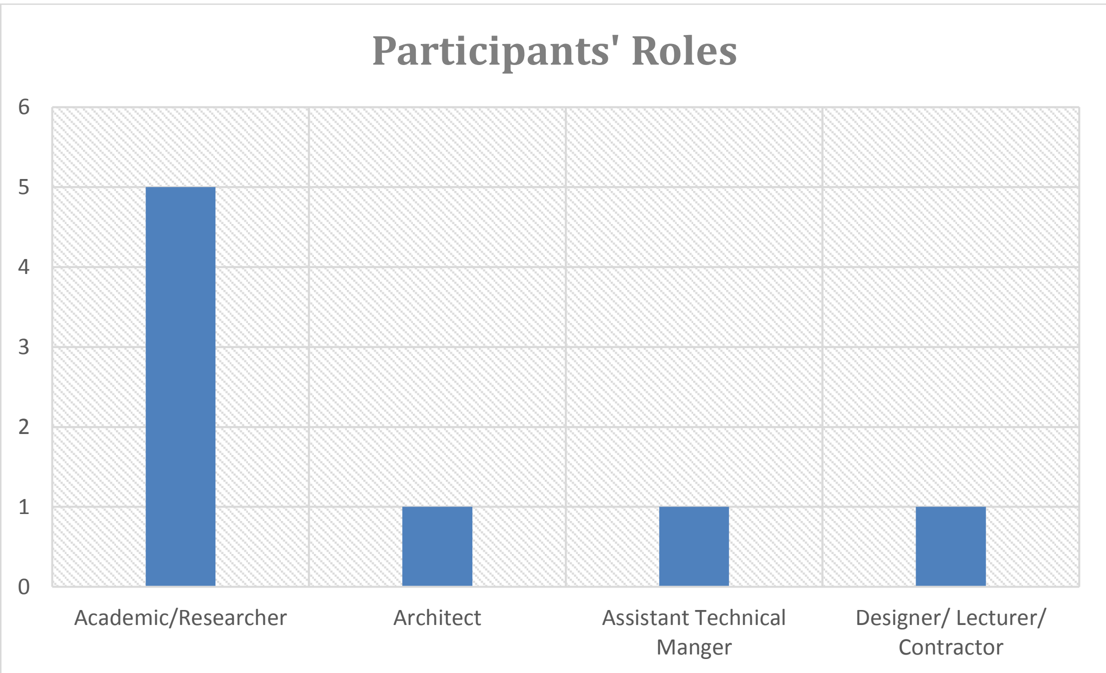


Figure 8-1: Participants’ roles

While the participants number on the evaluation may not adequately represent the practitioners in the industry, the content of their response is the targeted information to evaluate the system. At this stage, the received feedback from the participants is satisfactory to enhance the system as it only implemented at a prototype scale. Further research in the subject shall provide better avenues to gather more responses from practitioners for the development of an end-user software.

Q2. Work experience in years

This question was to ensure representative variations with regard to respondents' experience. The received answers were remarkable, since the lowest recorded experience was five years, and some respondents reported experience of 29 years. This provided another assurance that received feedback was from the most experienced designers and engineers with extensive knowledge and experience of the research area. When asked about their design experience, half of the participants (50%) reported that they had 5-9 years of experience (one with five years, two with six years, and one with nine years), while the other half have more than 10 years of experience, with a maximum of 29 years (Figure 8-2).

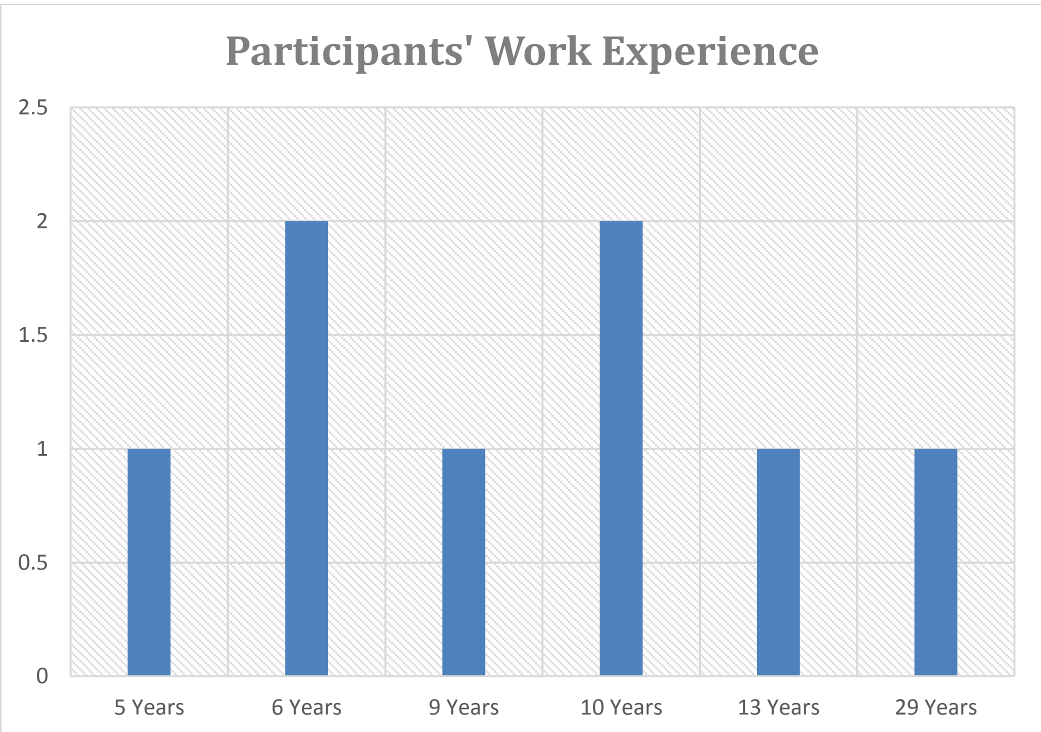


Figure 8-2: Participants' work experience

Q3. General impression

Q3.1. The system takes reasonable efforts to conduct the assessment

When asked about the required efforts to carry out the constructability assessment for a design model, all respondents agreed with the statement: 75% agree, and 25% strongly agree (Figure 8-3). This gives a good indication of the efficiency of the system compared to conventional methods in assessing design constructability, or the abstract nature of the concept and the possible factors that could be involved.

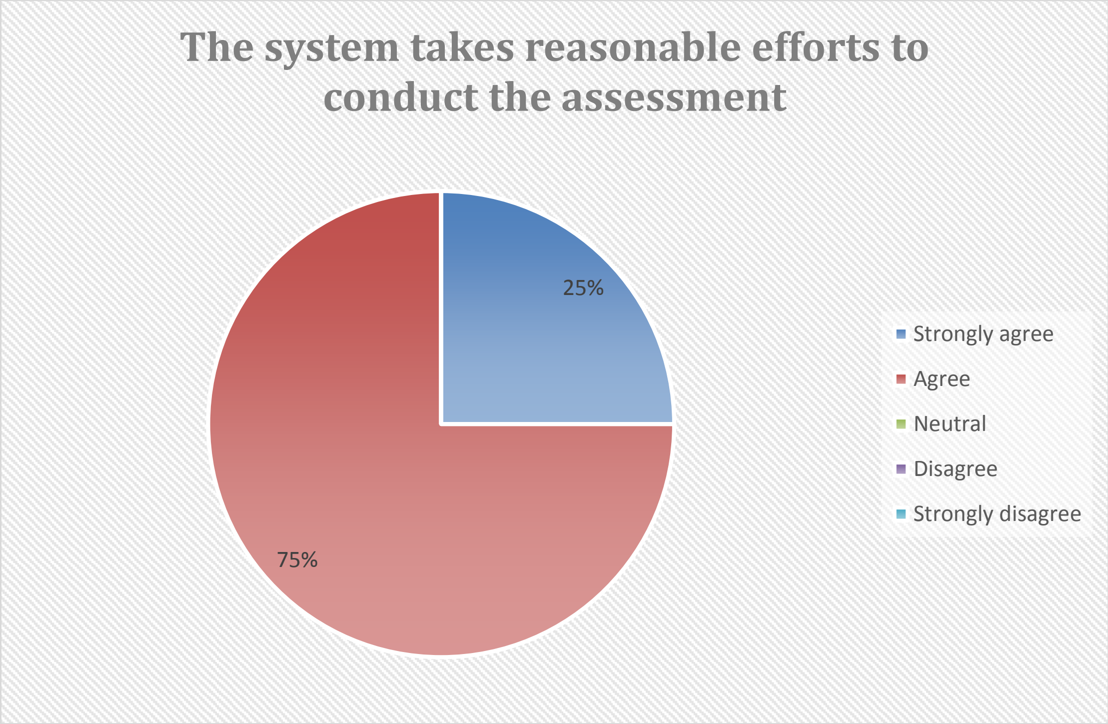


Figure 8-3: Required efforts to perform the constructability assessment

Q3.2. The system is capable of informing a decision on constructability

As shown in Figure 8-4, a quarter (25%) of participants indicated their neutrality on the capability of the system to inform a decision on constructability, while all agreed that it can contribute to the decision-making process. A possible explanation for this reluctance may be due to the lack of adequate understanding of achieved assessment outcomes. The assessment system is designed to highlights constructability aspects that deemed to be issued from the user perspective, based on the defined and used CM model. However, other users might not agree with such opinion, considering that the system did not highlight serious constructability matters. Therefore, the feature of model customisation to suit user requirements and capabilities is vital in making the proposed assessment method workable for various users.

The participants were generally of the opinion that the proposed system has the capability to inform constructability decision-making (Figure 8-4). This is expressed by (75%) of responses agreeing with the statement, while only (25%) were neutral. This is a good sign that the system achieved its main goal in assisting designers and users to decide on design constructability.

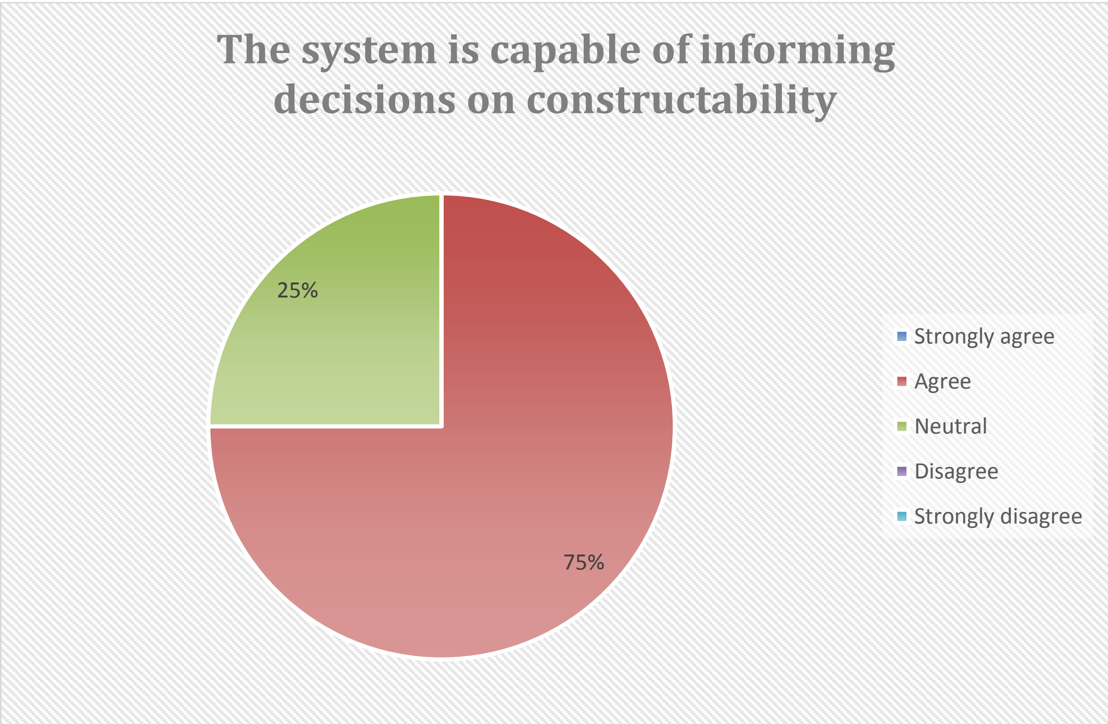


Figure 8-4: Capability of the system to inform on constructability status

Q3.3. The system enables to compare constructability of design alternatives

The interviewees were affirmative that the system enables a comparison between design alternatives. As indicated in Figure 8-5, half of them agreed, while the other half strongly agreed. This was demonstrated to interviewees in the presented case studies when three design options were assessed and compared to each other in their constructability performance, resulting in such expressed confidence among the respondents concerning system functionality.

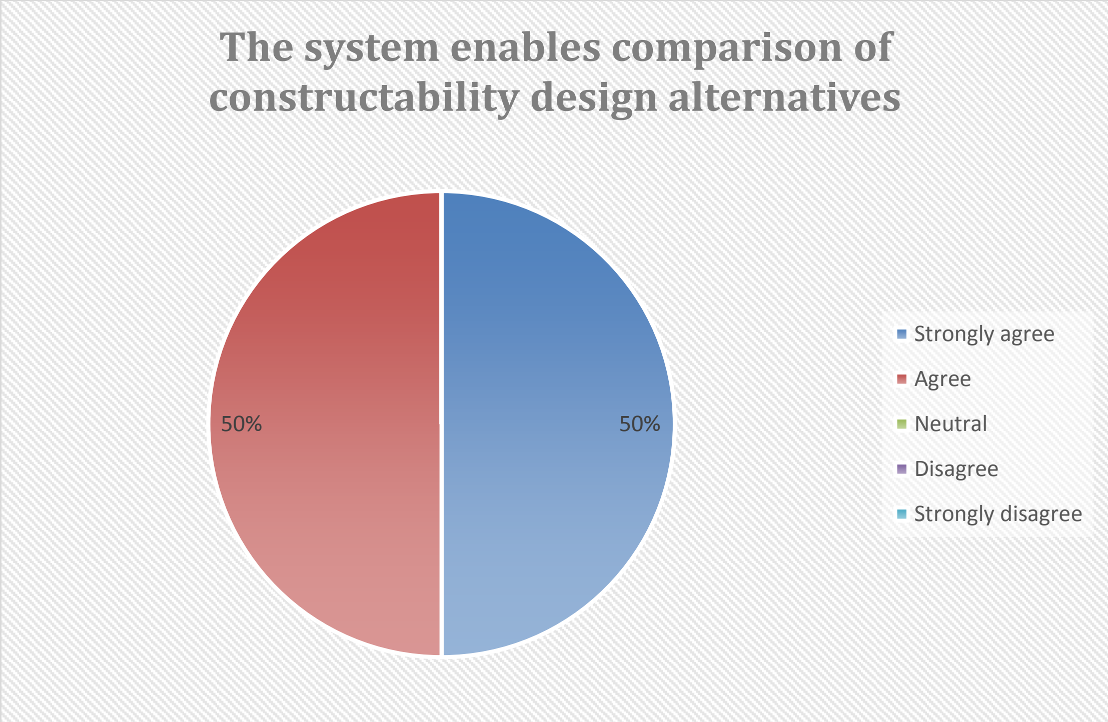


Figure 8-5: System-enabled comparison of constructability performances of design alternatives

Q3.4. The time spent on constructability assessment is acceptable

While this question would have been more insightful if participants had actually used the prototype more extensively and obtained familiarity with its features, it was illustrative to gauge their impressions on whether they would be willing to dedicate some time and effort to deploy the tool in constructability considerations. As shown in Figure 8-6, half (50%) of participants agreed that it is an acceptable time, with (37%) strongly agreeing, and (13%) being neutral. These positive responses suggest that participants are happy to invest time in assessing constructability if the proposed prototype performs as demonstrated to them.

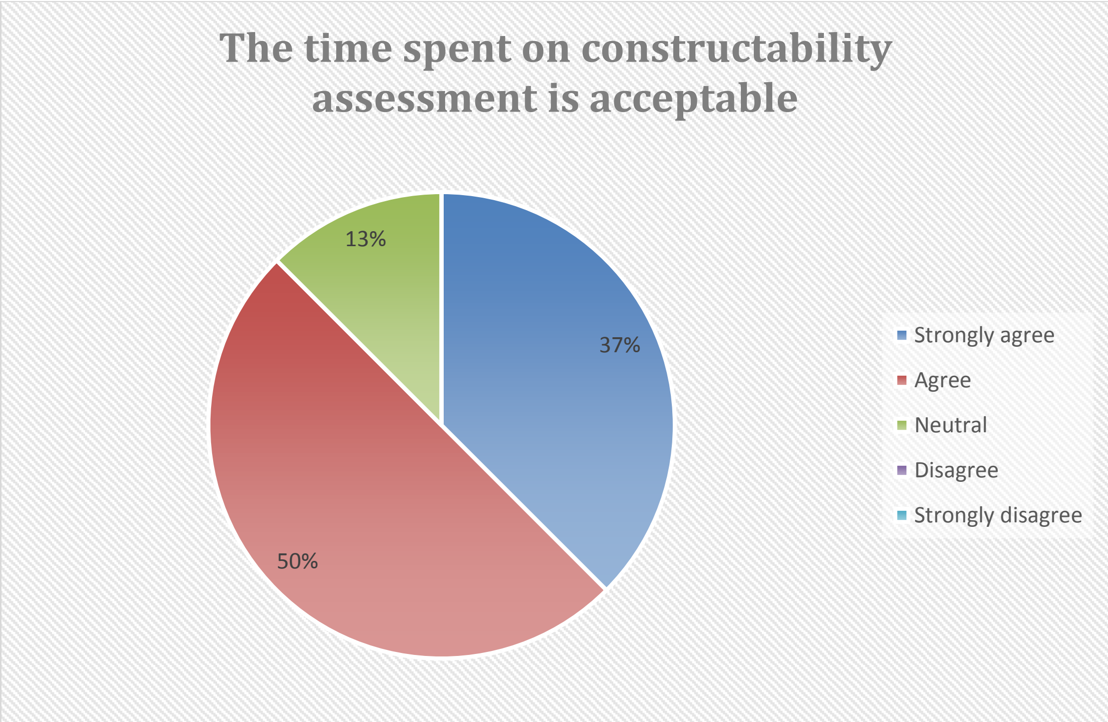


Figure 8-6: Practicality of required time to complete the constructability assessment

Q4. Satisfaction for implementation requirements

This section of the questionnaire asked participants to give information on the system satisfaction for identified requirements to be available on constructability assessment tools. Most of the responses, as shown in Figure 8-7, suggest that respondents were of the opinion that the system satisfies targeted requirements. All received responses were divided between three answers: “strongly agree”, “agree”, and “neutral”, with the “agree” response dominating the responses.

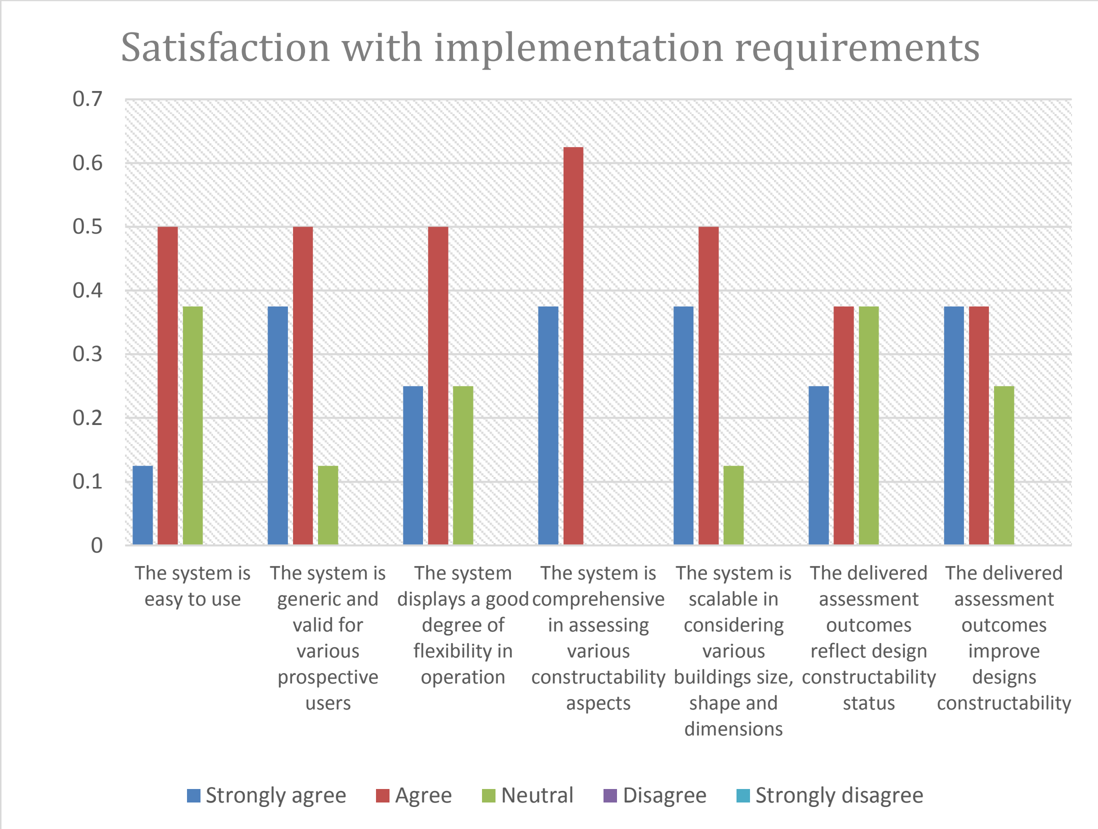


Figure 8-7: System satisfaction for implementation requirements for modelling design constructability

The following open-ended questions comprised the qualitative section of the survey. These responses provided more useful feedback on how to improve the current implemented version than responses to the first section (closed-ended questions), which was mainly concerned with practical assessment. However, it might not be feasible for participants to provide detailed comments on some aspects of the prototype due to its complex concepts or varying levels of completeness of implementation. Furthermore, some qualitative questions require participants to have actually used the system. Therefore, the questions were designed to target high-level feedback from participants, while remaining significant enough to contribute significantly to the proposed concept.

Q5. Will the proposed system affect design decisions for constructability considerations?

On the whole, participants agreed that received assessment feedback would inform decisions and would likely lead to impacts. They highlighted that the system is able to identify issues that require special management (e.g. large girders requiring a police escort). Related features allow the design team to put more consideration into their element selections or arrange for any special requirements to take place at the right time.

Q6. What are the potential challenges in adopting the proposed system?

Concerns were expressed about the extent of knowledge/decisions to be made about design variables. The system is only as accurate as the variables applied. Industry experts will be required to advise suitable values. However, they may not be appointed during the conceptual design process. This mainly stems from the lack of incentives to implement constructability at the design stage, assuming that it is the constructor's responsibility to deal with such issues. Such practice should be eliminated by standardising constructability assessment and enforcing its implementation as a part of design approval, as adopted in some countries (BCA, 2005).

Another reported issue was user training to make sure the system is used as intended. This is a common barrier among newly introduced techniques which can be facilitated by constant use and practice. Organising training workshops and training contributes largely to increase the awareness of the new system and equipping professionals with more confidence in adopting and effectively using new technologies.

Q7. Will the proposed system have impacts on improving construction industry performance?

The overall response to this question was very positive. Respondents were of the opinion that the system certainly contributes to the improvement of the construction sector. BIM-enabled constructability assessment of buildings design facilitates the construction process while achieving targeted design objectives. However, such capacity of the system is conditioned by its implementation at the right time, and also by the right party.

Q8. Which features of the system did you find particularly useful?

Mentioned features included the easy integration of the implemented prototype with the Revit software. Participants were generally impressed by the organisation of the system and its comprehensiveness in covering constructability concepts. Also, its ability to compare design alternatives based on multi-objective decision analysis could aid value engineers during the tender stage. Participants were particularly appreciative of the ease of visualisation using graphs and tables. Another mentioned feature is highlighting the model for components that do not comply with defined Rules of Thumb, enabling identification and troubleshooting of parts of the design needing attention.

Q9. What features do you recommend being added to the proposed system?

One interesting suggestion in response to this question was building a knowledge database based on previous CMs to be employed for new cases. The suggestion is to design the database to generate an average value or interval values as an outcome, rather than a deterministic score. This requires training the design machines on a CMs database to establish the ontologies between stored models' situations and particular situations under consideration.

Another suggestion was to enable adding new constructability parameters; however, this feature is already implemented on the current prototype. This is a key feature enabling the proposed model to work with various users to cater to their requirements, as needed.

There were some suggestions that the system should include the assessment of construction programme duration, and that it should consider health and safety. This is an important aspect when it comes to analysing constructability, however pure optimisation for the schedule is beyond the scope of this research. The implemented prototype allows users to prioritise different design objectives, including construction duration. This will typically be reflected on any assigned scores to favour a construction system that is quick to build.

It was also suggested to ensure the integrity of the connection between Revit in terms of its naming system for the families and the proposed plug-in, otherwise there would be miscommunication between the two sides. However, this was carefully considered in the designed assessment system. It has a feature to automatically extract the name of families when assigning scores to various construction systems. However, the option to manually input material names enables the system to work on a standalone basis (without BIM data) for simple cases and applications.

Q10. Any other comments

During the discussion session, one of the participants raised the issue of site drainage as a critical constructability aspect requiring careful consideration, but which is not addressed by the CM. This comment was addressed by explaining it is beyond the scope of the current implemented prototype to examine common site issues. The scale of implementation is meant mainly to demonstrate the concept.

However, to further analyse the implications of this suggestion on the proposed assessment concept, it is suggested that this practitioner may have experienced this specific issue during projects, and it most likely affected deliverables. While documenting this matter in terms of lessons learnt is not an issue of concern, enforcement in future projects could avoid past challenges, while retaining focus on other issues. Most importantly, such aspects imply how constructability is observed and handled by different users, entailing that any proposed assessment system should accommodate various perspectives. This is exactly what the proposed assessment system seeks to deliver, by providing flexibility in adding, amending, structuring, and deleting constructability decision-making criteria.

Also, the design engineering value was discussed and the differences between the rewards and benefits of implementing a constructability concept are explained. It is clarified that the engineering value examines the design solution to identify construction resources that could be saved by adopting an alternative solution while performing the same functionality. On the other hand, constructability examines design solutions based on the capabilities of their constructor to build, and which might not be optimal in terms of value engineering.

8.5. Discussion and remarks

This study set out the requirements to accomplish a successful constructability assessment framework. They are derived from existing knowledge to accommodate shortcomings of current practice when modelling constructability in building design (Fadoul et al., 2018a). This section analysis how the implemented prototype managed to satisfy these requirements.

The examined case study and its subsequent evaluation suggest that the implemented system is successful in meeting the lacking qualities in existing solutions. Its concept and implementation are generic, to be valid for application in various types of buildings. The reason for this is the reliance of the assessment process only on users' inputs as a source of constructability knowledge (i.e. the BIM model and the CM). This eliminates the necessity for collected knowledge through surveys and interviews, which may restrict its application in specific regions. It should also provide users with accurate feedback, as the assessment is based on their designs, and customised models that reflect their construction capabilities.

The scalability of the model is demonstrated in its ability to assess varying building sizes, as long as they satisfy the required level of detail. However, users need to use suitable CMs for assessing different design solutions. They need to consider building sizes and types when customising their CMs, and incorporate any preferences that may depend on that. An example of this would be the use of prefabrication techniques for small building projects.

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 identified in the literature, as well as current practice. While this indicates the comprehensiveness of the model, users are not obliged to assess all parts. This gives users the flexibility to tailor their model and include only critical aspects that they usually face during construction.

Furthermore, the system is able to adjust itself to the accessible level of information. Users should decide on what they would like to assess based on what they have in the model. Otherwise, sections that lack information will not be included in the assessment outcomes, warning users of such errors. For instance, missing sizes and dimensions in a BIM model will disable the assessment of their elements against any defined rules that require such information as inputs. Once the information is made available in the model, their associated rules will be executed on the next performed assessment. This feature enables designers to carry out the assessment with multilevel design details throughout all design phases.

Moreover, the integration of the assessment prototype with a BIM authoring tool (Revit software in this case) facilitates its use. Also, the separation of customised CMs from the assessment process enables their reuse for assessing similar types of buildings with carrying out necessary adjustments. These features simplify the assessment process and save user time and effort, encouraging their use of constructability in their designs.

In addition, the assessment process delivers meaningful feedback that assists in improving design constructability. It shows how each construction system performs with respect to what is expected, and its contribution towards fulfilling the desired design objectives (particularly in terms of financial and time parameters). This enables assessors to better understand their designs and identify targeted areas for improvements.

8.6. Summary

This chapter evaluated the proposed system for assessing design constructability and its implementation based on defined requirements for such a system. The main goal is to assess the prototype's contribution in enabling constructability assessment of building design and informing decisions at an early design stage. The evaluation results indicate the success of the prototype, evidenced by an applied case study of typical design alternatives. Aspects of the prototype performance and its delivered outcomes were also discussed with suggestions for further improvements.

9. Conclusion and Recommendations

9.1. Introduction

This chapter discusses how the objectives of this study were achieved. It recapitulates the key research findings and contributions to the current body of knowledge. Furthermore, recommendations for future work are suggested.

9.2. The realisation of aim and objectives

The research aim was the development of BIM-enabled constructability assessment of buildings design. To accomplish this, the research objectives explained in the introduction were defined. The ways in which the research has achieved these are summarised below.

- *Objective 1: Investigate existing approaches for measuring design constructability and their underlying theories, and ascertain the observed challenges associated with such processes.*

This objective was undertaken to study the developed approaches for assessing constructability in existing knowledge and practice. The relevant literature was examined to evaluate assessment mechanisms of various models and identify their shortcomings. This was carried out in line with available information technologies, such as BIM, and their potential to facilitate the assessment process. Consequently, it revealed the current limitations in modelling design constructability and established a set of requirements for any introduced assessment system as criteria for measuring success.

- *Objective 2: Identify requirements for modelling constructability implications of alternative design solutions of the building product.*

Further analysis of the constructability concept and its attributes was carried out to understand implications for the construction process and product design. This enabled targeting of design-relevant construction knowledge and the appropriate approach for its formulation, using BIM in the acquisition and mapping of such knowledge. The employment of decision-making techniques such as AHP facilitated objectifying the constructability concept from a user perspective, and accommodating its abstract nature. Such re-engineering for the mechanisms of knowledge formulation and application paved the way to lay-out the structure of targeted assessment framework and define its components.

- *Objective 3: Develop a modelling framework to inform design performance from a constructability perspective.*

A BIM-based model was introduced to assess building design constructability. It described the modelling framework in three parts: the conceptual design model, the CM and the AM. The framework is designed to exploit the benefits of construction knowledge-based systems, object-based programming technology, and decision-making tools for modelling design constructability.

- *Objective 4: Implement the framework in a constructability design-decision-support software prototype.*

The proposed framework was implemented through a prototype using Application Programming Interface (API) as a Revit extension. The plug-in software for Revit was implemented in the .NET Framework environment using the C# programming language. This allowed for feature extraction from design models for the purpose of mapping formulated constructability knowledge. Furthermore, the process of assessment was achieved while being interfaced with Revit UI for users' convenience, including customisation and management of CMs, prompting the constructability assessment and the delivery of its accomplished results.

- *Objective 5: Validate the framework by using the prototype in assessing the constructability of typical designs, and through interviews and a focus group with the industry practitioners.*

A case study was defined, and the described framework was employed to assess the constructability of considered design alternatives. The system demonstrated high capabilities in informing its users of the constructability performance of various design options. Obtained assessment results reflected users' capabilities and constraints expressed in customised CMs on examined options, suggesting potential areas for improvements.

The model validation is also augmented through courses of discussion with the industry experts to assess its behaviour and practicality. As a result, the BIM-based model has been found to provide the capability to represent constructability assessment knowledge within its Constructability Model. In addition, it demonstrated capabilities to employ produced knowledge-bases to reason about the constructability of alternative designs.

- *Objective 6: Evaluate the effectiveness of the prototype and the framework in improving constructability assessment of design solutions.*

Evaluation results showed that the proposed system is capable of informing design constructability and enable comparison of its alternatives. Furthermore, it was found to fulfil the defined criteria as a measure of success by meeting the identified requirements that are lacking in current assessment tools, and it is a generic, scalable, flexible, comprehensive, simple, accurate, and effective constructability assessment tool.

9.3. Research findings

To improve the practice of designing for constructability, this study was designed to address the question of ***how to map and model design constructability with the employment of knowledge-based systems and data modelling techniques to inform design decisions*****.**

To answer the established question, the research adopted a mixture of research strategies. It started with an abductive and retroductive reasoning approaches to identify issues in current systems, leading to induct their requirements to model constructability. This has set the stage to retroductively formulate the research hypothesis to derive the development of targeted assessment framework. Findings from these key steps are summarised below:

9.3.1. Associated issues with constructability knowledge representation:

The constructability status is fundamentally different from one design to another, and from one constructor to another. Such subjectivity stems from contrasting requirements of various constructors to match their construction capabilities and experience. As such, any introduced constructability assessment system should account for such subjectivity when informing constructability. However, the current employed process to represent constructability knowledge results in many limitations to reason with the formulated knowledge. These include:

1. **Design-relevant construction knowledge identification**: The knowledge is typically extracted through surveys and interviews with construction experts. As a result, it is normally identified, classified, captured based on the pre-designed surveys and interviews' questionnaires, developed by the model creator. Potential users of the model have no input in structuring such knowledge database to suit their requirements, or to include constructability aspects that only relate to their situations (i.e. considering the weather factor which might not be an issue in some places). Designing generic knowledge-based repositories to be used by anyone, without personalising its content to their construction circumstances, questions the accuracy of obtained assessment results.
2. **Knowledge classification**: Current systems adopt either a numerical system to assess constructability quantitatively, or a rule-based system to assess constructability qualitatively. However, each of the approaches partially addresses constructability concerns, while an ideal solution should consider both of them concurrently to model constructability in its multidimensional aspects.
3. **Knowledge elicitation:** The extracted knowledge itself, through the response to designated surveys and interviews by a third party, might not necessarily represent the views and capabilities of potential design constructors. Part of measuring design constructability is to measure someone's' ability to construct that design.
4. **Knowledge Formulation**: Current established models are not formulated in the form of object-oriented knowledge bases, and

hence they don't support automatic reasoning about constructability when used with object-based BIM modelled features.

5. **Knowledge store**: Current knowledge bases are rarely stored in digital formats. Consequently, this does not facilitate enquiring their contents or investigating their suitability to assess specific design cases.
6. **Knowledge update**: Furthermore, a static represented knowledge that is only extracted once, at the time of its elicitation, cannot be updated to suit various construction situations, or to accommodate new invented construction techniques and methods.
7. **Knowledge reasoning**: The lack of a design tool that can effectively reason the captured knowledge onto assessed design features to inform constructability performance, is a big hurdle in the process of designing for constructability. Current assessment systems demand manual calculations and interpretations. As such, it discourages practitioners from employing them, given the dynamic of design process and the need for ongoing modifications in designed products. Even if they go through the process once, they are unlikely to do it a second time to test design modification capabilities.

Following the said establishment, it necessitates the formulation of user-based metrics to reflect their construction capabilities. This is only attainable from users directly; and hence, they need to be consulted when constructing such repositories. The primary goal of modelling design constructability is to critically assess that its constructors can build it, given their construction capabilities and availability of resources, in addition to that it is constructible in general, by anyone (i.e.no major issues that prevent anyone, regardless of their construction capabilities, to construct it).

9.3.2. Induced systems requirements to model design constructability:

The utilised, case-based, theory-building research tactic is drawn upon the grounded theory analysis method, enabling to unveil system's requirements that are lacking in developed constructability assessment systems. Consequently, they set up a success criterion to deductively confirm or invalidate the effectiveness of new introduced constructability assessment systems. These are presented in having an assessment system that is:

a) *Generic*: The system can be employed to assess different design solutions (i.e. residential, commercial, etc.) at the various stages of the design process.
b) *Flexible*: The system users can decide on constructability aspects to be considered within the assessed models. Typically, by enabling a customisation feature that allows to add, amend, and delete the content of formulated knowledge as they see appropriate.
c) *Scalable*: The system is valid to assess varied building sizes and its implementation covers individual design elements.
d) Simple: The system can be easily applied and integrated within a design environment.
e) *Comprehensive*: The system accommodates the assessment of constructability in its multidimensional aspects, quantitatively as well as qualitatively.
f) *Accurate*: Assessment outcomes accurately reflect the design constructability.
g) *Effective*: Enables designers to improve their design constructability

9.3.3. Introduced measures to address the flagged challenges:

The summary of research aspects aimed at rectifying the identified issues to accomplish the defined requirements are:

I. Separate between the process of constructability knowledge formulation and its reasoning on design models.
II. Devise a system that can live capture users' requirements to formulate a user-based knowledge that reflects their constructions capabilities and requirements.
III. Bring the perspective of object-based link data to assist in the formulation of object-oriented constructability knowledge bases.

IV. Devise a technology-based assessment engine to perform the processes of knowledge extraction, formulation and reasoning.

V. Employ a BIM-based parametric modelling tool to capture constructability related information to be mapped with specialised knowledge to inform design decisions.

VI. Design a scoring system that accommodates assessment of both quantitative and qualitative constructability aspects. This entails the employment of a mixture of techniques including rule-based systems and decision-making techniques (i.e. AHP) for modelling design constructability.

VII. Design an accessible, searchable database to store formulated constructability knowledge models, to allow their re-use for assessing constructability of similar cases, with the possibility of updating or amending contents of such models.

9.4. Research contributions

The novelty of this research is represented in devising an interactive system that is capable to model design constructability with accommodating its subjectivity among its users. It captures constructability knowledge live from a user's perspective to formulate a persona-based knowledge base. It then reasons such knowledge onto design features to inform decision-making. The contributions of this study to existing knowledge include the following:

- This research identified the demand for profession-specific constructability assessment mechanism in the AEC Industry.
- The research critically evaluated current developed systems to model constructability and identified their shortcomings. Consequently, it systematically categorised key requirements to guide the development of constructability assessment framework and accordingly its implementation.
- The research identified the major challenges associated with the process of modelling constructability, including how relevant-design construction knowledge is identified, classified, elicited and formulated

in a knowledge-based system as well as mapping it back on modelled design features.

- The research retroductively hypothesised a set of measures aimed at addressing the identified issues and filling the gap. They established the ground basis to develop the sought constructability assessment framework.
- The research produced an assessment framework that is capable to model the subjectivity of constructability concept. The framework is designed to exploit benefits of construction knowledge-based systems, object-based programming technology, and decision-making tools for modelling design constructability.
- The research demonstrated the possibility of using BIM in constructability assessment of buildings design alternatives through feature mapping and data modelling technique.
- The research established an information modelling representation capturing the human element of construction knowledge and experience, the inherent process and database information and associated mappings to a conceptual building information model for informing design decision.
- The research deductively validated the implemented prototype for featuring the qualities lacking in current constructability assessment systems (being: generic, scalable, flexible, comprehensive, simple, accurate, and effective assessment system). The employed case study demonstrated the satisfaction of established criteria of success through the discussion of accomplished assessment results.

9.5. Recommendations for further work

- Test the proposed model in a real-life case study and evaluate its impacts on delivering a smooth construction process with achieving its targeted objectives.
- Extend the current implementation to assess BIM models in IFC format and not only Revit files. This enables the operability of the concept in assessing various BIM models produced by other BIM authoring tools.

- Encourage governmental bodies and professional institutes concerned with improving AEC industry productivity to establish standard CMs. They ought to use their expertise to tailor models that can be easily adapted and customised by local designers, consultants, and contractors. Such models can also be employed to introduce any legislation schemes that require designs to obtain certain scores to qualify for construction, as currently adopted by some countries.
- Design an intuitive platform for constructability optimisation. This was intended to be implemented within the Explore tab to visualise the sensitivity of constructability performance to design changes in real-time. It allows users to examine the impact of changing design quantities and construction systems on design constructability.
- Expand the scope of the implemented prototype to cover more constructability aspects. This includes elements that are structured within the proposed assessment system but not implemented due to the research scope or others that are referred to in the literature.
- Extend the implemented design rule package to include more generic rules that can be personalised by end-users. This will eliminate the necessity for model users to acquire programming skills in order to add new design rules.
- Integrate Geographical Information System (GIS) applications with the BIM model to better observe and assess the impact of a project location on constructability performance. 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 conditions), which would enable deeper insight for better decision-making.
- Employ virtual and augmented technologies for constructability assessment to facilitate the process, providing an immersive environment for users to observe all aspects of assessed designs and identify any potential challenges, enabling users to make the right judgement at the right time.

9.6. Research dissemination

The following publications were produced in connection with this study.

- FADOUL, A. & TIZANI, W. (2017) "Evaluation of current practice and associated challenges towards integrated design". *Advances in Computational Design* 2.2: 89-105.

- FADOUL, A. & TIZANI, W. (2017) "Optimization of energy performance of building using building information modelling (BIM)". *Proceedings of the 19th Young Researchers' Conference*. Institution of Structural Engineers, London, UK.

- FADOUL, A., TIZANI, W. & KOCH, C. (2017) "Constructability model for buildings design". *Proceedings of 24th International Workshop on Intelligent Computing in Engineering*. University of Nottingham, Nottingham, UK.

- FADOUL, A. & TIZANI, W. (2018) "An approach to assess design constructability using building information modelling (BIM)". *Proceedings of the 20th Young Researchers' Conference*. Institution of Structural Engineers, London, UK.

- FADOUL, A., TIZANI, W., KOCH, C. & OSORIO-SANDOVAL, C. A. (2018) "A constructability assessment framework for buildings design using BIM". *Proceedings of 17th International Conference on Computing in Civil and Building Engineering*. Tampere, Finland.

- FADOUL, A., TIZANI, W. & KOCH, C. (2018) "Building information modelling for constructability assessment of buildings design". *Proceedings of Conference on Civil Engineering*. University of Khartoum, Sudan.

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- FADOUL, A. & TIZANI, W. (2020) "An approach to assess design constructability using building information modelling (BIM)". *Proceedings of the 22th Young Researchers' Conference*. Institution of Structural Engineers, London, UK.

9.7. Research summary

Despite the recognised benefits of designing for constructability, it has been challenging to devise a tool that implements the concept. In modern practice, evaluating design constructability paradigms is a complex process and demands more efforts, resources, and time than can usually be devoted to it in real construction projects. The design team has limited technical support to oversee and assess the possible consequences of decisions concerning constructability taken at various steps during the design stage. Many aspects of constructability are left out of consideration for a later stage, when it is too late to improve the constructability performance of the design. There is a much greater need to enhance and support the process using specialised tools during the conceptual design stage, where critical decisions are made, rather than during the later detailing stages, where changes are more complex and costly.

BIM technologies have emerged as potential platforms for facilitating the design process of buildings. However, the potential use of their capabilities to design for constructability has not been fully realised. This research, therefore, investigated how contemporary process- and object-oriented models can be used to provide a mechanism that represents the subjectivity of design constructability to inform decision making.

In the course of this research, and through knowledge review, the study identified numerous challenges that are associated with the process of modelling design constructability to inform decision making. These challenges have been found to be critical when devising constructability assessment systems for decision-support. The employed practice of identifying, classifying, acquiring, formulating, storing and reasoning about constructability knowledge, produces knowledge-based systems that come with many limitations in their use. The formulated knowledge repositories fall short of representing the subjectivity of constructability aspects among constructors, due to their different capabilities and requirements. This typically questions the accuracy of any achieved assessment results without bringing the perspective of users' requirements in the assessment process.

To this end, the research set up a workflow for the analysis of system engineering requirements in order to define implementation requirements to devise a constructability assessment tool. This is based on evaluating current constructability systems to identify their shortcomings in exhibiting constructability. The process started with observing the pros and cons of each tool, moving on to detect patterns and regularities, and eventually coming up with conclusions. This premise sets the stage for identifying the targeted requirements. These are represented in a generic, scalable, flexible, comprehensive, simple, accurate and effective assessment system to model the constructability in an abstract sense.

To meet these requirements, the study hypothesised a set of measures aimed at rectifying the shortcomings of current systems. It included aspects such as separating the processes of knowledge representation and knowledge reasoning, allowing the formulation of a persona-based knowledge system, and hence representing the subjectivity of constructability among constructors. It also employed a technology-based system for live interaction with users' captured requirements and mirroring them in formulated knowledge models. In particular, using a BIM-based platform brought the perspective of linked data to assist in the development of object-oriented knowledge-based architecture, facilitating the reasoning process on the platform. The system devised in this way replaces the practice of approaches such as surveys and interviews as a means to elicit constructability knowledge, eliminating the limitations to reasoning that are introduced with such knowledge.

Consequently, this has paved the way for developing an assessment framework that measures the constructability of BIM-based design solutions. The framework is designed to exploit the benefits of construction knowledge-based systems, object-based programming technology, and decision-making tools for modelling design constructability. An information modelling representation is produced to capture human elements of construction knowledge and experience, the inherent process and database information, and associated mapping to the BIM model to inform design decisions. The modelling framework is composed of three key parts: the *Constructability Model (CM),* which formulates user-based knowledge; the *BIM Design Model,* which provides required data for the assessment; and the *Assessment Model (AM),* which reasons with the formulated knowledge and the BIM Design Model.

The assessment framework is designed to accommodate constructability in its multidimensional aspects. Whereas these can be articulated precisely, such as matching the design product to accessible construction resources, some non-tangible constructability attributes are hard to measure, such as designing for simplicity, standardisation, and automation. As such, the CM is composed of various components to ensure the assessment of diverse constructability qualities. These are classified into four main modules, represented in:

1. **AEC Systems**: This part of the model establishes a numerical system to score the constructability of featured design alternatives based on a user's captured requirements and construction capabilities. It employs AHP to develop the targeted scores, based on input scores by users. Obtained scores rank the constructability of design elements from the user's perspective, accounting for their design preferences and constraints. Thus, it enables the deployment of captured human construction knowledge and experience and incorporates it into the design platform, enabling designers to quantify that which is currently unquantifiable, usually requiring manual reading and interpretation.
2. **Rules of Thumb**: This part of the model employs a rule-based system to assess design constructability. These rules are typically applied to impose constraints on the design variables which may affect the construction process later. These include limitations related to design spacing, layout, dimensions, etc. Such a feature enables the incorporation of the established practice to assess constructability, using approaches such as checking lists. The aim is to automate aspects of rule execution, using embedded information, while numerically reporting the performance in the form of compliance with rules.
3. **Complexity**: This part brings the perspective of linked digital data from the design environment to interpret qualitative aspects of constructability. It inspects some design qualities against common

constructability attributes. Such attributes are commonly mentioned in the literature as characteristics of constructible designs, but with no tangible measures provided to examine the level of their existence in a specific design.

4. **Location**: This part of the model assesses 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 the way they are installed. Additionally, site accessibility and proximity to delivery sources play a vital role in choosing construction methods (e.g., precast or *in situ* casting for concrete components). In the proposed CM, 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.

The modelling framework is implemented in C#, using .NET Frameworks, SQL database management and Revit API. The compatibility of object-oriented programming in .NET with object-based parametric modelling provides an ideal environment to develop the prototype as a plug-in to the BIM software Revit extension. It enables reasoning with established object-oriented constructability knowledge based on features extracted from the design model. The four pillars of object-oriented programming, i.e., abstraction, polymorphism, encapsulation and inheritance, were useful in the prototype development.

The prototype was illustrated using typical design case studies to evaluate its usefulness in informing constructability decision-making. This covered aspects related to prototype operations, including customisation of an example-based CM, as well as running the AM to reason with the customised CM. It demonstrated the prototype's ability to explore different design alternatives and decide on a design based on constructability performance.

The model was then validated through different approaches, including interviews with experienced practitioners and a focus group comprising experts from industry and academia. As a result, the BIM-based model was found to provide the capability to represent constructability assessment knowledge within its Constructability Model. In addition, it demonstrated the ability to employ generated knowledge-bases to reason about the constructability of alternative designs. Furthermore, practitioners confirmed that the model is highly applicable in the industry and greatly needed to improve the practice of designing for constructability.

The main issue that practitioners need to be aware of is that the quality of the output depends on the quality of the input (CM) and they should not treat the output as the absolute answer. The users also saw a potential for the system to be extended to include sustainability assessment.

The examined case study and its subsequent evaluation showed the success of the prototype system in meeting the previously specified implementation requirements of constructability assessment tools. The prototype proved to be generic, since there were no restrictions for its use to inform constructability of the considered case study. It also showed a high level of flexibility by allowing the assessment of only constructability aspects that matter to the user, imposing priorities by imputing associated weighting factors, and selecting the design features to be assessed. It was scalable by enabling the assessment of various sized BIM models. The simplicity of its use was obvious, not only when customising a bespoke CM to fit for the purpose, but also using it to assess design alternatives, without the need to re-customise or input the design data, as these are automatically obtained from associated BIM models.

Furthermore, the prototype was comprehensive in assessing diverse attributes of constructability. This was demonstrated in the four assessed CM modules:

- the AEC Systems: inspecting the featured AEC Systems matching the capacity of accessible construction resources and limitations;
- the Rules of thumb: validating satisfaction with featured design products for tailored rules to impose specific requirements and constraints;
- the Complexity: measuring the extent to which the outlined design observes constructability qualities to facilitate its construction, covering aspects such as standardisation, replication and automation;

- and Location: ascertaining that any restrictions introduced due to the project location are accounted for in the design product.

Additionally, the assessment outcomes delivered by the prototype accurately informed the constructability of the design cases considered. This is because the assessment is based on users' input at the customisation stage and design features extracted at the assessment stage. Also, they were meaningful enough to provide an avenue for improving performance, based on solid facts and measurements.

An evaluation of the prototype was performed as a part of the research methodology to collect feedback on the proposed system in regard to its effectiveness, applicably, and ease of use. This evaluation targeted civil engineering practitioners and researchers to get their insights into the prototype's performance in informing the constructability of design alternatives. The participants were generally of the opinion that the proposed system has the capability to inform constructability decision-making. They affirmed that the system enables a comparison between design alternatives. While the number of participants who took part in the evaluation may not adequately represent the practitioners in the industry, the content of their response is sufficiently targeted information to evaluate the system. At this stage, the feedback received from the participants is satisfactory to enhance the system, as it has only been implemented at a prototype scale. Further research in the subject will provide better avenues to gather more responses from practitioners for the development of an end-user application.

Concluding Remarks

The thesis presented a BIM-enabled constructability assessment for building design by investigating existing assessment methods, identifying modelling requirements for contractibility, designing and implementing a modelling framework in a software prototype, validating it for typical designs, and evaluating its effectiveness. The study concludes that the devised modelling framework can be used to represent the subjectivity of constructability in its multidimensional aspects and inform decisions at the early stages. It enables the exploration of design alternatives for their constructability performance and, hence, improvements to meet the design objectives.

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Appendix 1: Notification Requirements for Abnormal Loads Movements

Source: **Highways England**

Published 20 July 2012

Last updated 28 August 2018

Available: https://www.gov.uk/government/publications/abnormal-load-movements-application-and-notification-forms [Accessed 25.09.2019].

Length

C&U loads:- length exceeding 18.65m (61ft 2in) up to 27.4m (90ft) - See C&U Regulations 1986 for definition of length STGO loads:- length exceeding 18.75m (61ft 6 ins) - See part 2, article 12 of the Road Vehicles (Authorisation of Special Types) (General) Order 2003 (Commonly known as STGO) for definition of length	2 clear days notice to Police
Overall length of a part 2 vehicle-combination exceeding 25.9m (85ft)	2 clear days notice to Police
Maximum length exceeding 30.0m (98ft 5ins) – see STGO Schedule 1, part 4, paragraph 25 for definition of maximum length NB For some very light loads, such as yacht masts, that are moved on conventional motor vehicles not exceeding 12 tonnes gross weight or trailers not exceeding 10 tonnes gross weight, a Highways England Special Order* will be required if the rigid length exceeds 27.4m (89ft 11ins)	Highways England Special Order* plus 5 clear days notice to Police and 5 clear days notice with indemnity to Road and Bridge Authorities.

Width

C & U loads:- width exceeding 2.9m (9ft 6ins) up to 4.3m (14ft 1 ins) STGO loads:- width exceeding 3.0m (9ft 10ins) up to 5.0m (16ft 5ins)	2 clear days notice to Police
Width exceeding 5.0m (16ft 5ins) up to 6.1m (20ft)	Highways England form VR1** plus 2 clear days notice to Police
Width exceeding 6.1m (20ft)	Highways England Special Order* plus 5 clear days notice to Police and 5 clear days notice with indemnity to Road and Bridge Authorities

Weight

Gross weight of vehicle carrying the load exceeding C & U limits up to 80,000kgs (78.74 tons)	2 clear days notice with indemnity to Road and Bridge Authorities.
Gross weight of vehicle carrying the load exceeding 80,000kgs up to 150,000kgs (147.63 tons)	2 clear days notice to Police and 5 clear days with indemnity to Road and Bridge Authorities.
Gross weight of vehicle carrying the load exceeding 150,000kgs (147.63 tons)	Highways England Special Order* plus 5 clear days notice to Police and 5 clear days notice with indemnity to Road and Bridge Authorities

NOTE 1 "Clear days Notice" excludes Saturdays, Sundays or a public holiday in any part of Great Britain in relation to movements authorised by the Special Types General Order only, there being no such exclusion in Special Orders unless specifically stated.

NOTE 2 There is no statutory limit governing the overall height of a load, however, when applying for a Special Order or VR1 it should, wherever possible, not exceed 4.95m (16ft 3ins) in order that the maximum use can be made of the motorway and trunk road network.

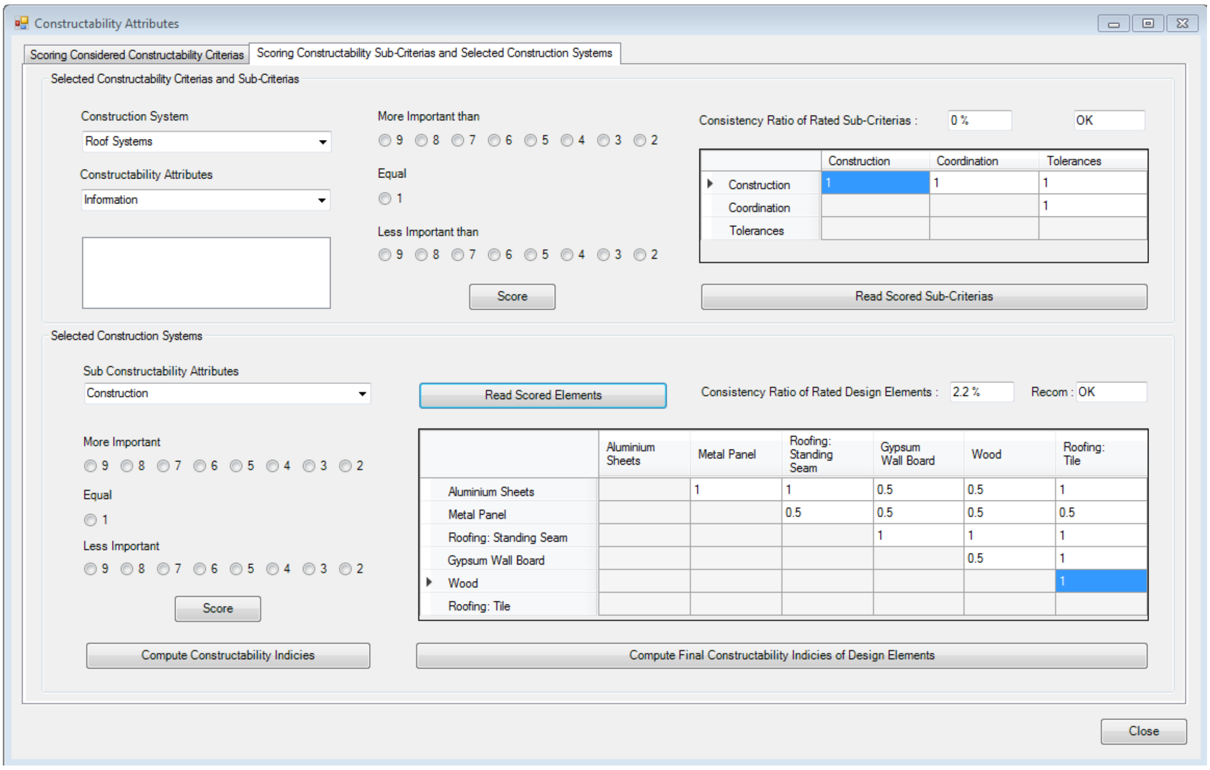
NOTE 3 The notification requirements for mobile cranes can be found in the Road Vehicles (Authorisation of Special Types) (General) Order 2003, statutory instrument number 1998 (Part 2 Articles 10 to 18), which is available on the OPSI website: http://www.legislation.gov.uk/uksi/2003/1998/contents/made

NOTE 4 Application to move Special Types or Special Purpose vehicles, such as very large agricultural vehicles, that may not be fully permitted by the Construction & Use (C&U) Regulations or fall outside the scope of the Special Types General Order should be made to the Vehicle Certification Agency (VCA). Their website is at http://www.dft.gov.uk/vca/

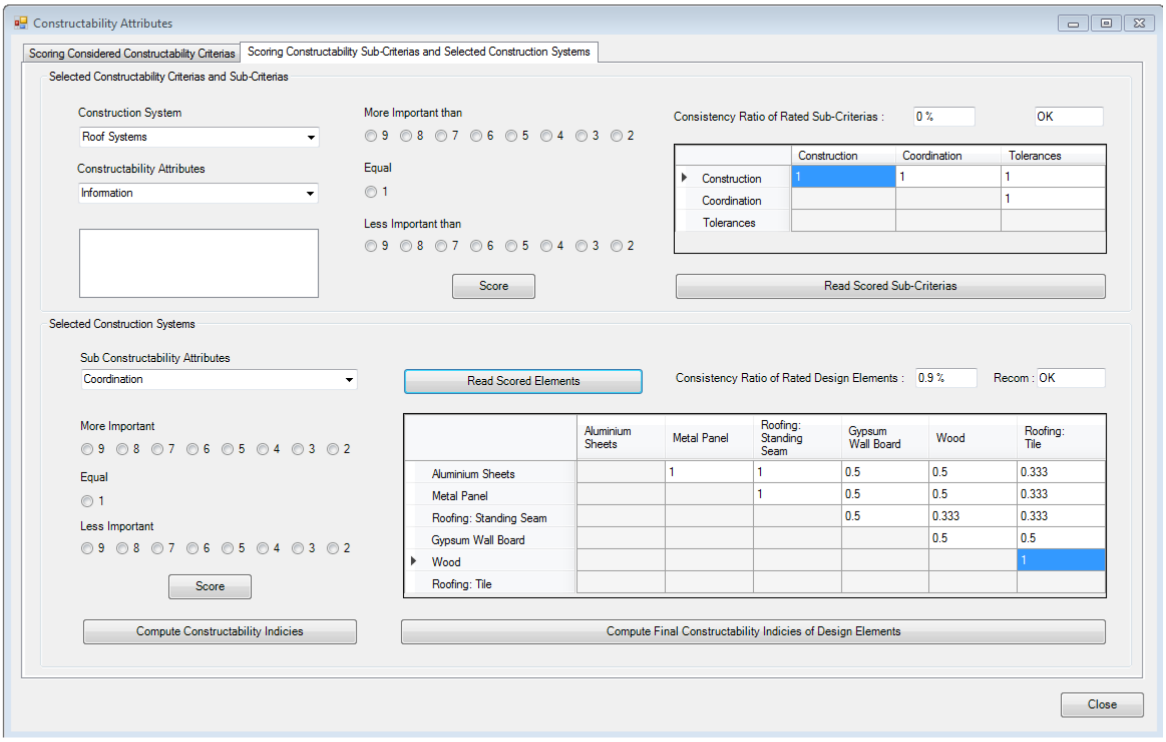
Appendix 2: CM Customisation for illustrative case studies

The figures below show recorded scores for the performed pairwise comparisons of various construction systems alternatives, with respect to selected criteria and sub-criteria. This was performed as a part of the customisation process of the developed CM to be used for illustrative case studies. Outputs from this series of pairwise comparisons are indices that rank constructability performance of various design alternatives, categorised under main construction systems (i.e. Roofs, floors, walls, envelopes, foundations, structural frames).

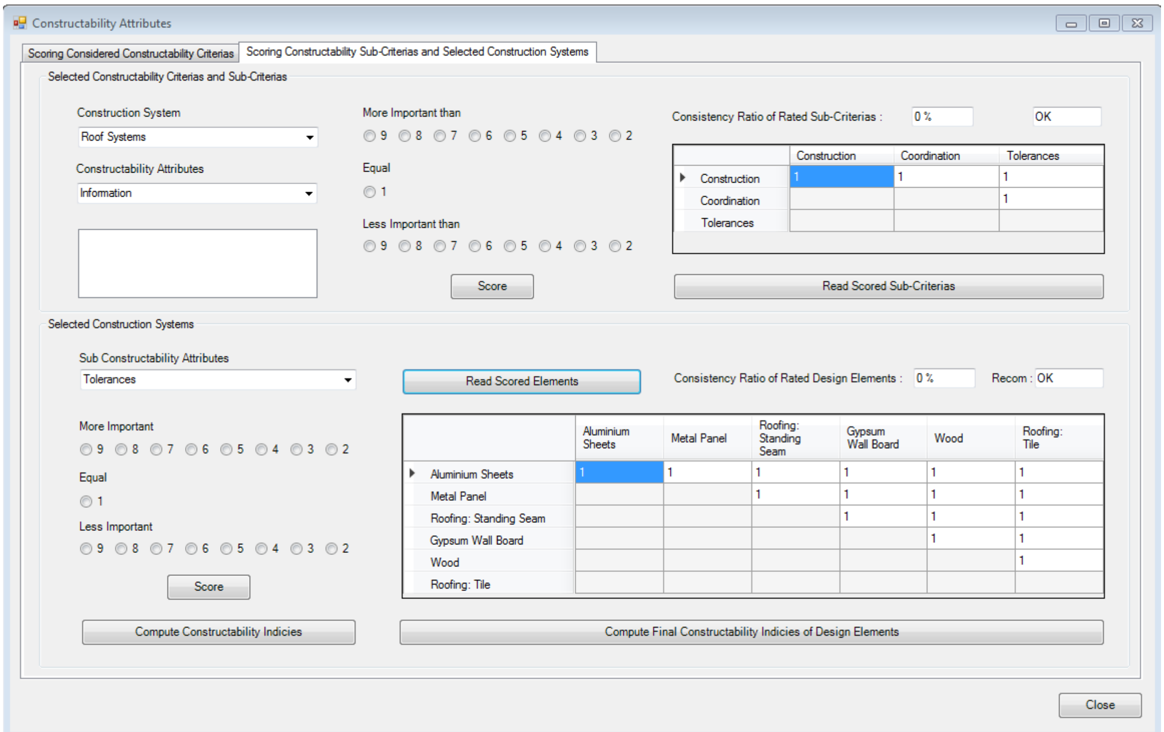
Roof Systems:



*Scoring **Roof options** with respect to **Construction** branch sub-criteria clustered under **Information** criteria*



*Scoring **Roof options** with respect to **Coordination** branch sub-criteria clustered under **Information** criteria*



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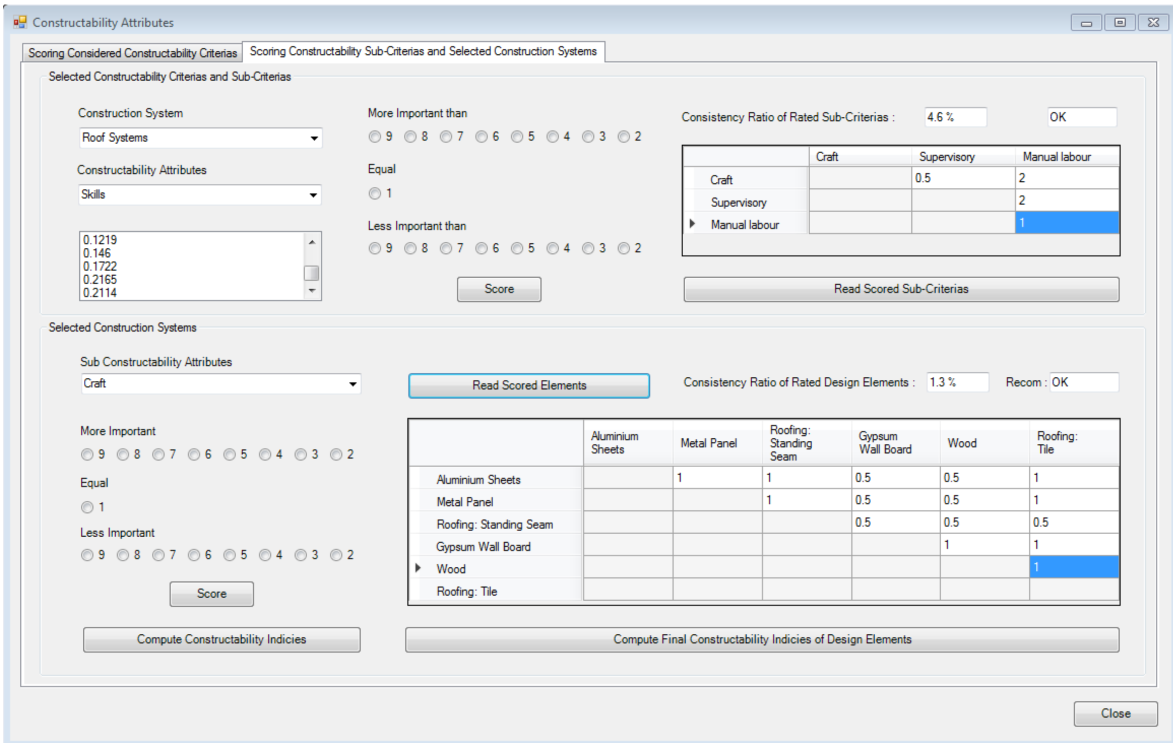
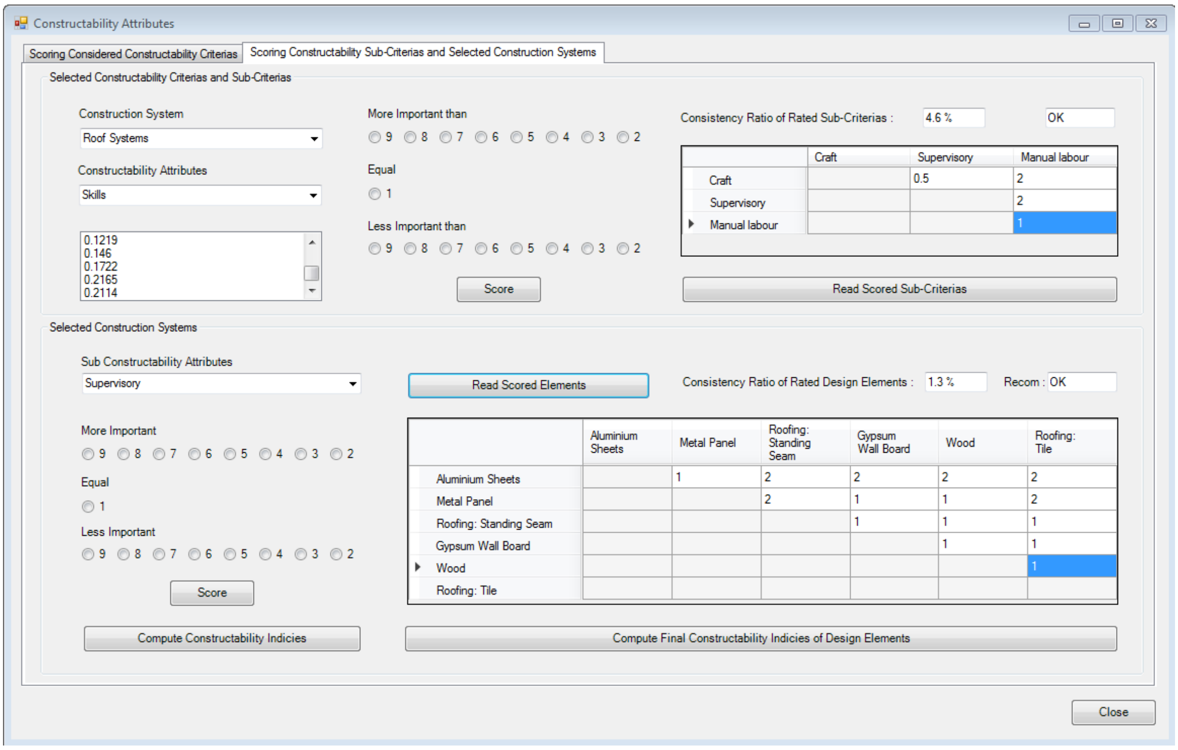
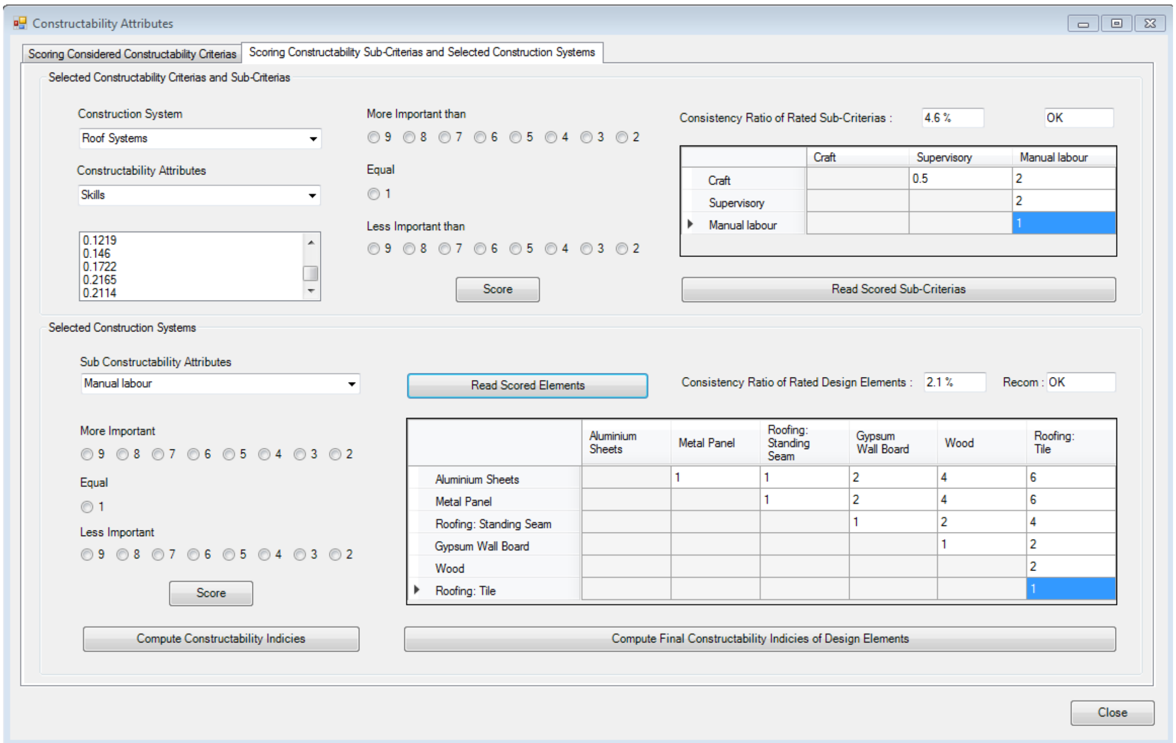


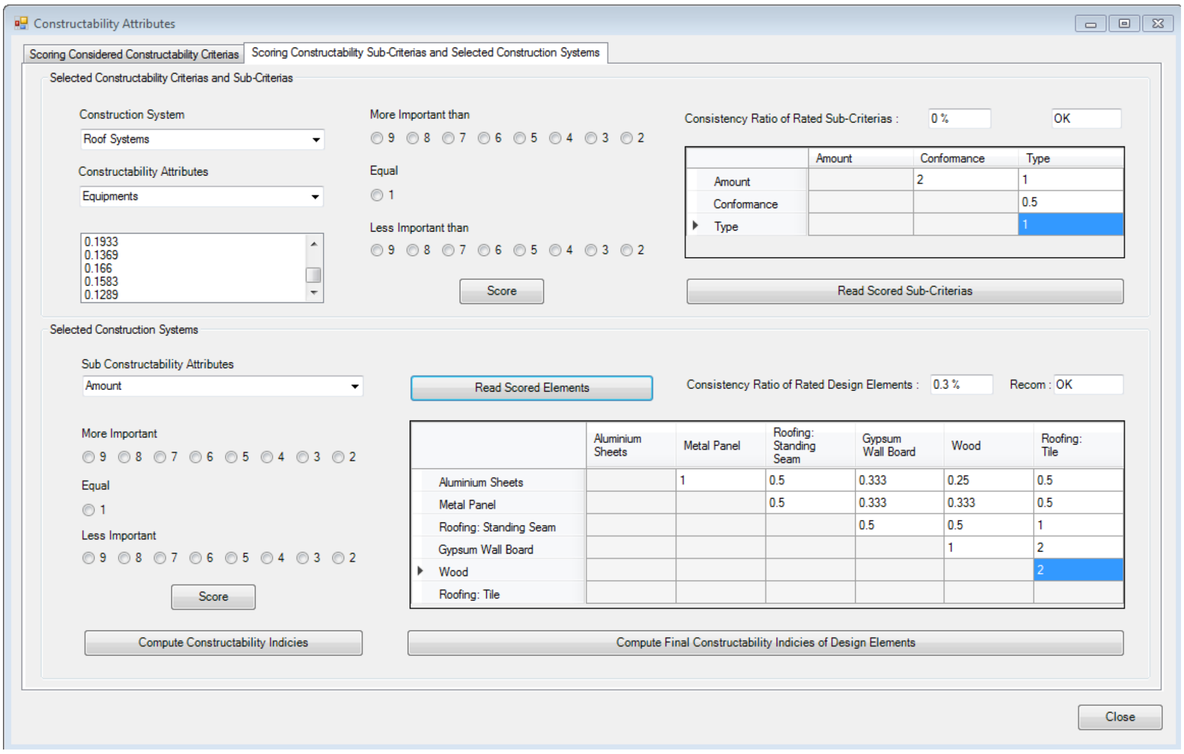
*Scoring **Roof options** with respect to **Craft** branch sub-criteria clustered under **Skills** criteria*



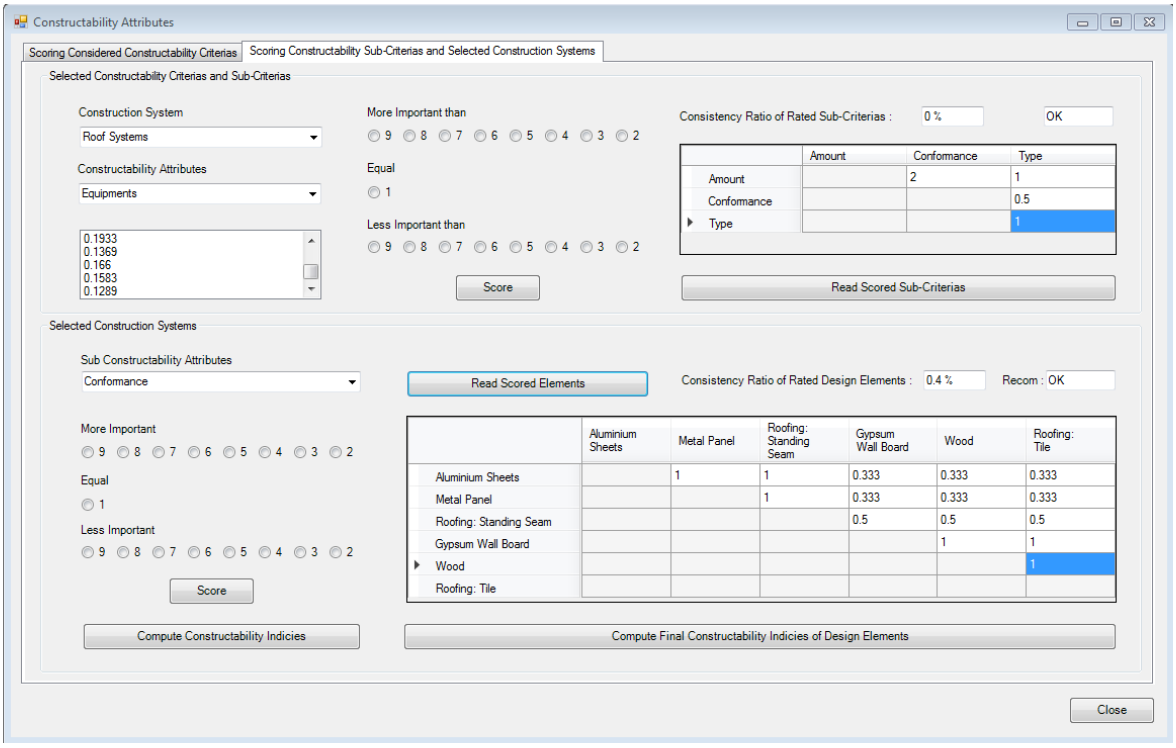
*Scoring **Roof options** with respect to **Supervisory** branch sub-criteria clustered under **Skills** criteria*



*Scoring **Roof options** with respect to **Manual labour** branch sub-criteria clustered under **Skills** criteria*



*Scoring **Roof options** with respect to **Amount** branch sub-criteria clustered under **Equipment** criteria*



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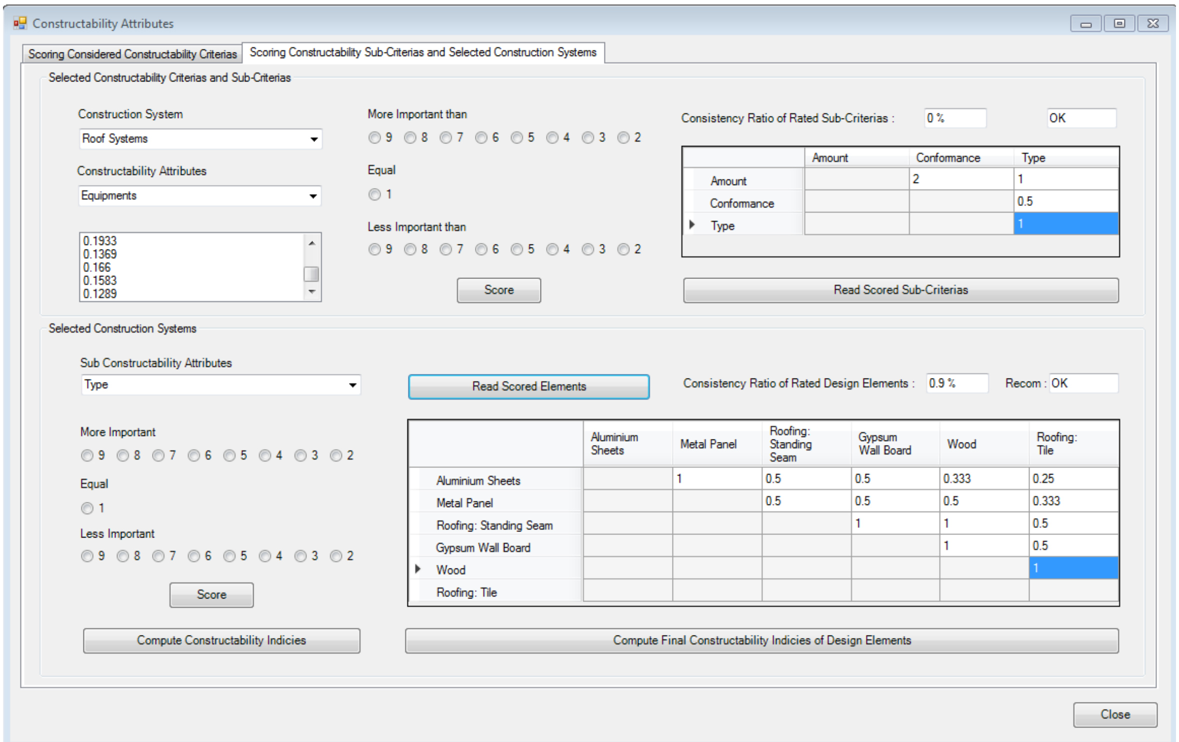
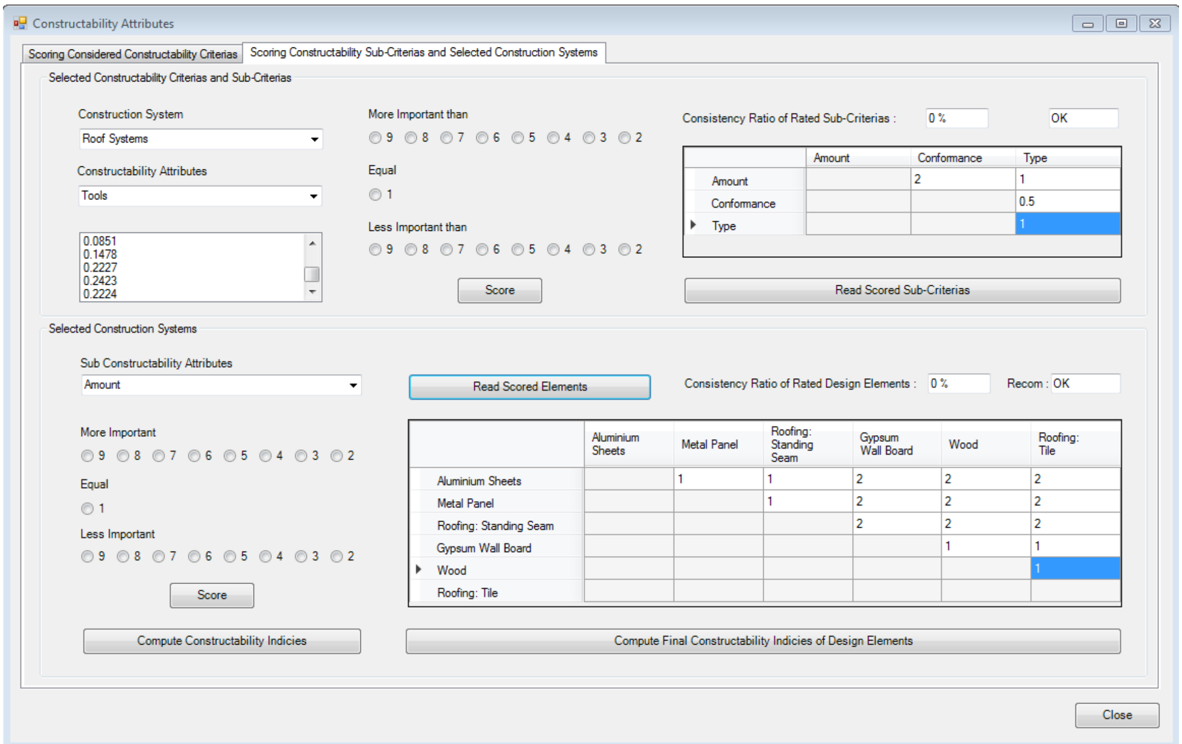


*Scoring **Roof options** with respect to **Type** branch sub-criteria clustered under **Equipment** criteria*



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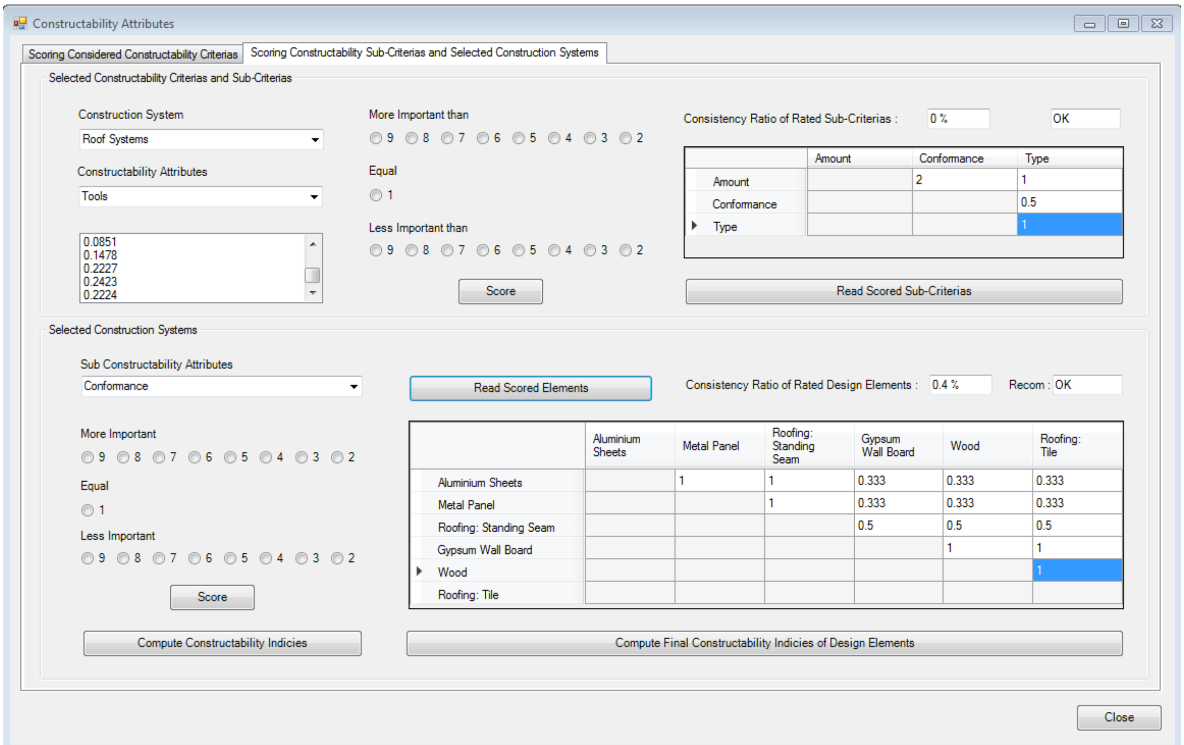

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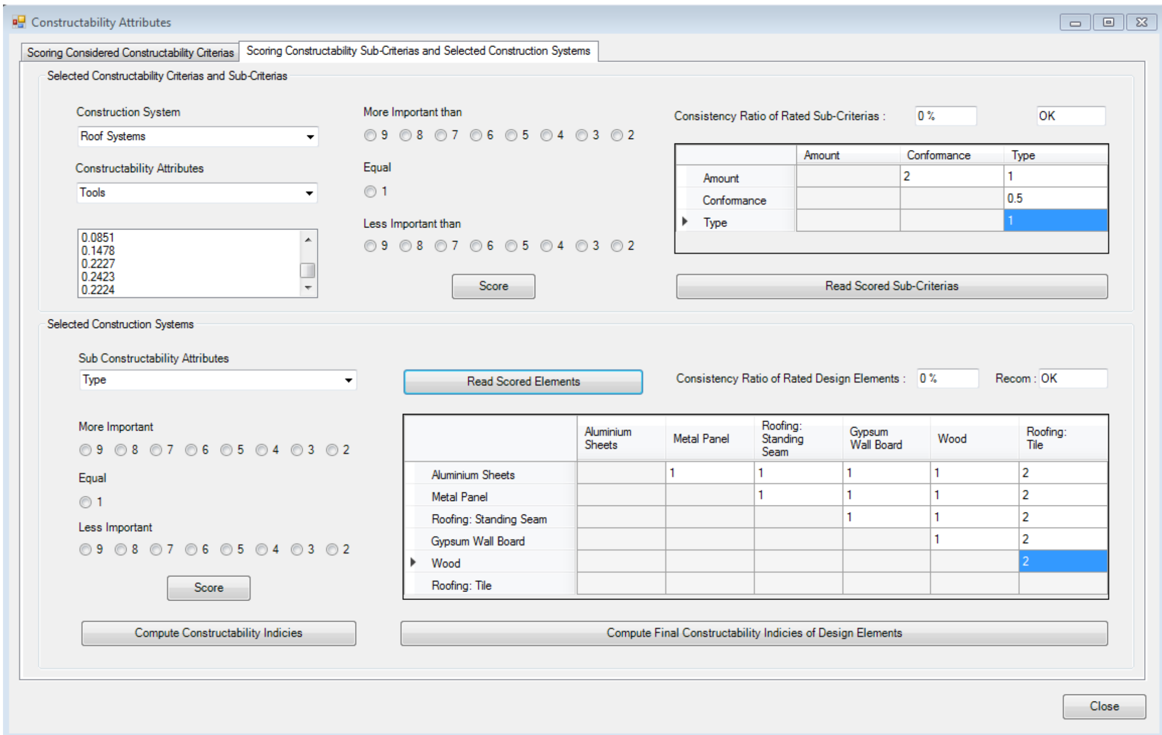

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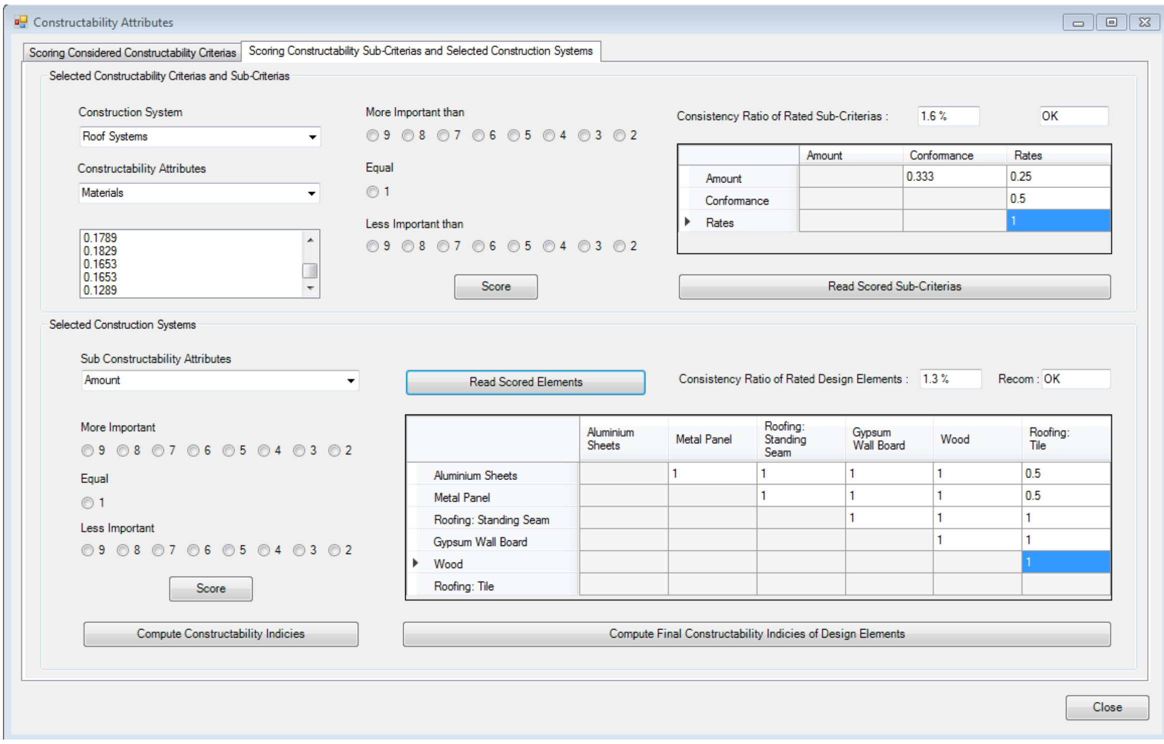
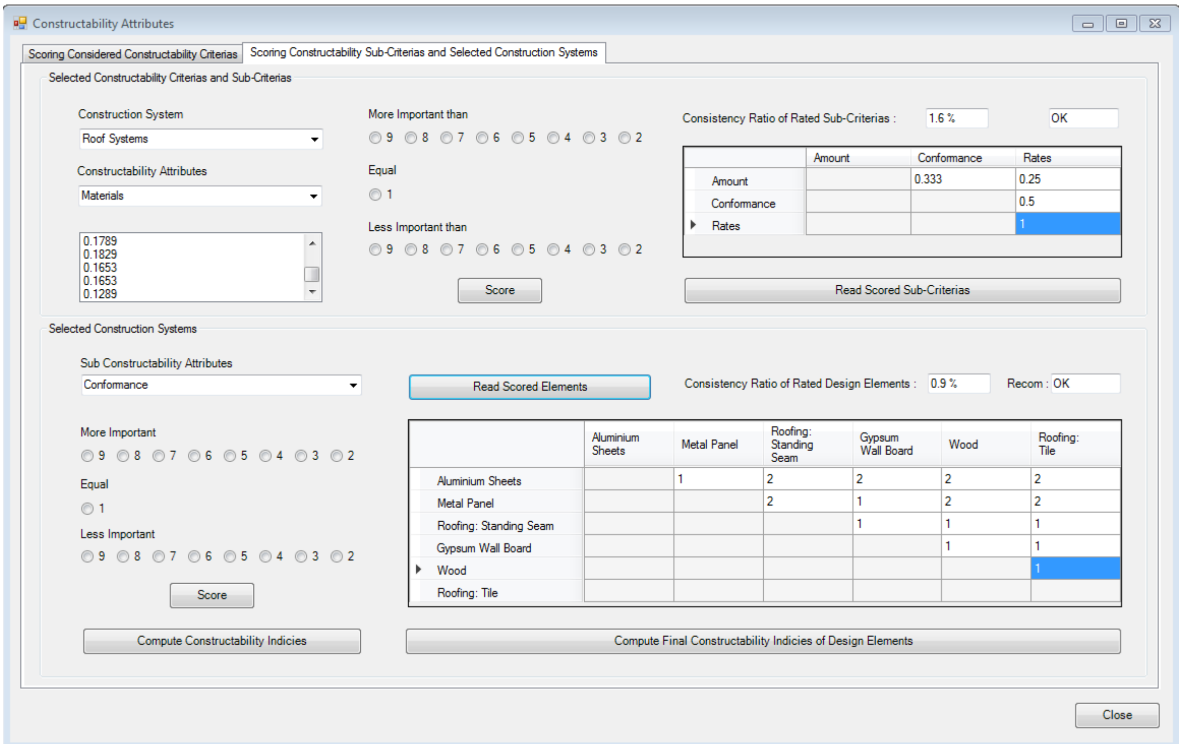


*Scoring **Roof options** with respect to **Amount** branch sub-criteria clustered under **Materials** criteria*



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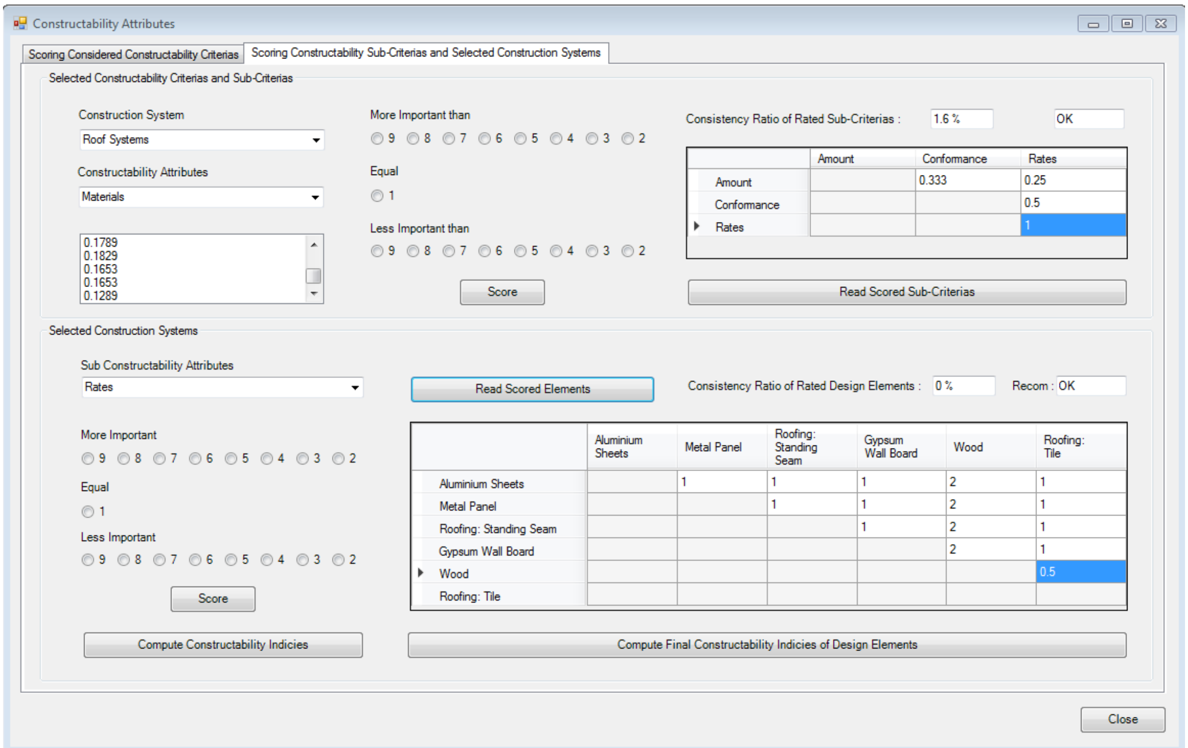
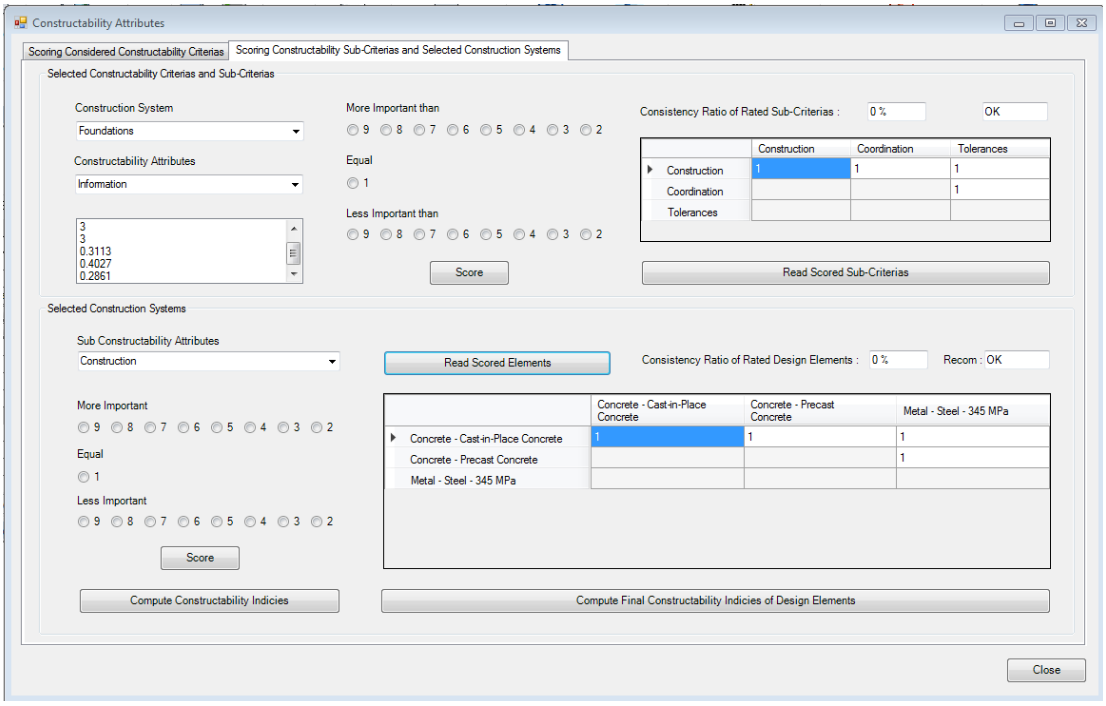
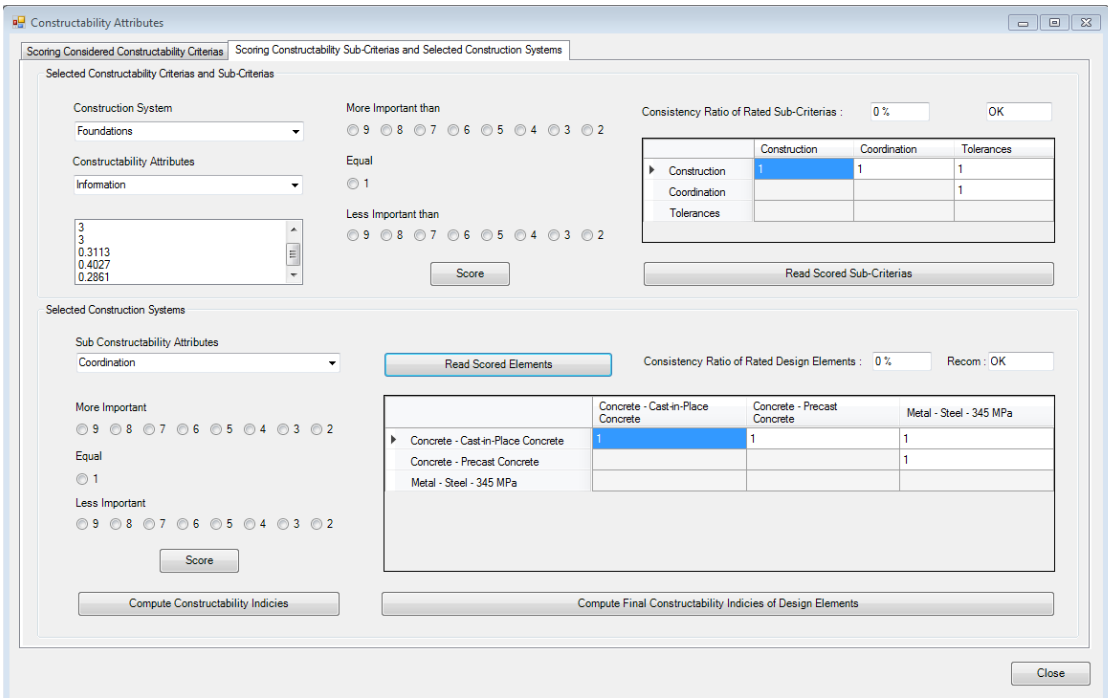


*Scoring **Roof options** with respect to **Rates** branch sub-criteria clustered under **Materials** criteria*

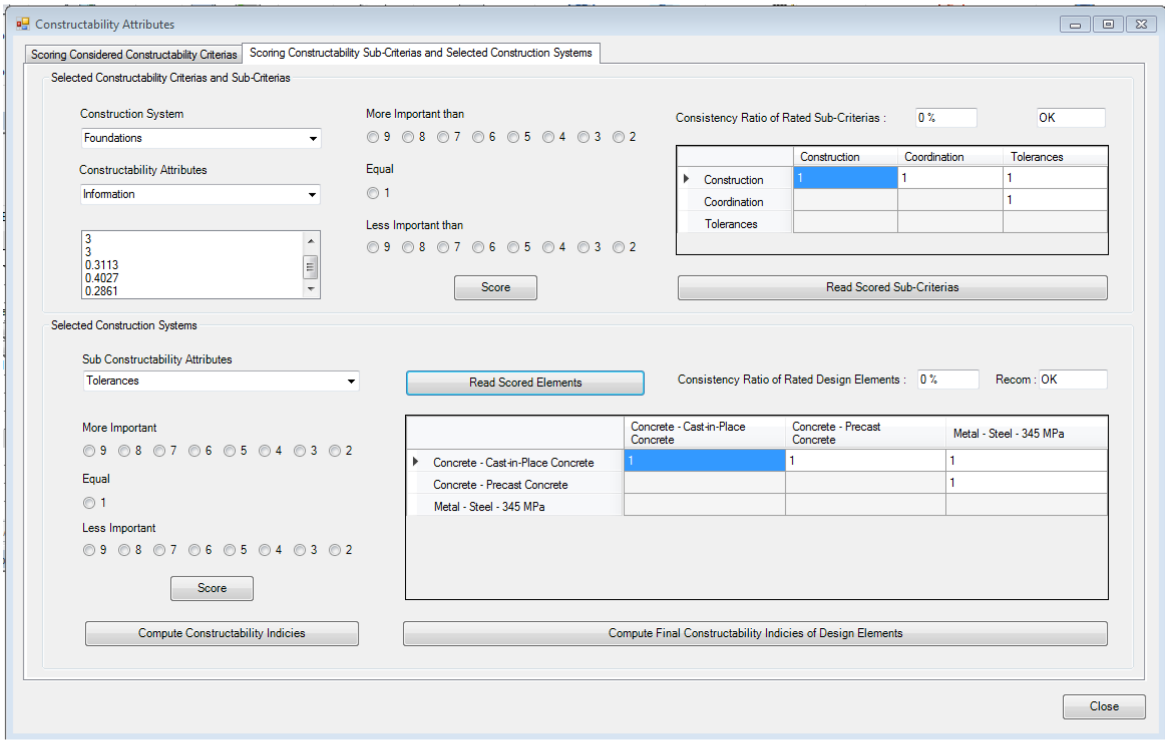
Foundation Systems:



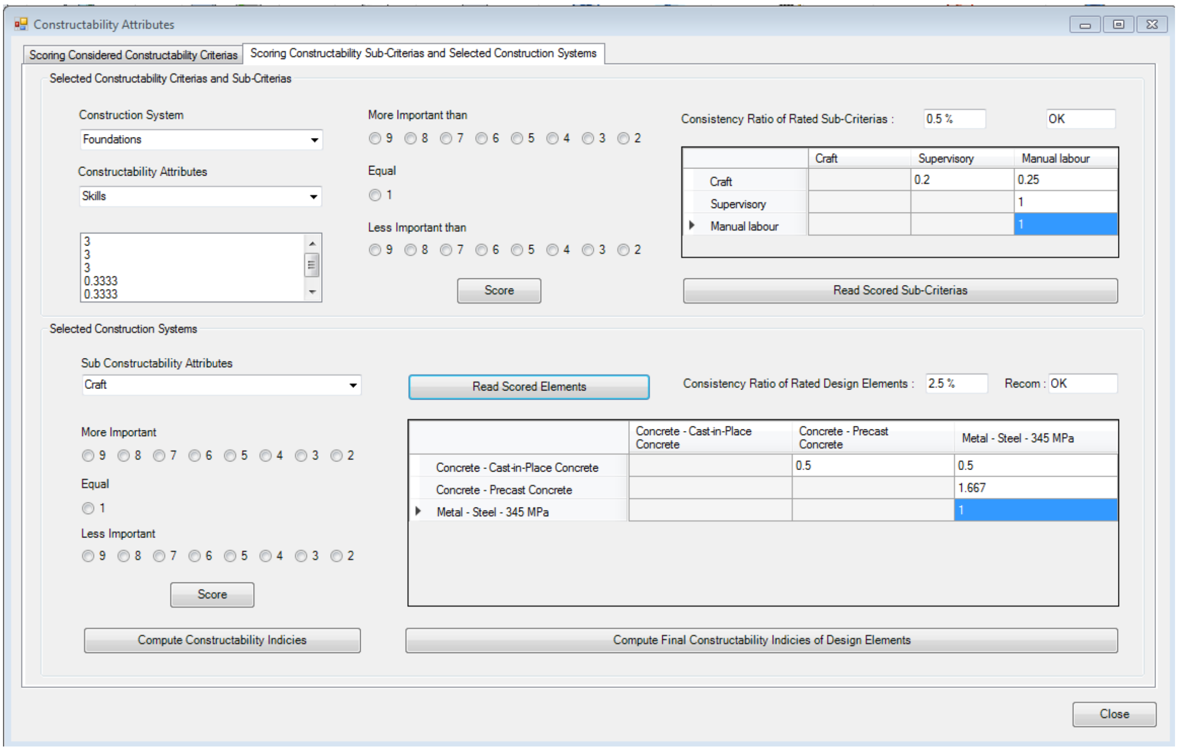
*Scoring **Foundation options** with respect to **Construction** branch sub-criteria clustered under **Information** criteria*



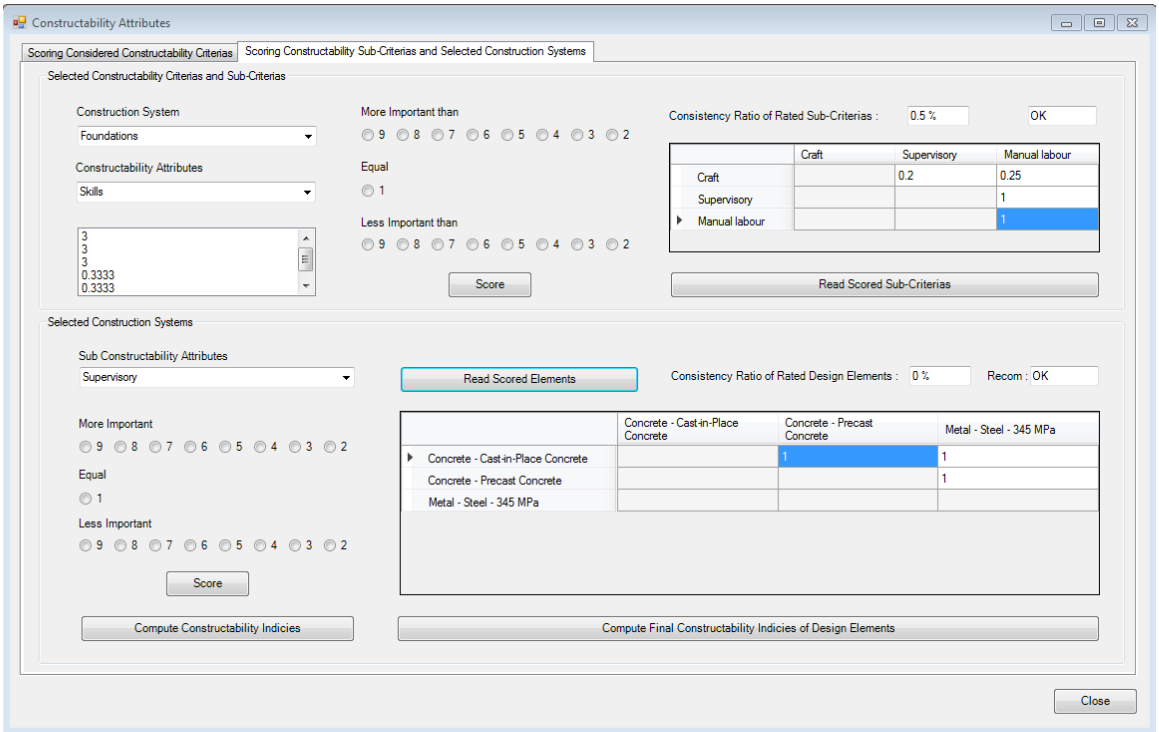
*Scoring **Foundation options** with respect to **Coordination** branch sub-criteria clustered under **Information** criteria*



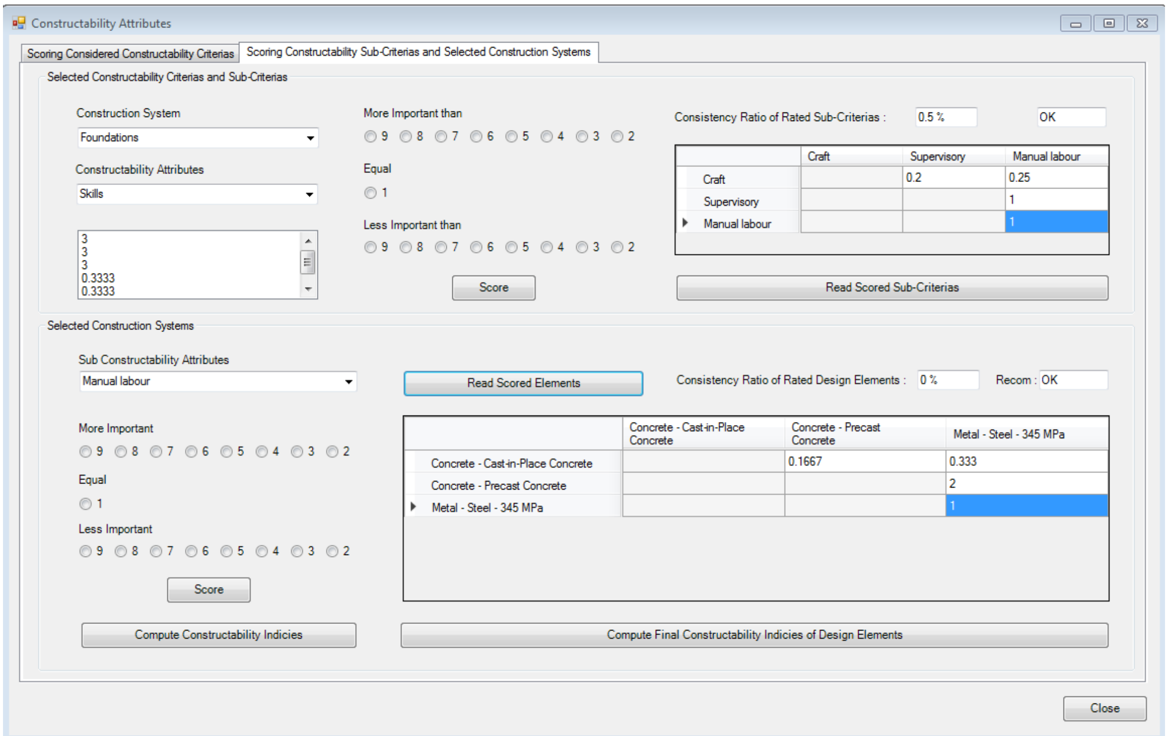
*Scoring **Foundation options** with respect to **Tolerance** branch sub-criteria clustered under **Information** criteria*



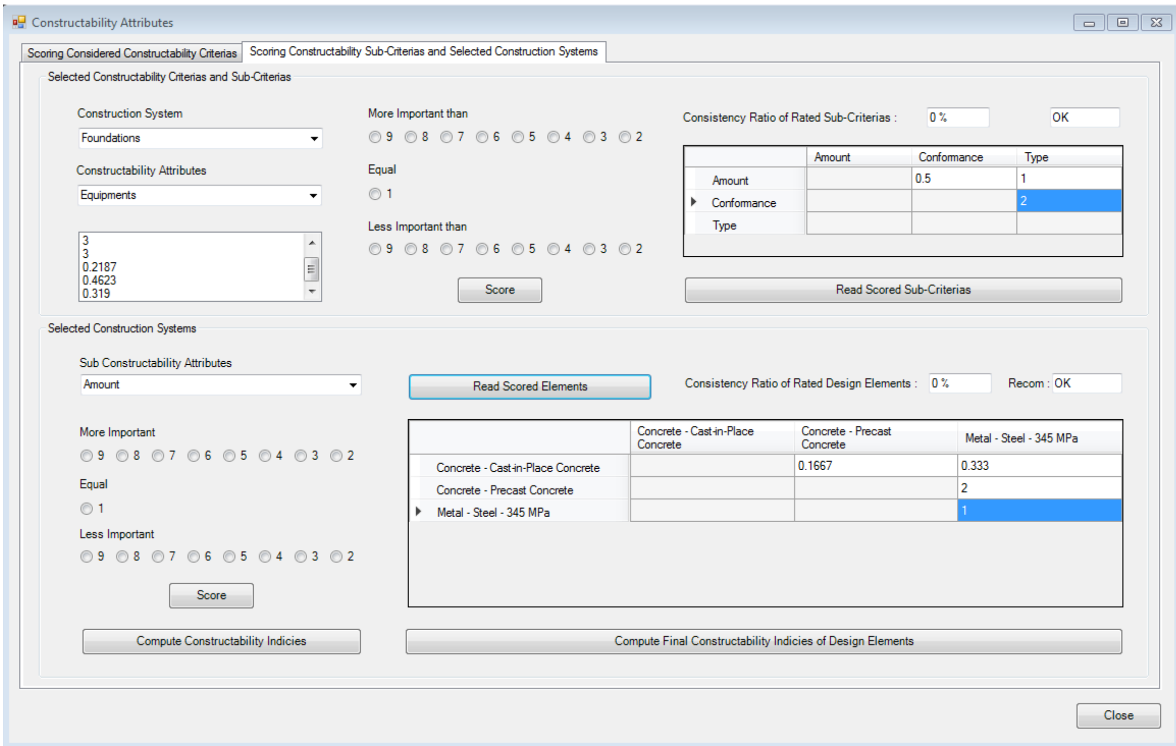
*Scoring **Foundation options** with respect to **Craft** branch sub-criteria clustered under **Skills** criteria*



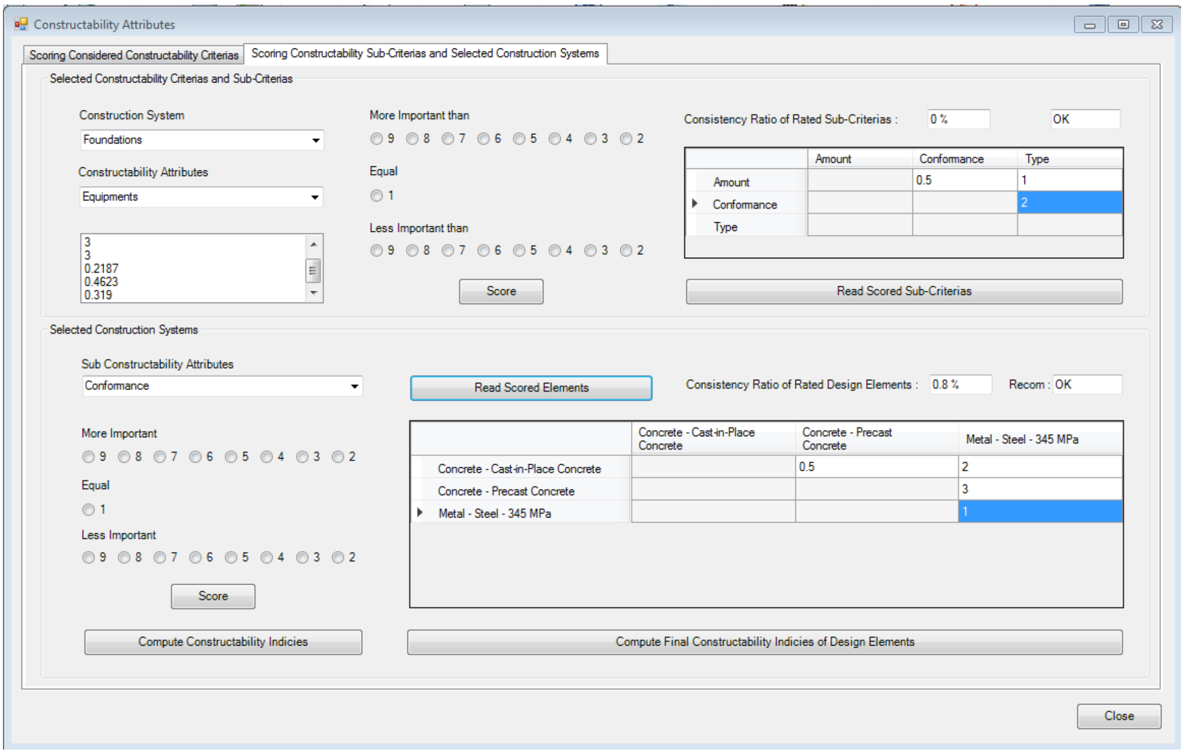
*Scoring **Foundation options** with respect to **Supervisory** branch sub-criteria clustered under **Skills** criteria*



*Scoring **Foundation options** with respect to **Manual labour** branch sub-criteria clustered under **Skills** criteria*



*Scoring **Foundation options** with respect to **Amount** branch sub-criteria clustered under **Equipment** criteria*



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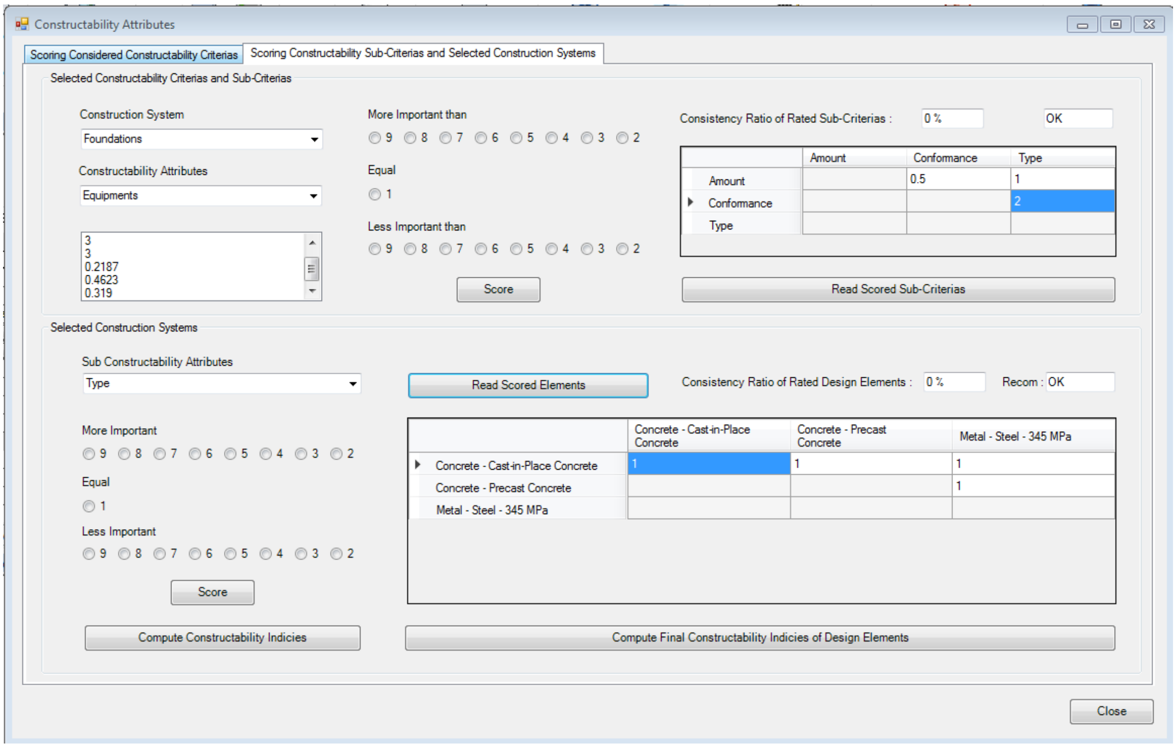
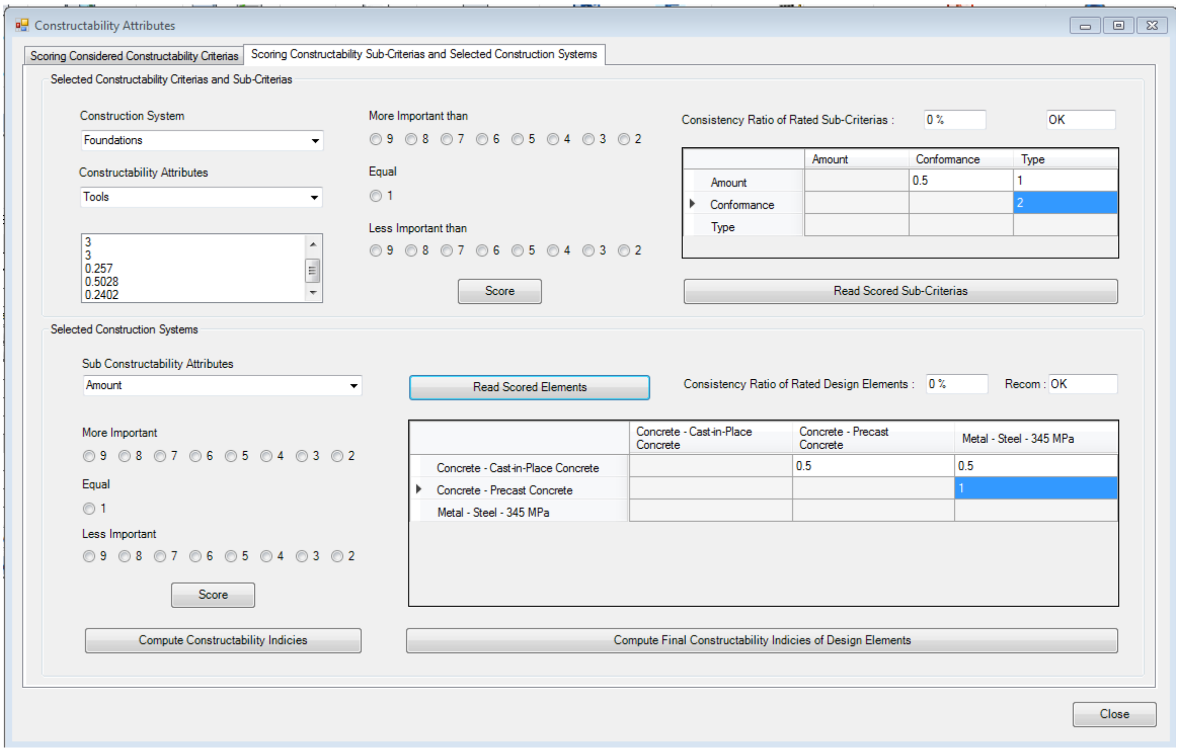
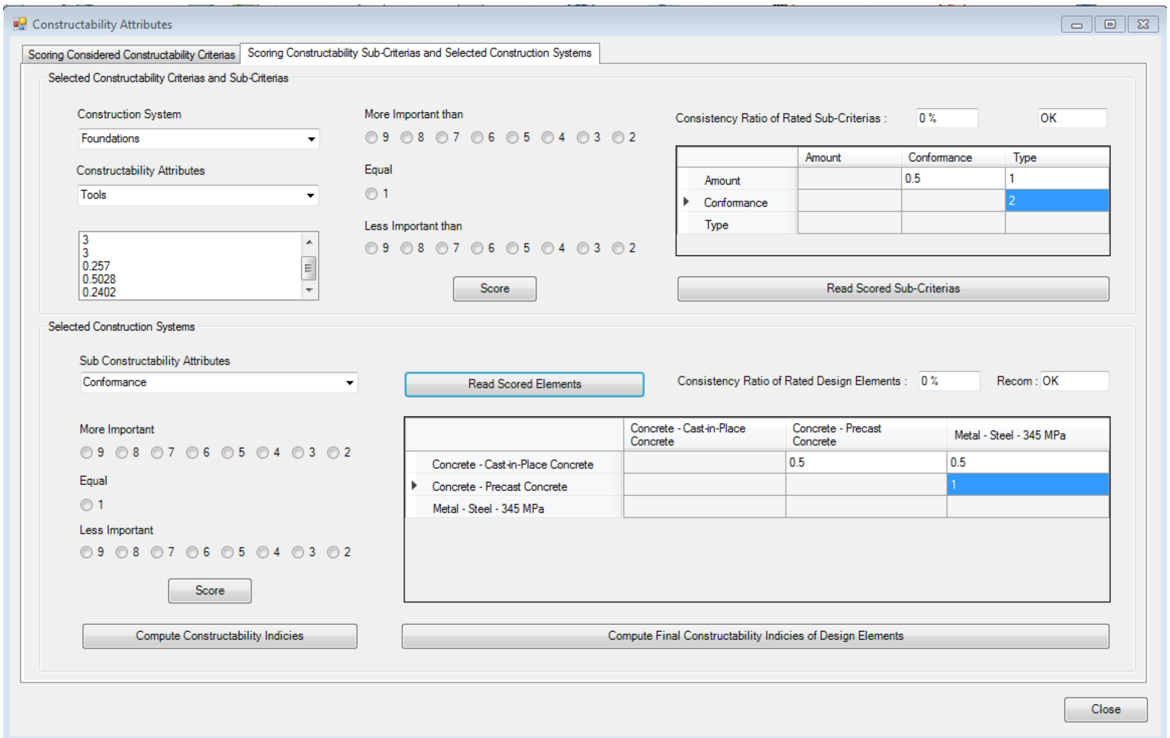


*Scoring **Foundation options** with respect to **Type** branch sub-criteria clustered under **Equipment** criteria*



*Scoring **Foundation options** with respect to **Amount** branch sub-criteria clustered under **Tools** criteria*



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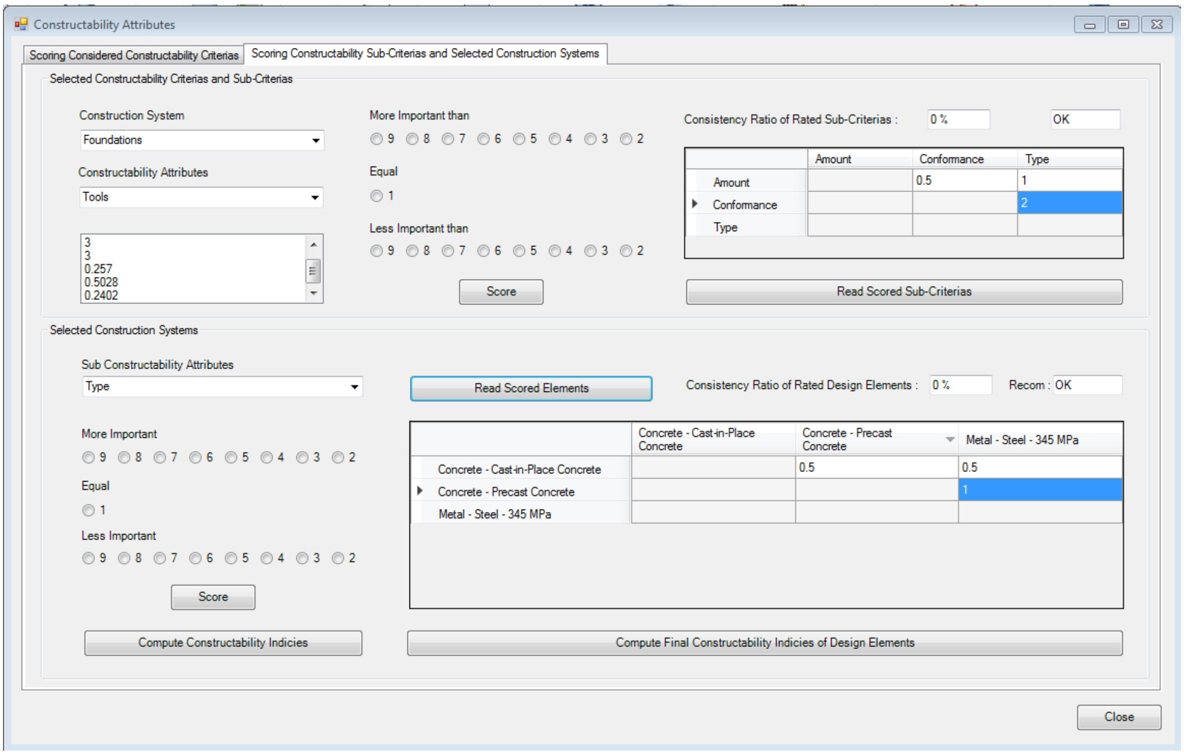
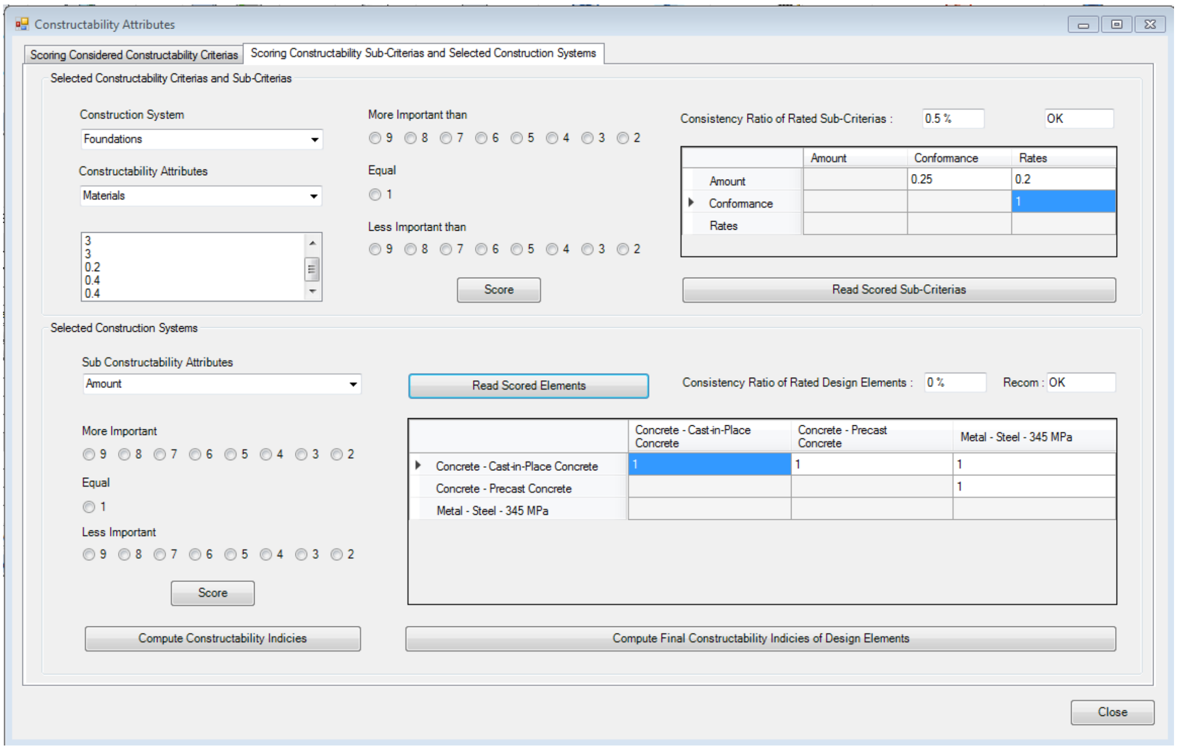
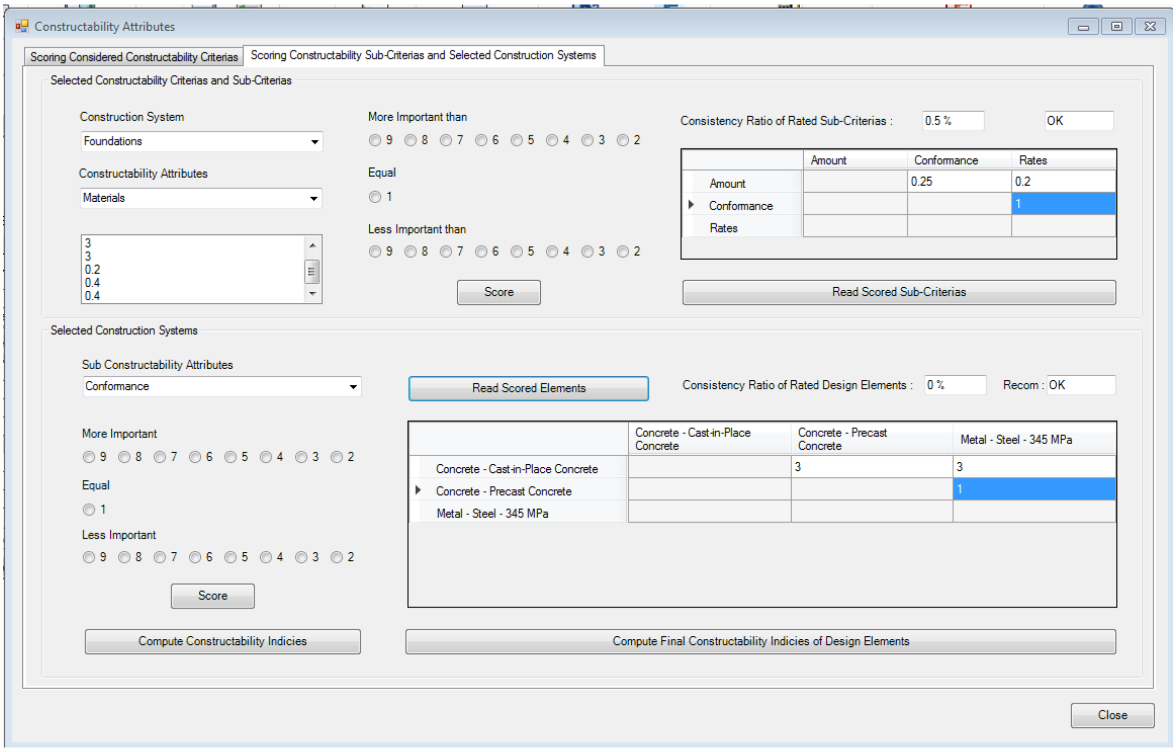


*Scoring **Foundation options** with respect to **Type** branch sub-criteria clustered under **Tools** criteria*



*Scoring **Foundation options** with respect to **Amount** branch sub-criteria clustered under **Materials** criteria*



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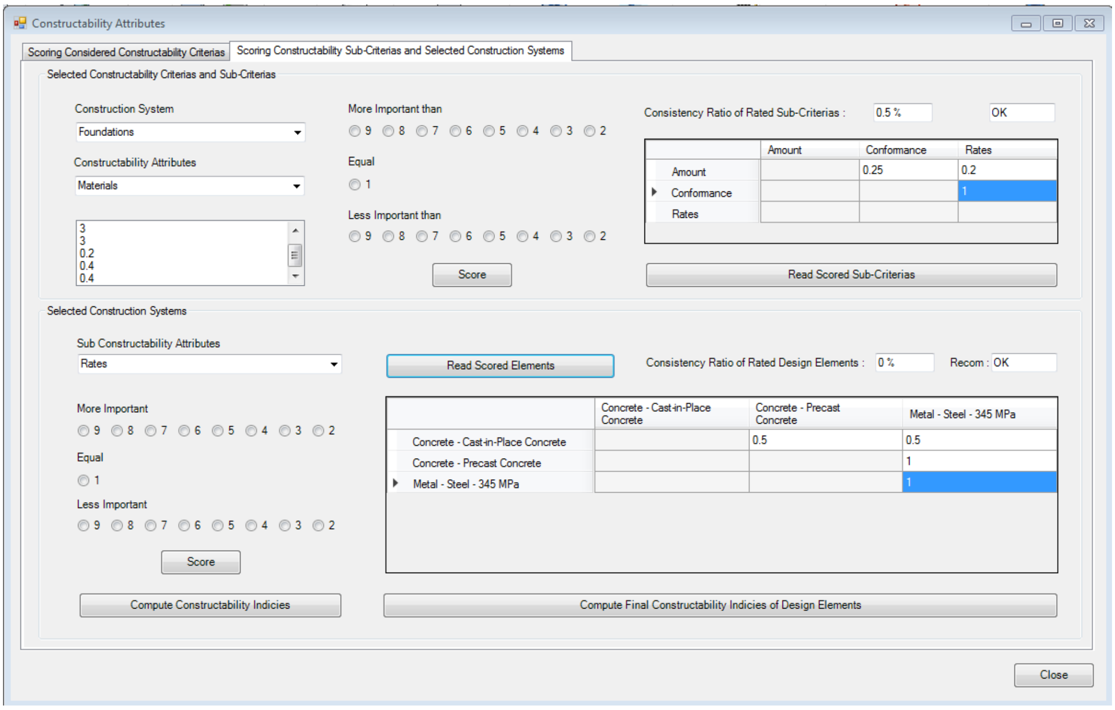
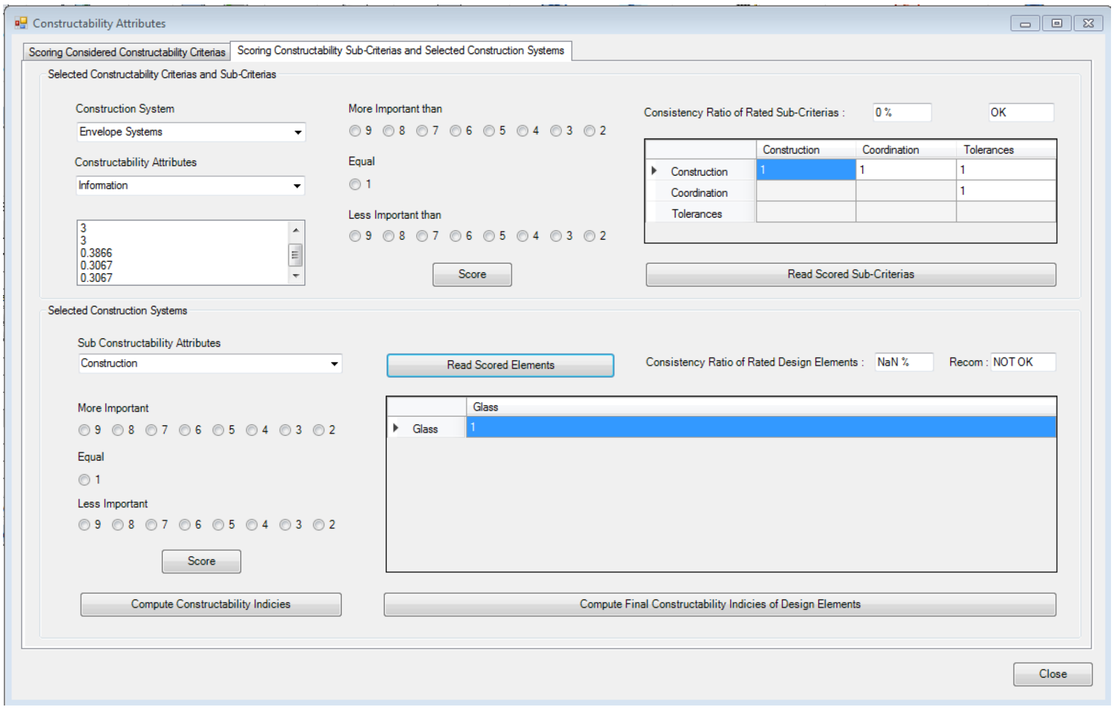


*Scoring **Foundation options** with respect to **Rates** branch sub-criteria clustered under **Materials** criteria*

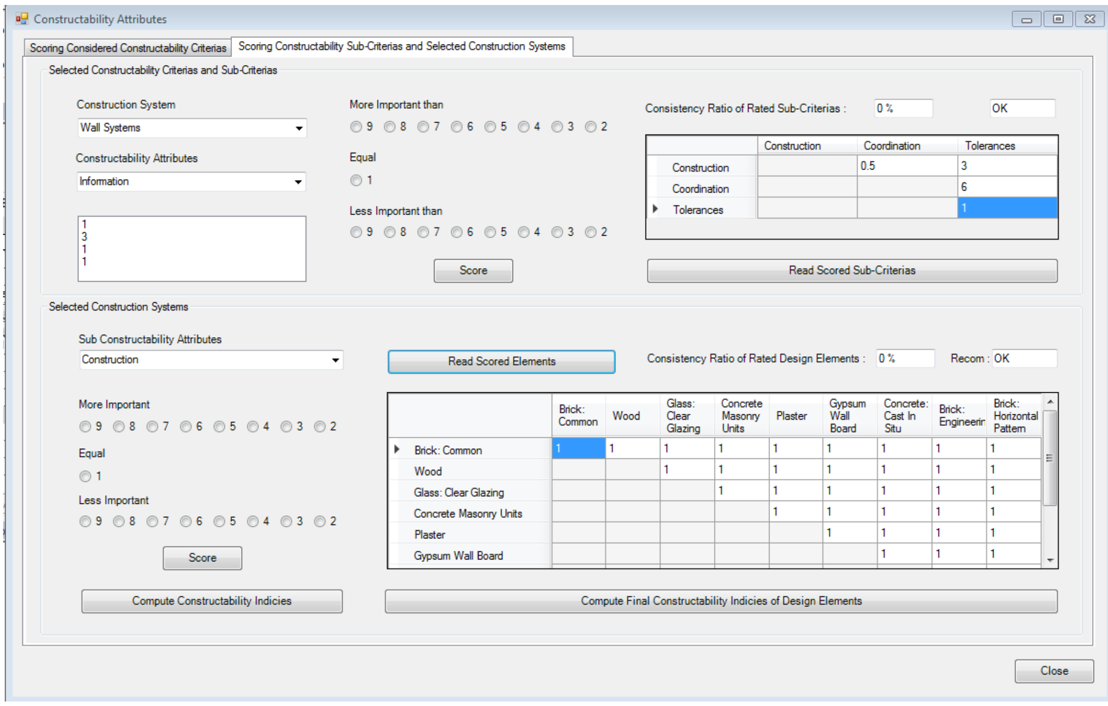
<u>Envelope systems:</u>

As there is only one option for envelop system (i.e. Glass), therefore, it will be assigned the full score of 1. There is no need to carry on with the scoring process for this system. In practical implementation, it implies that the user has no choice but only to use the glass alternative. As such, there are no other options that are considered competitive to the glass in ordered to be compared against with respect to specific criteria, and hence it will have the full score. While it would be useful to assign an absolute score that reflect the actual capacity of user to construct such option. However, the AHP technique produces a relative score through the series of pairwise comparisons to enable the decision-making between the considered alternatives.

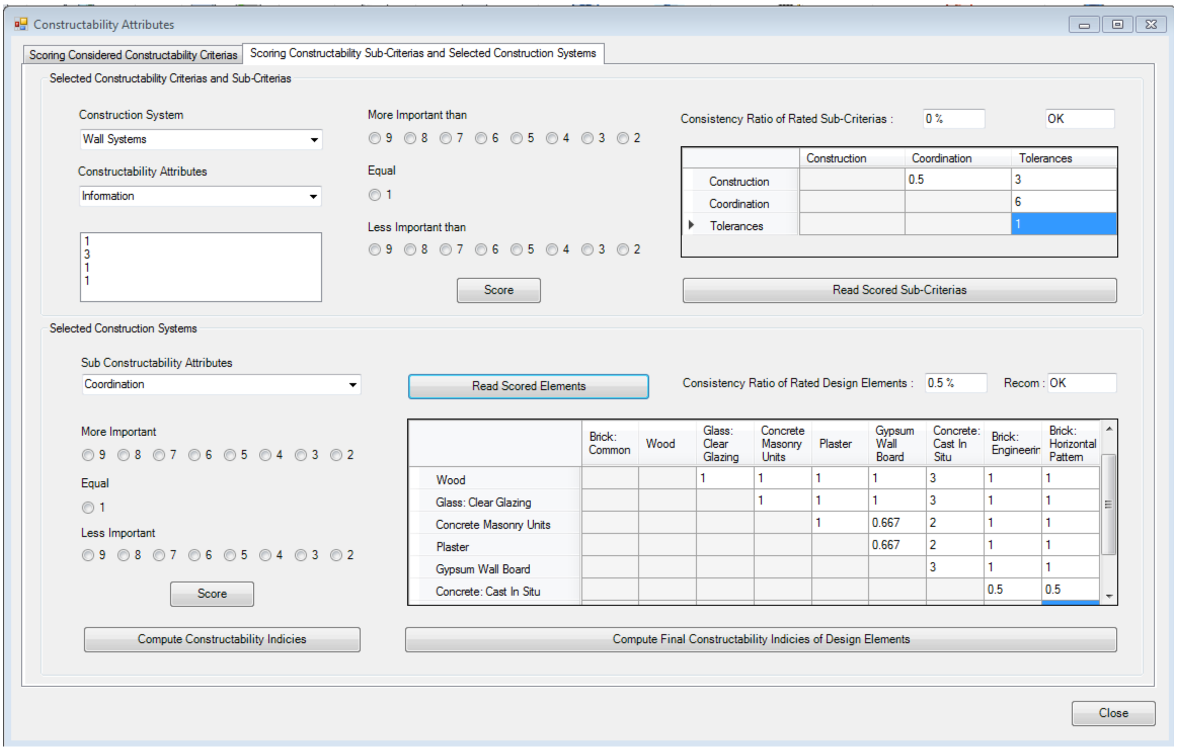


*Scoring **Foundation options** with respect to **Construction** branch sub-criteria clustered under **Information** criteria*

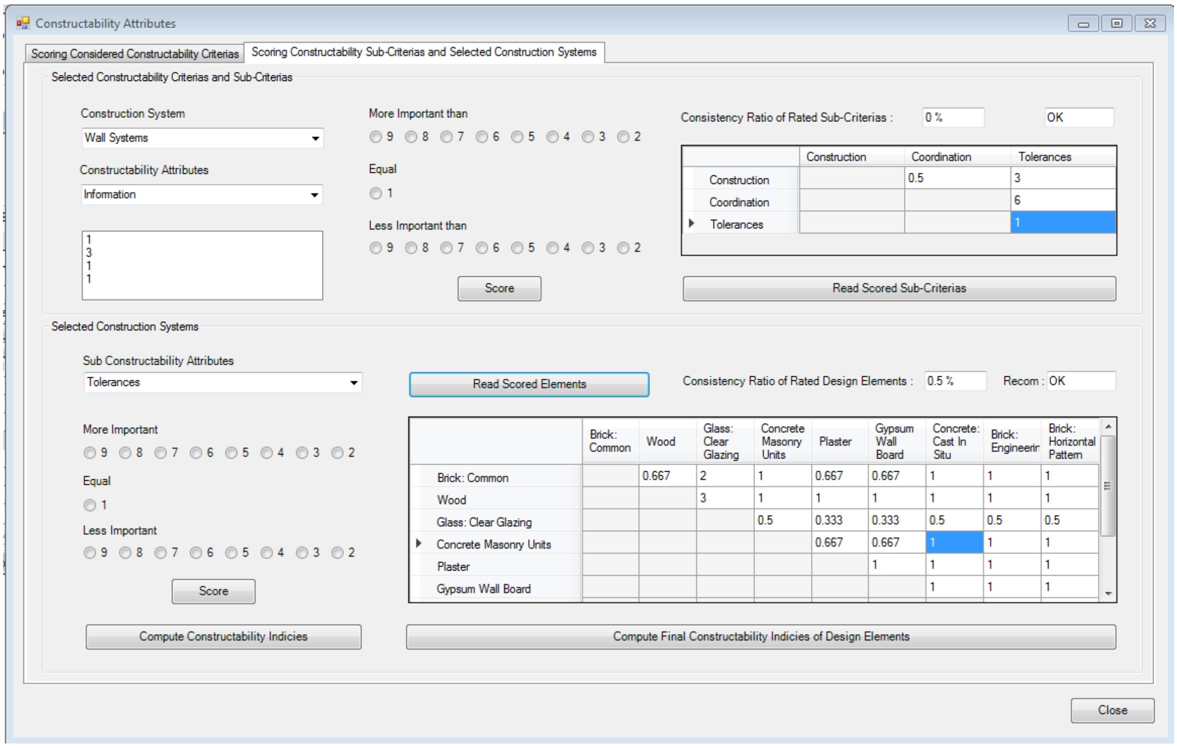
Walls System:



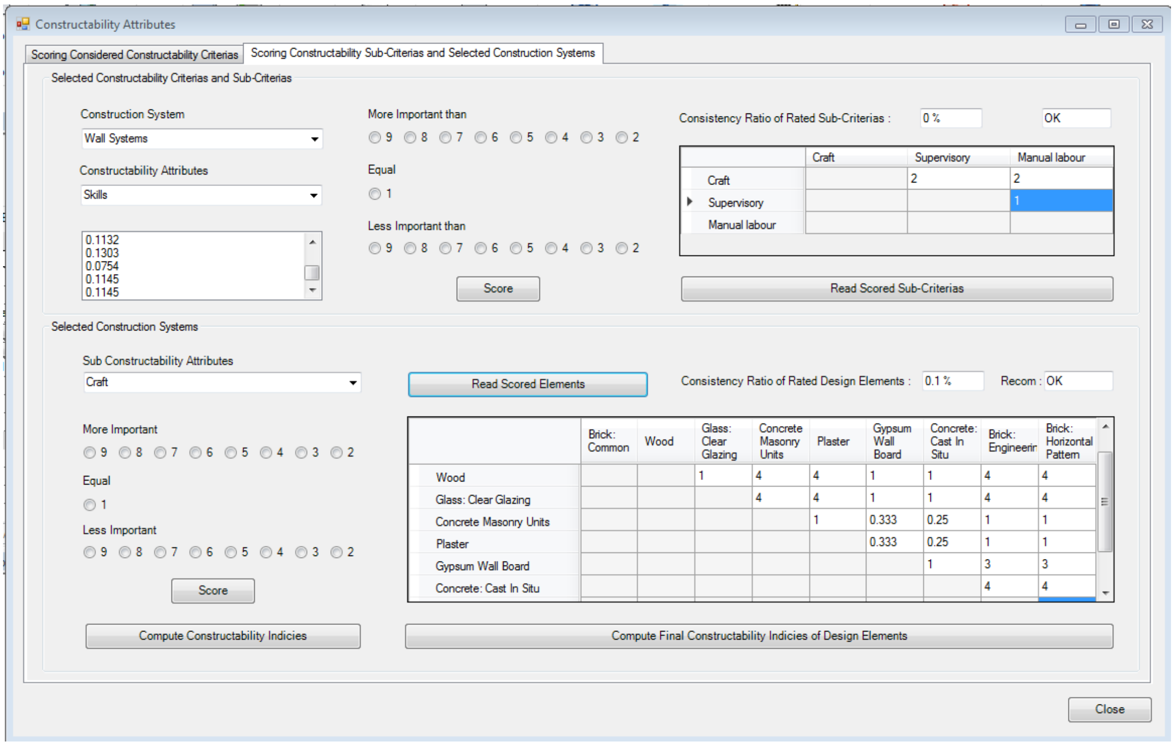
*Scoring **Wall options** with respect to **Construction** branch sub-criteria clustered under **Information** criteria*



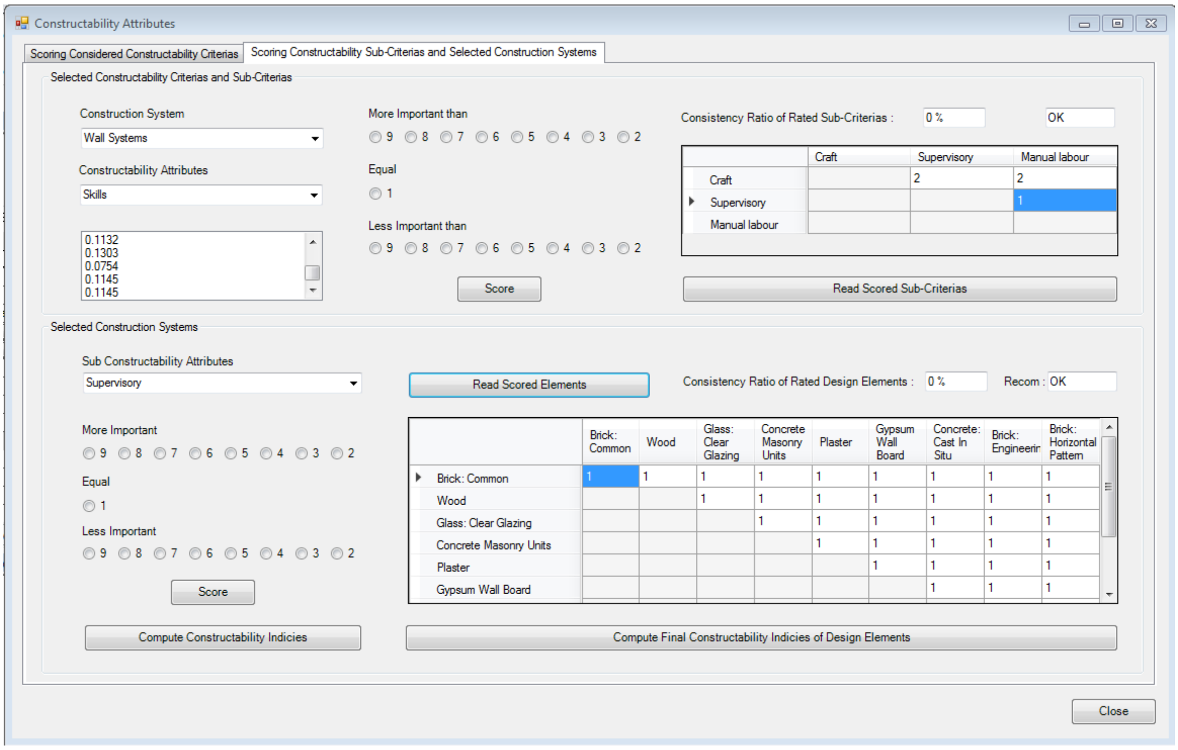
*Scoring **Wall options** with respect to **Coordination** branch sub-criteria clustered under **Information** criteria*



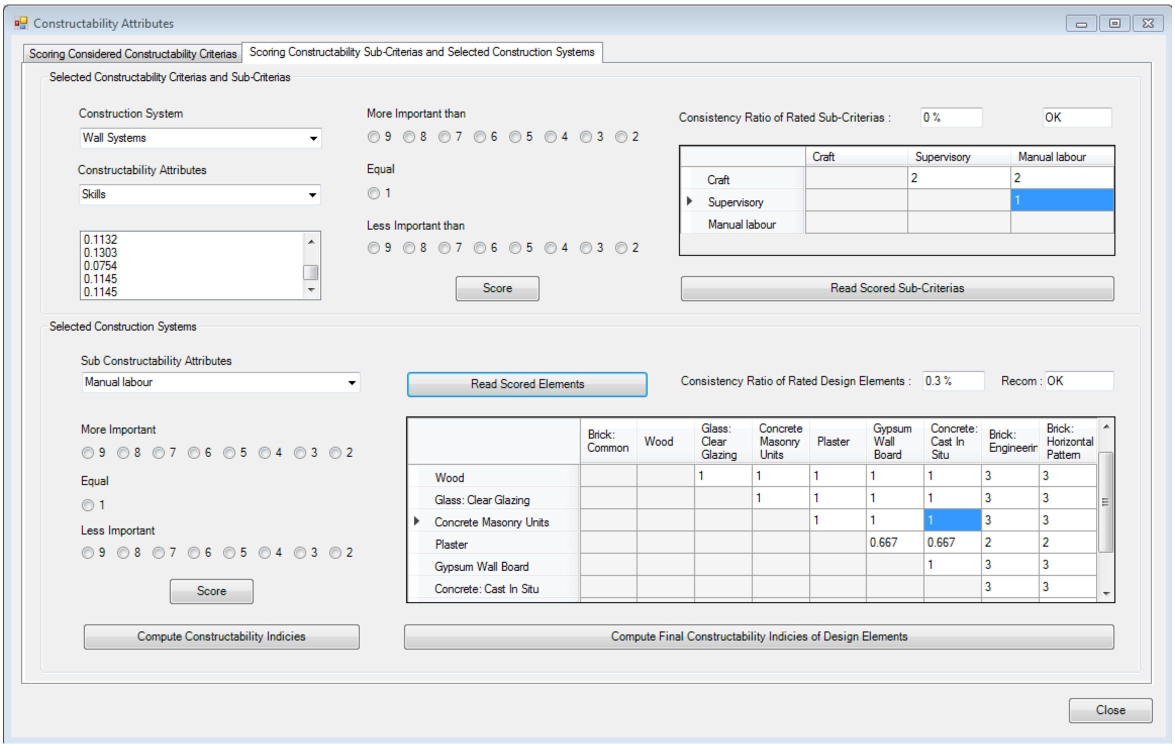
*Scoring **Wall options** with respect to **Tolerance** branch sub-criteria clustered under **Information** criteria*



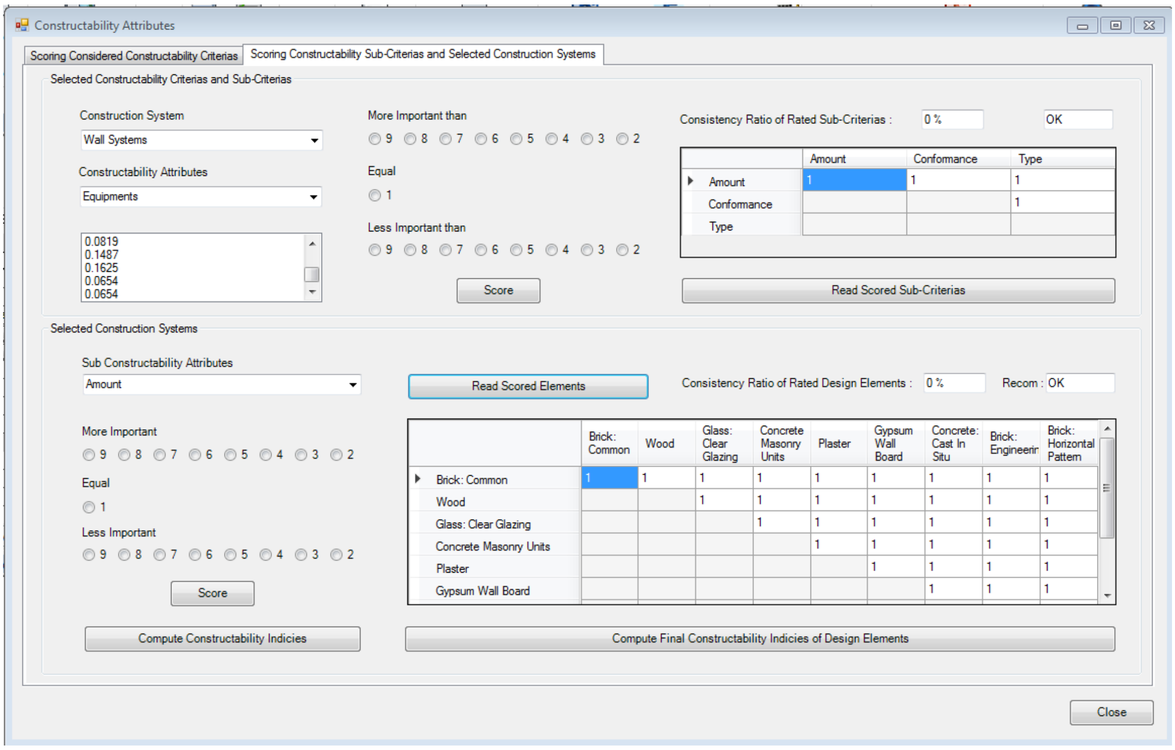
*Scoring **Wall options** with respect to **Craft** branch sub-criteria clustered under **Skills** criteria*



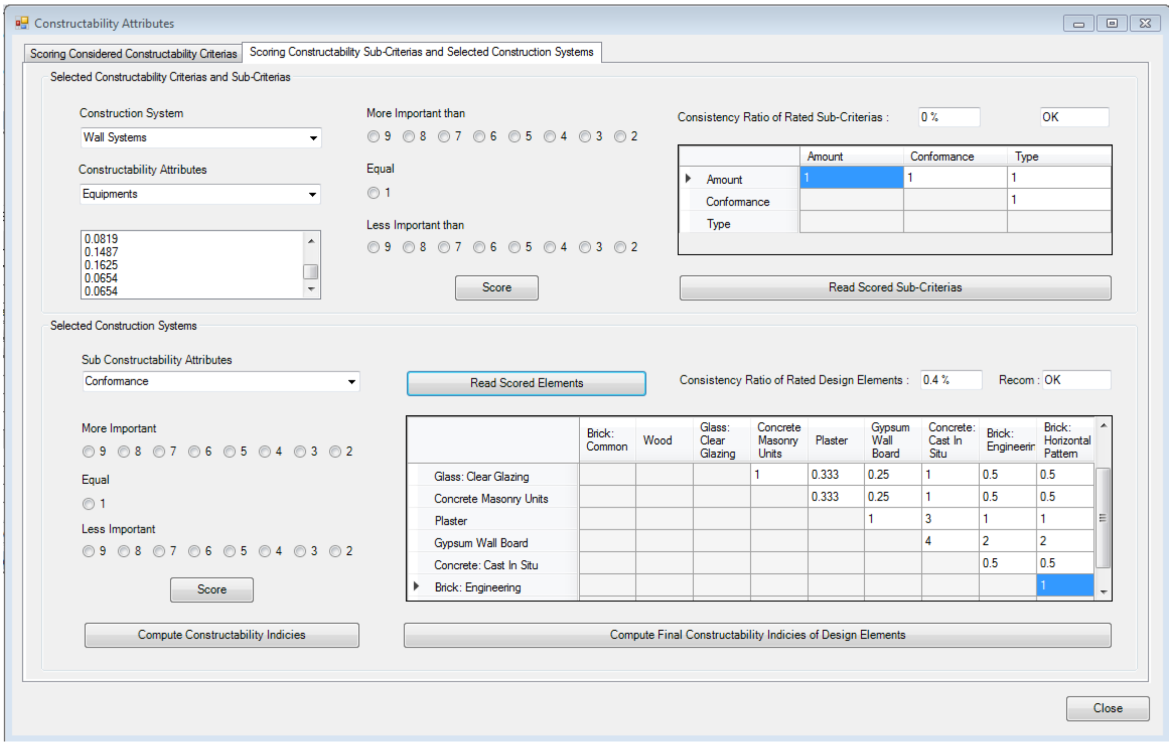
*Scoring **Wall options** with respect to **Supervisory** branch sub-criteria clustered under **Skills** criteria*



*Scoring **Wall options** with respect to **Manual labour** branch sub-criteria clustered under **Skills** criteria*



*Scoring **Wall options** with respect to **Amount** branch sub-criteria clustered under **Equipment** criteria*



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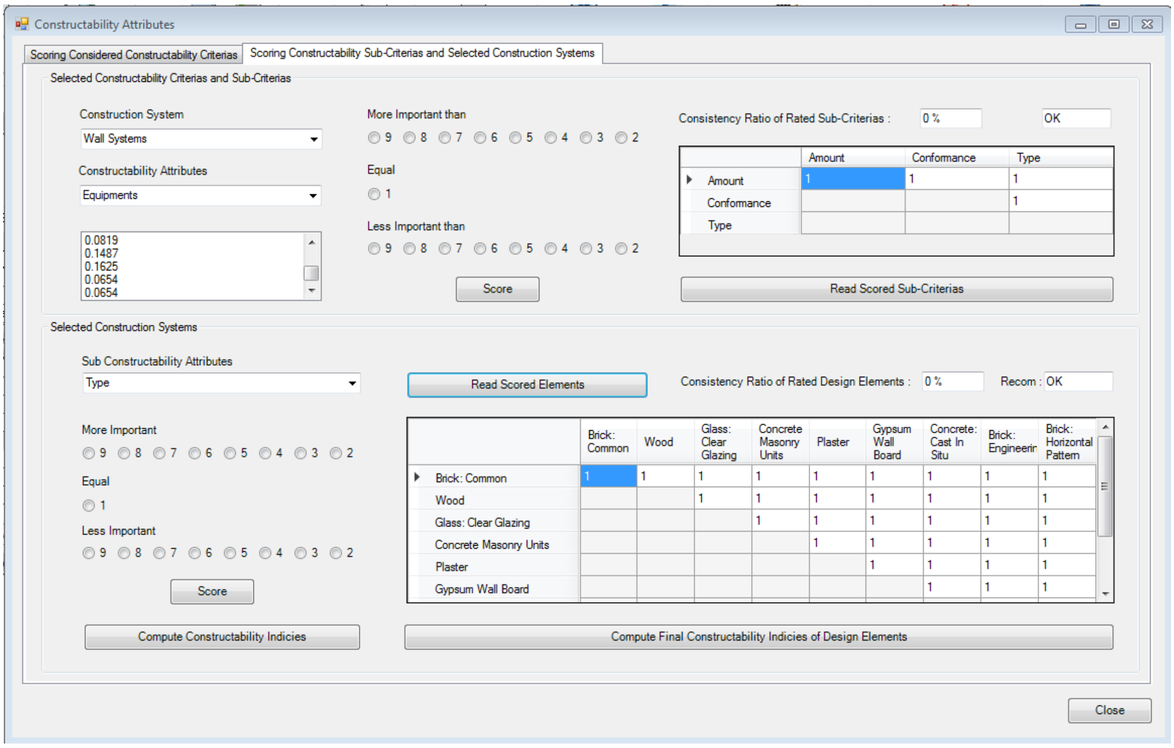
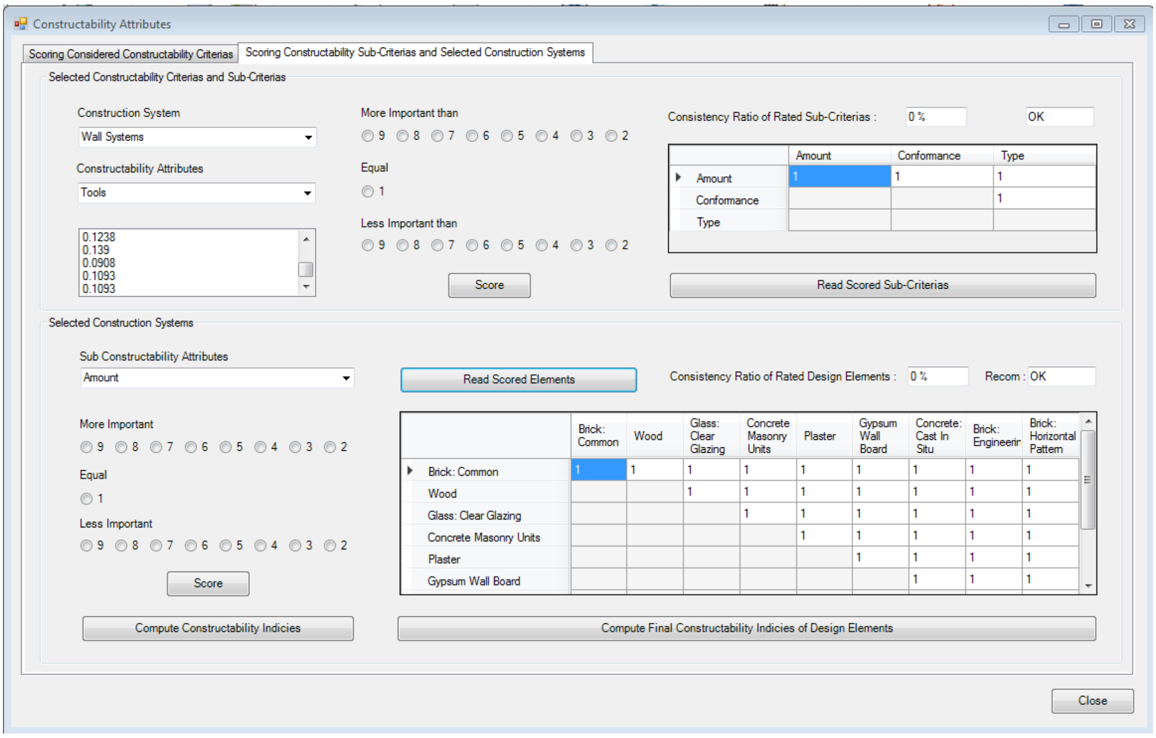
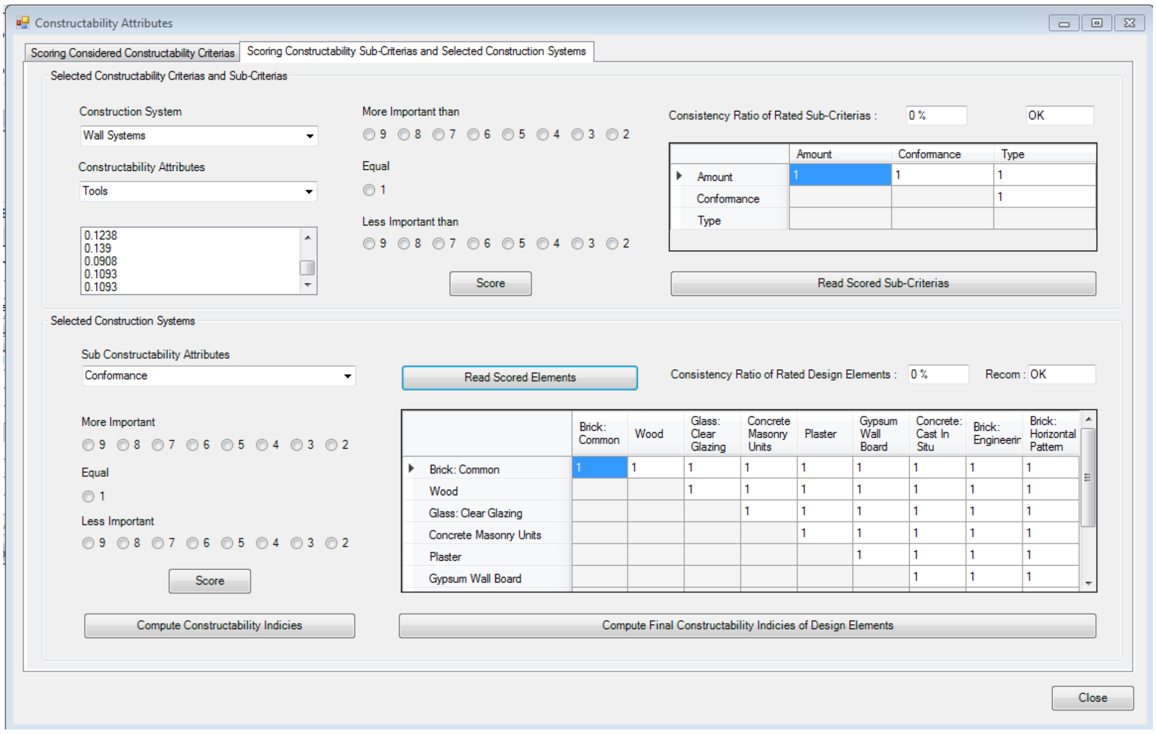


*Scoring **Wall options** with respect to **Type** branch sub-criteria clustered under **Equipment** criteria*



*Scoring **Wall options** with respect to **Amount** branch sub-criteria clustered under **Tools** criteria*



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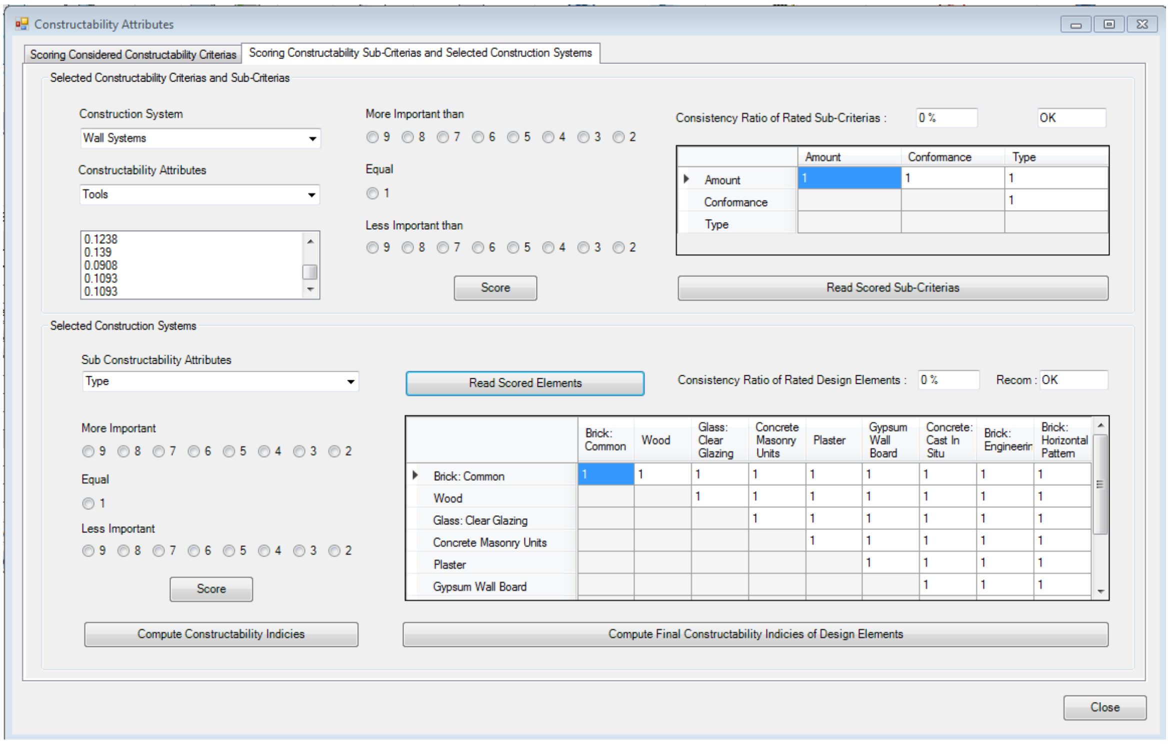
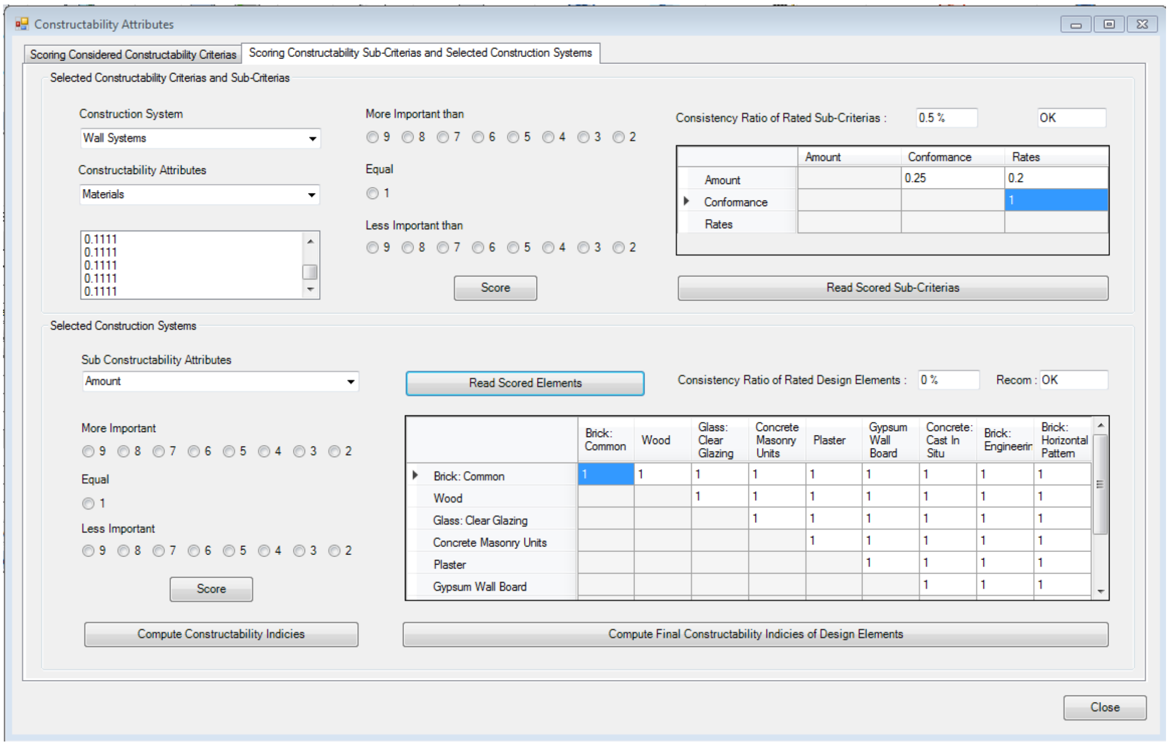
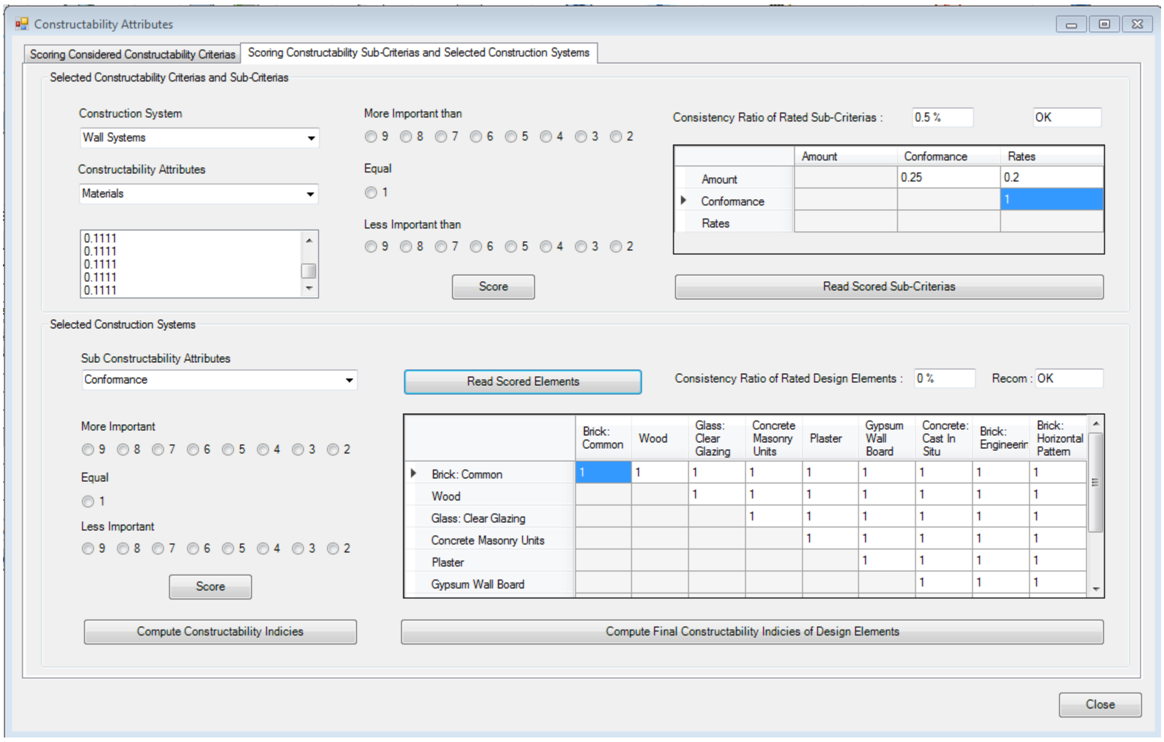


*Scoring **Wall options** with respect to **Type** branch sub-criteria clustered under **Tools** criteria*



*Scoring **Wall options** with respect to **Amount** branch sub-criteria clustered under **Materials** criteria*



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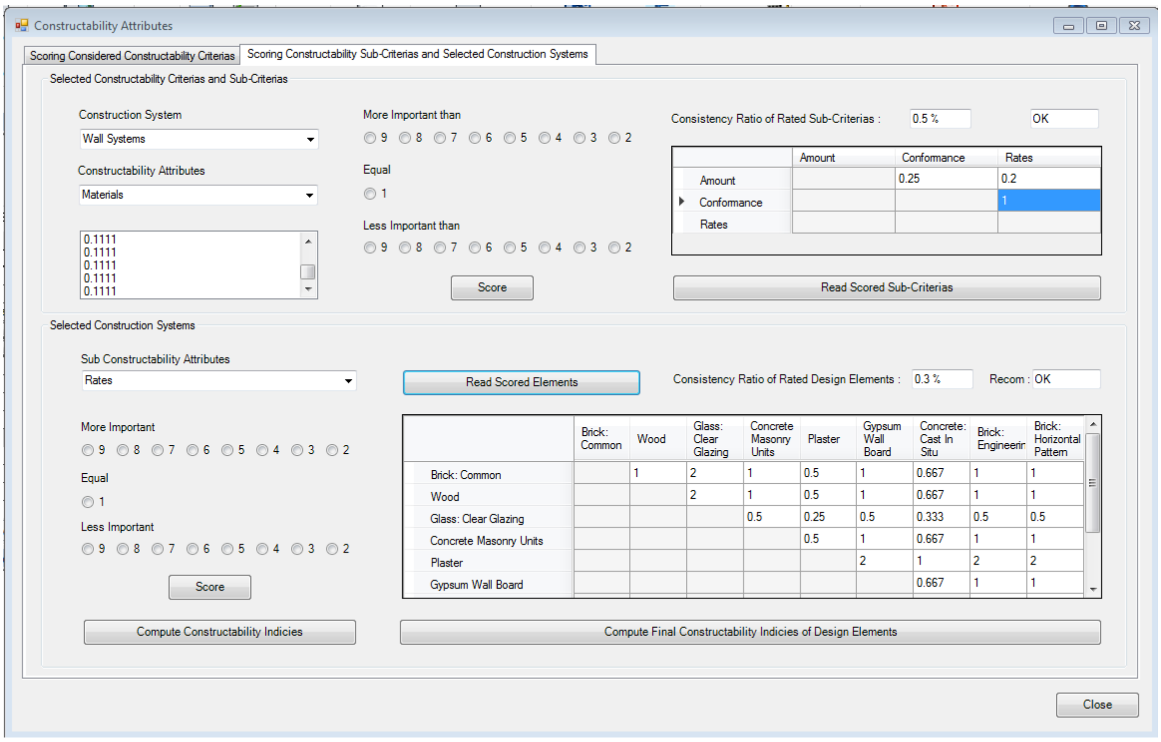
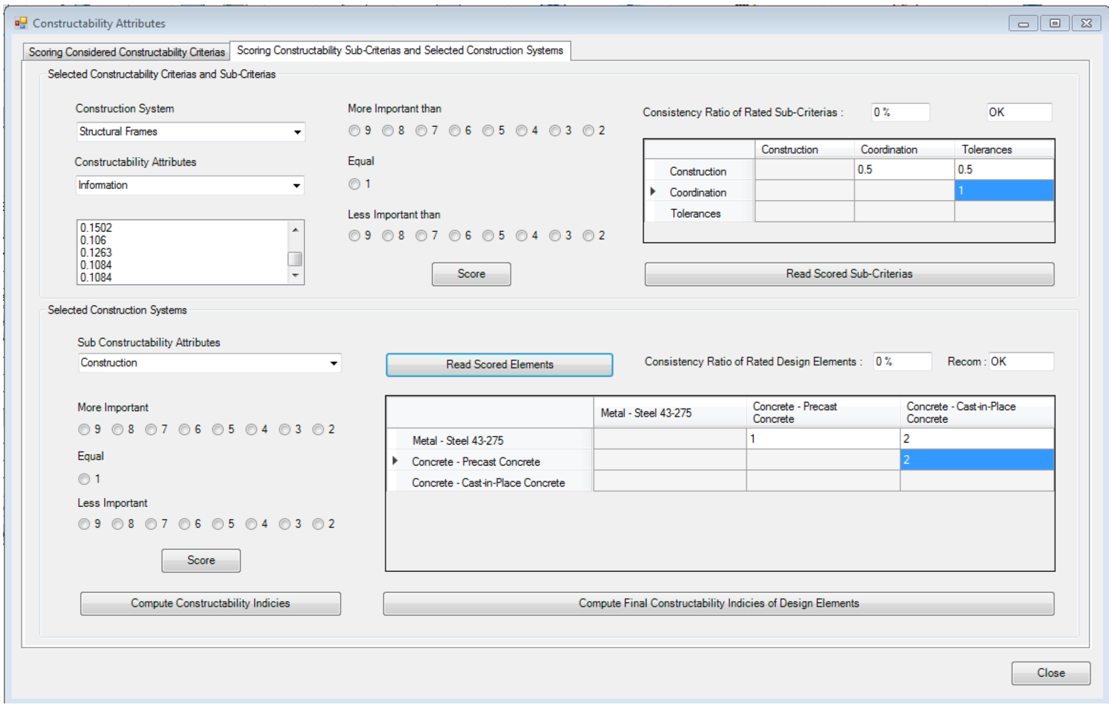
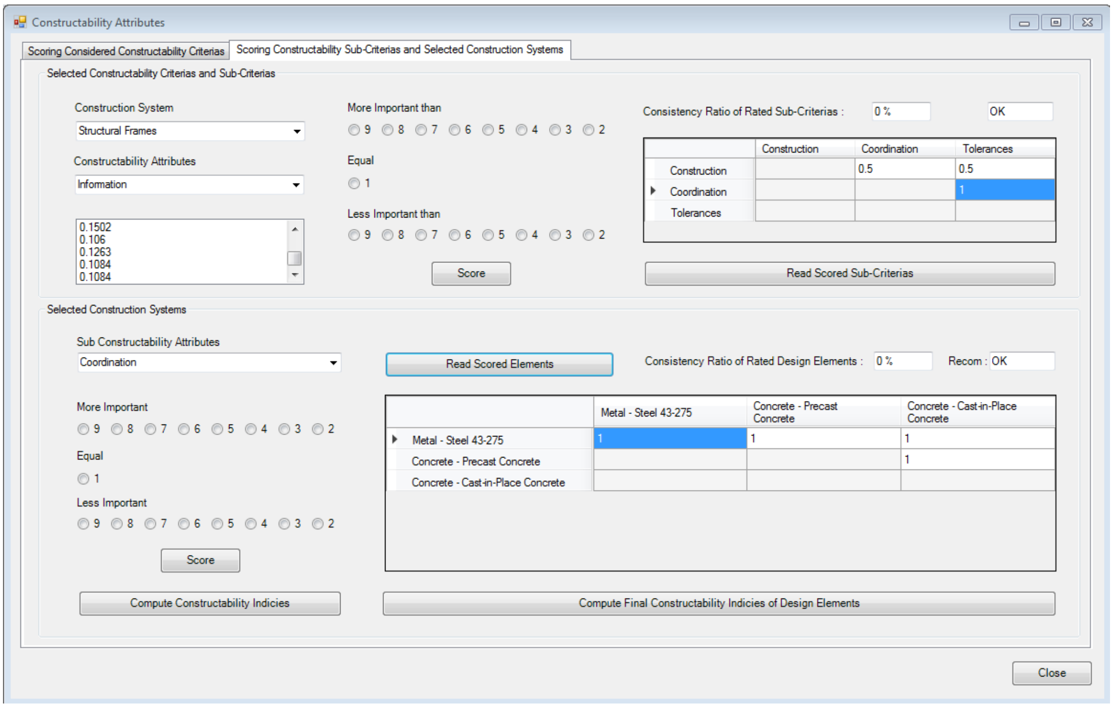


*Scoring **Wall options** with respect to **Rates** branch sub-criteria clustered under **Materials** criteria*

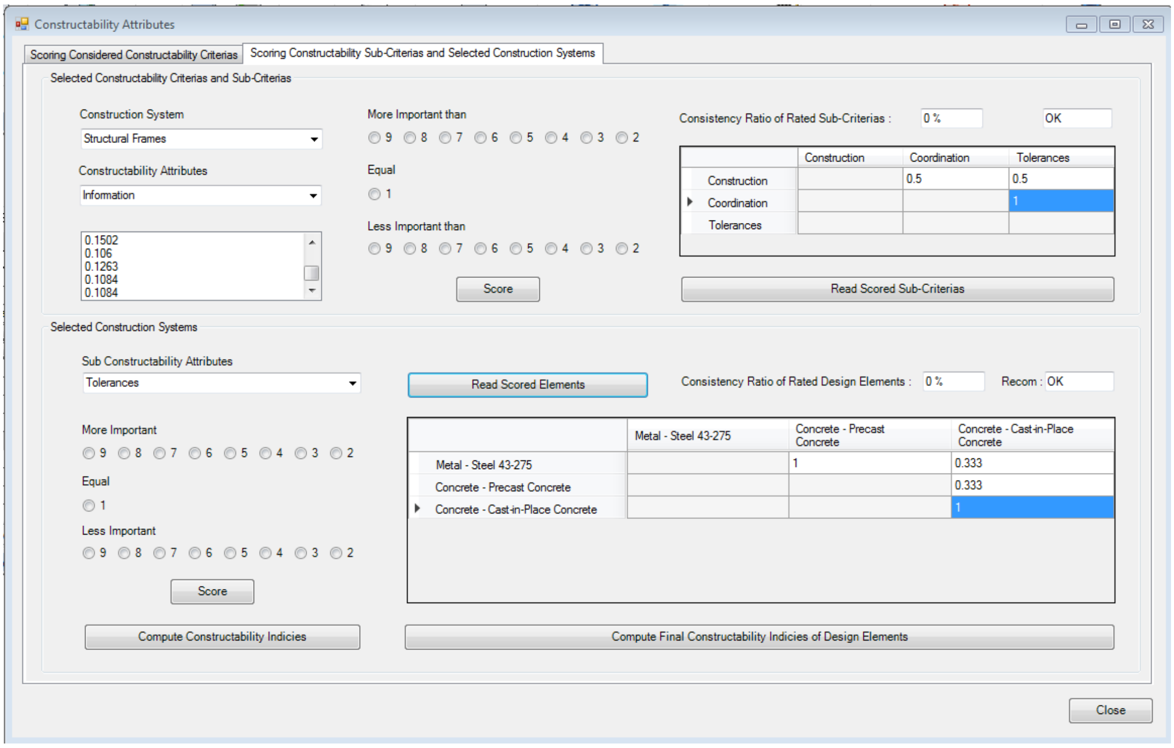
Structural Frames:



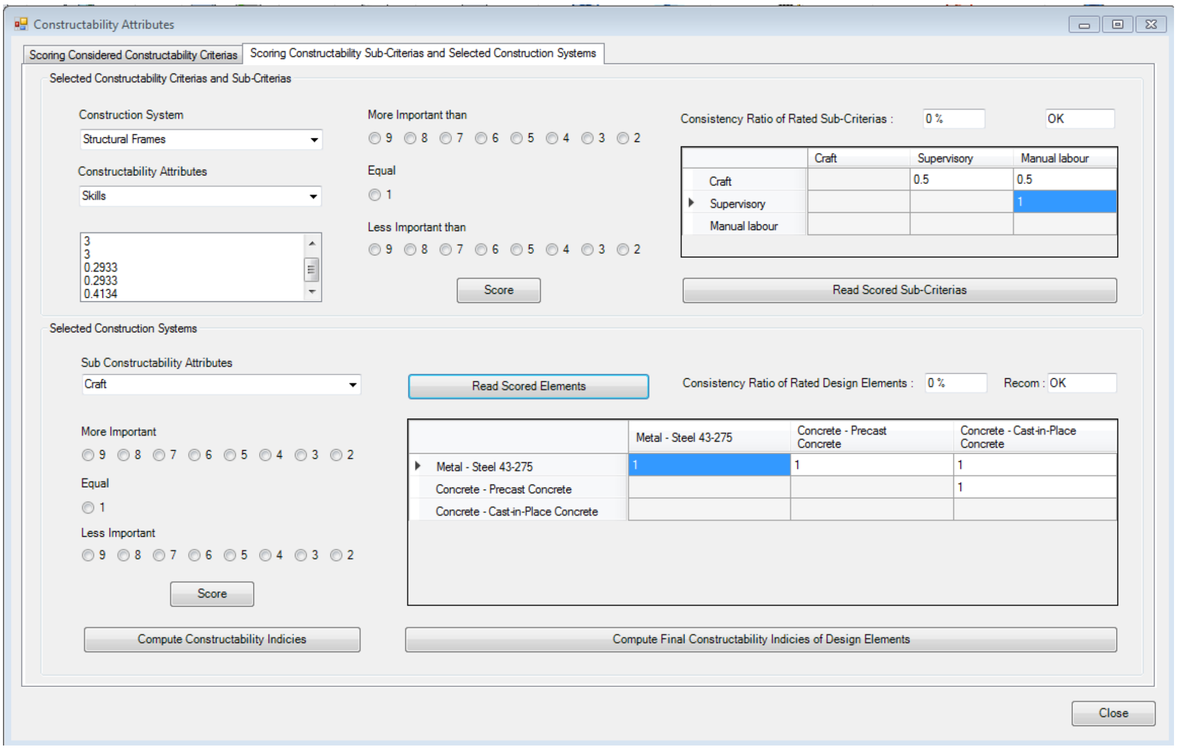
*Scoring **Structural Frame options** with respect to **Construction** branch sub-criteria clustered under **Information** criteria*



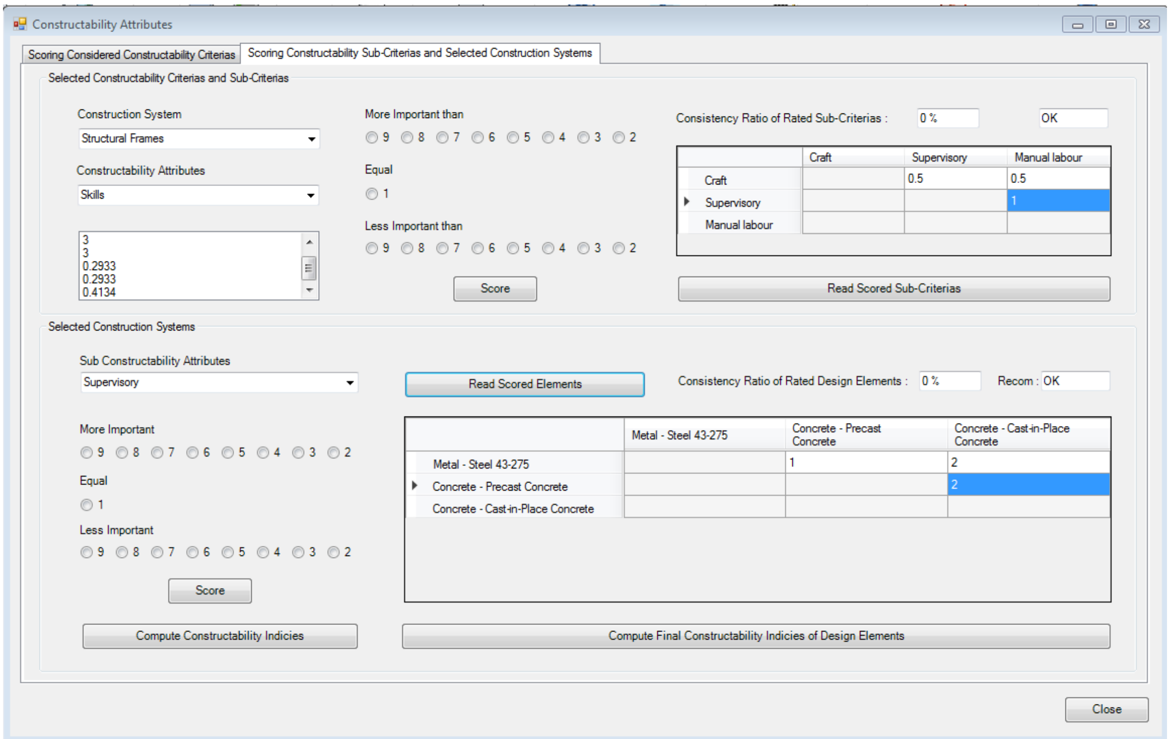
*Scoring **Structural Frame options** with respect to **Coordination** branch sub-criteria clustered under **Information** criteria*



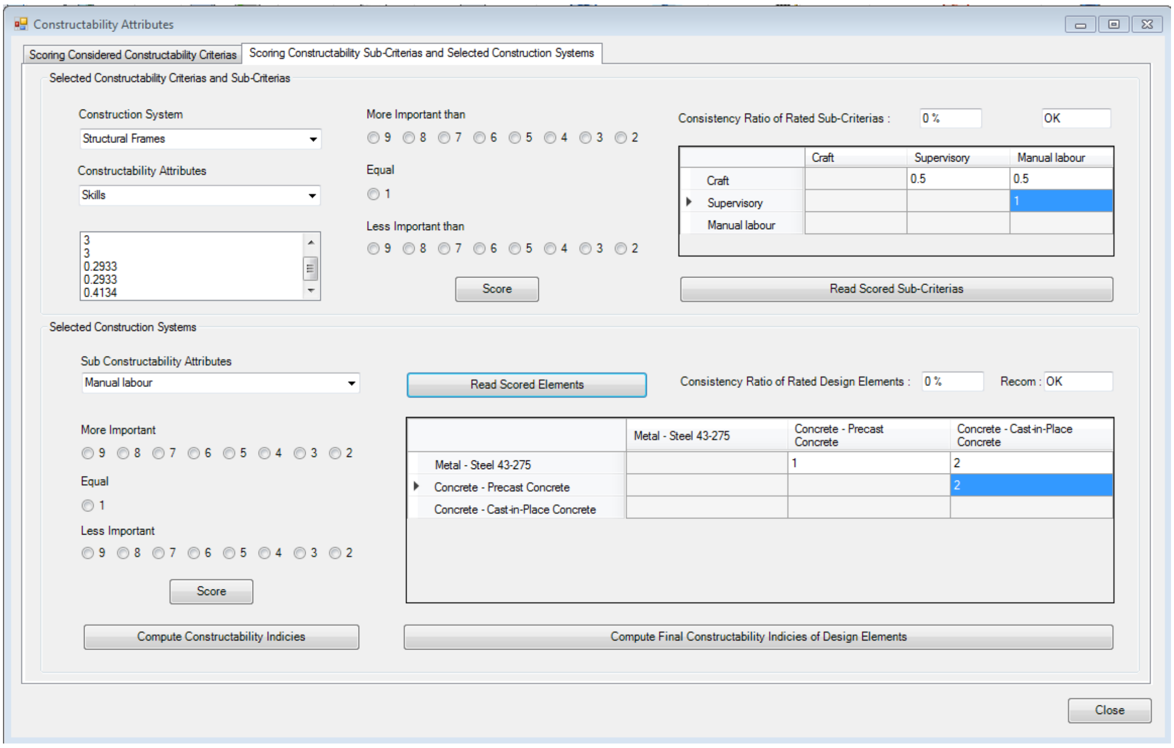
Scoring ***Structural Frame options*** *with respect to* ***Tolerance*** *branch sub-criteria clustered under* ***Information*** *criteria*



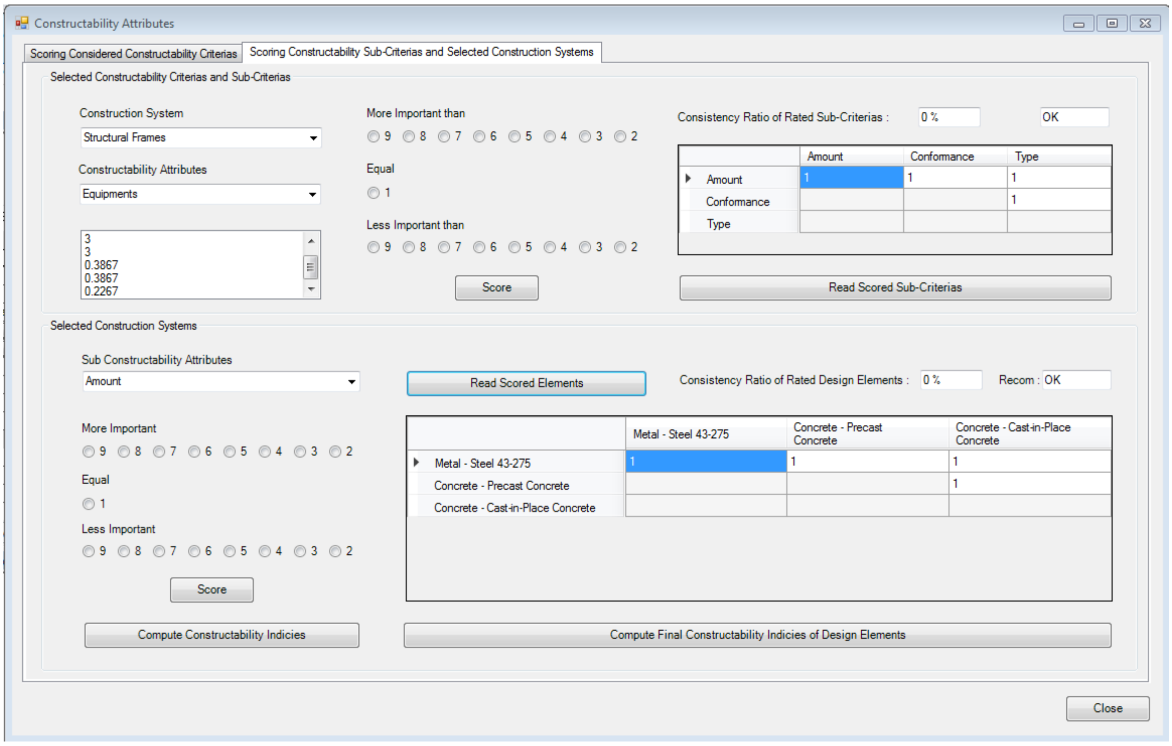
Scoring ***Structural Frame options*** *with respect to* ***Craft*** *branch sub-criteria clustered under* ***Skills*** *criteria*



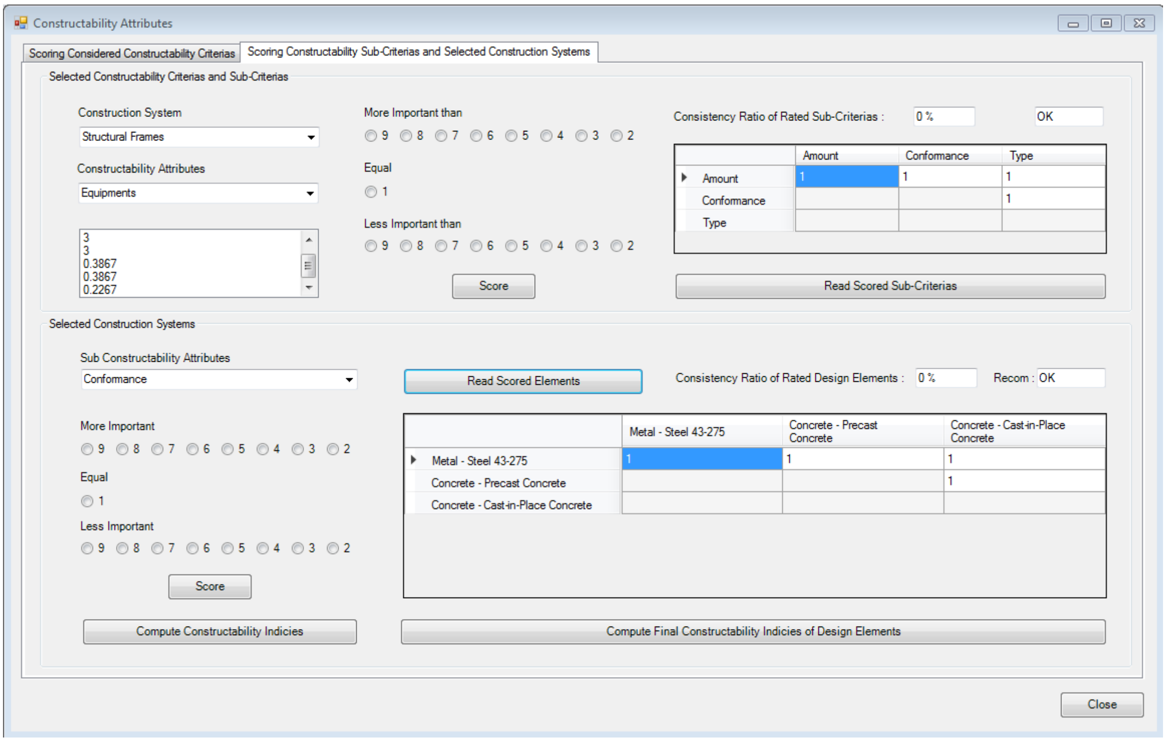
Scoring ***Structural Frame options*** *with respect to* ***Supervisory*** *branch sub-criteria clustered under* ***Skills*** *criteria*



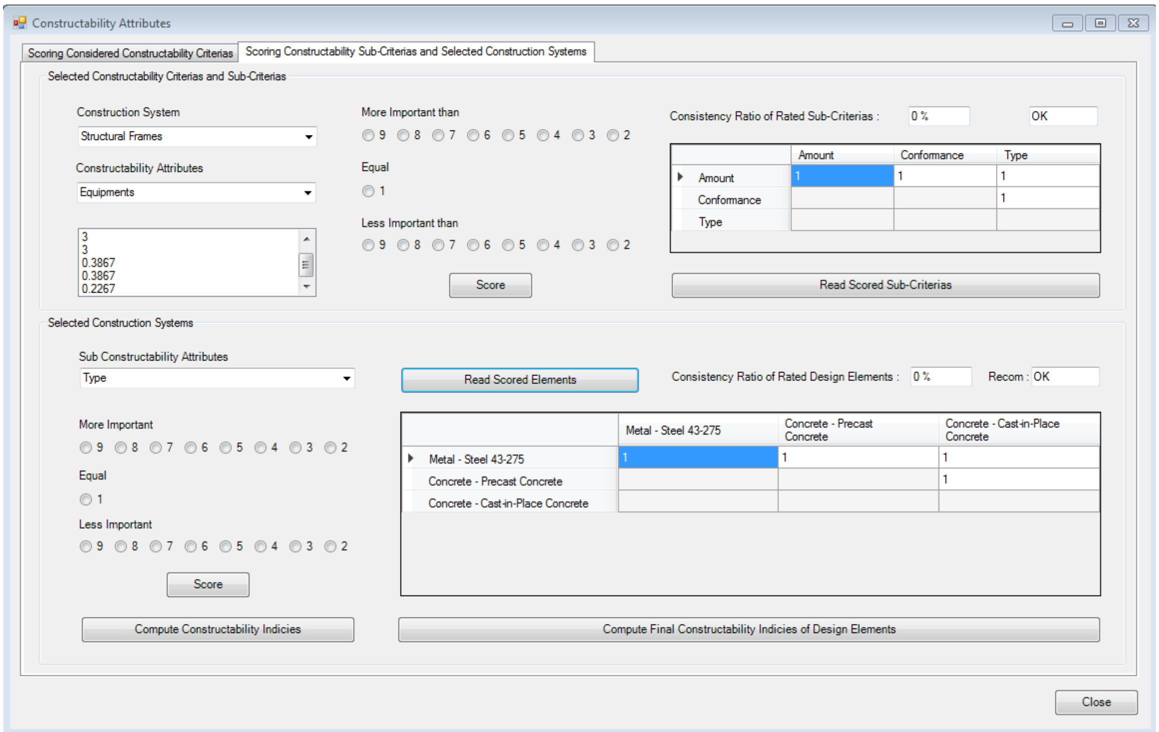
Scoring ***Structural Frame options*** *with respect to* ***Manual labour*** *branch sub-criteria clustered under* ***Skills*** *criteria*



*Scoring **Structural Frame options** with respect to **Amount** branch sub-criteria clustered under **Equipment** criteria*



*Scoring **Structural Frame options** with respect to **Conformance** branch sub-criteria clustered under **Equipment** criteria*



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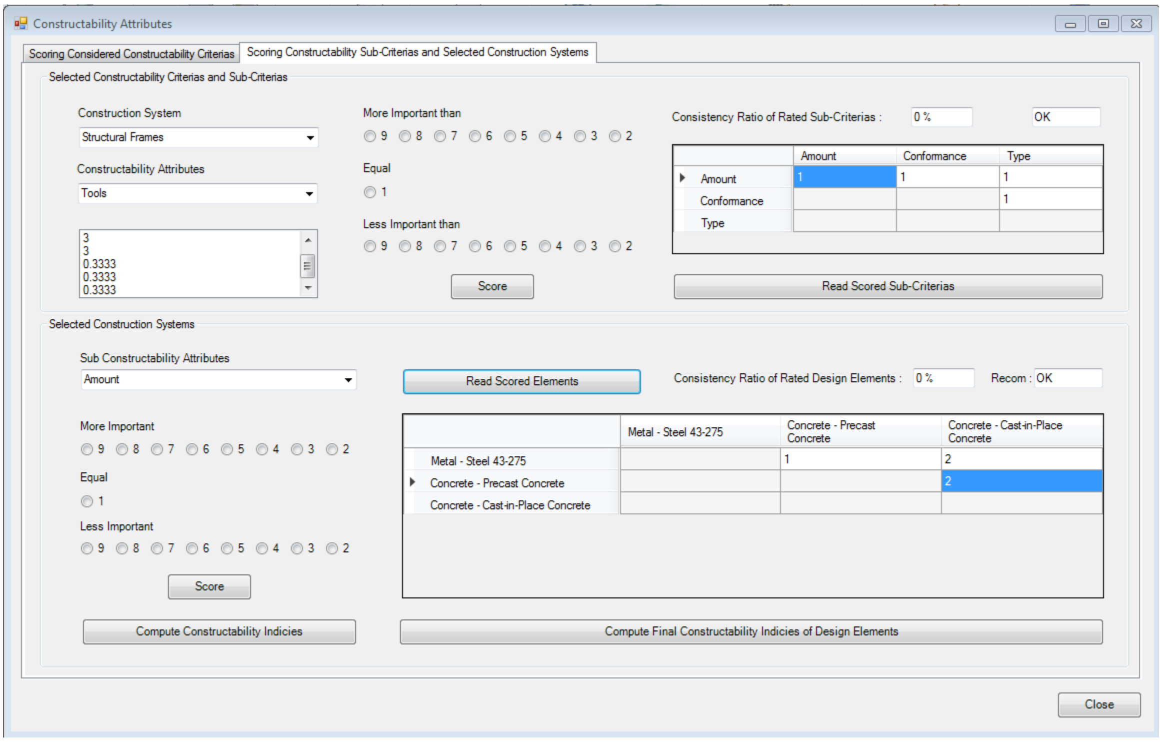
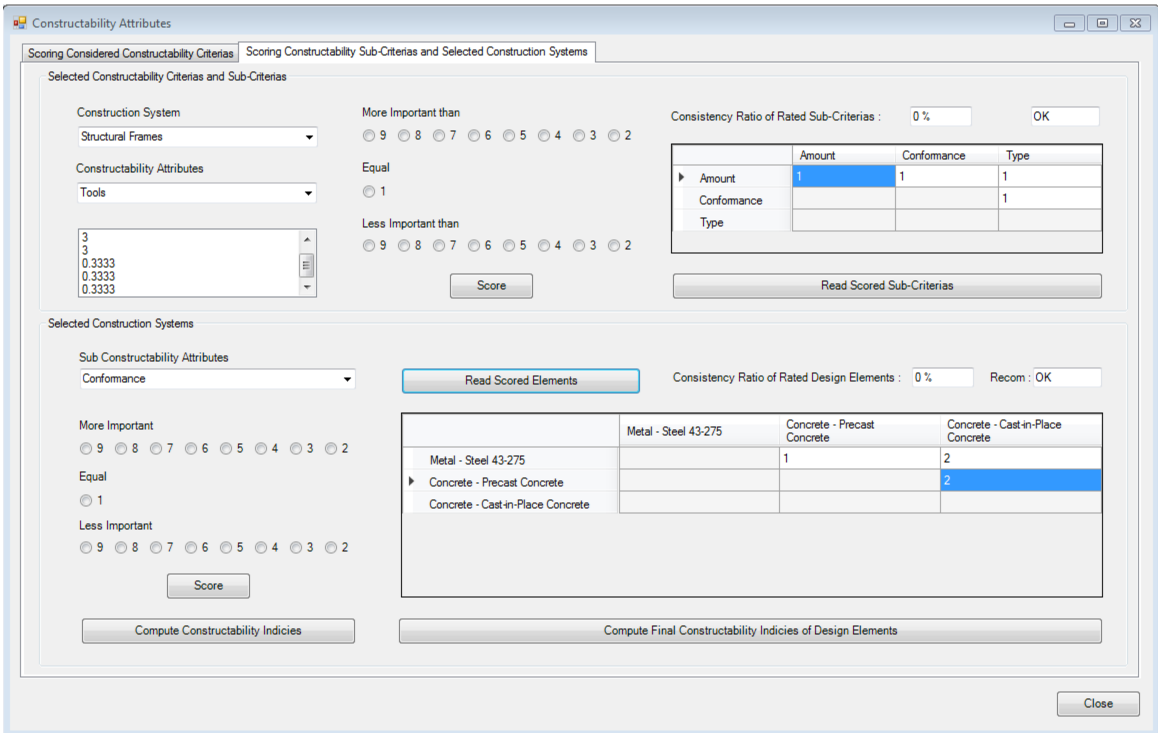


*Scoring **Structural Frame options** with respect to **Amount** branch sub-criteria clustered under **Tools** criteria*



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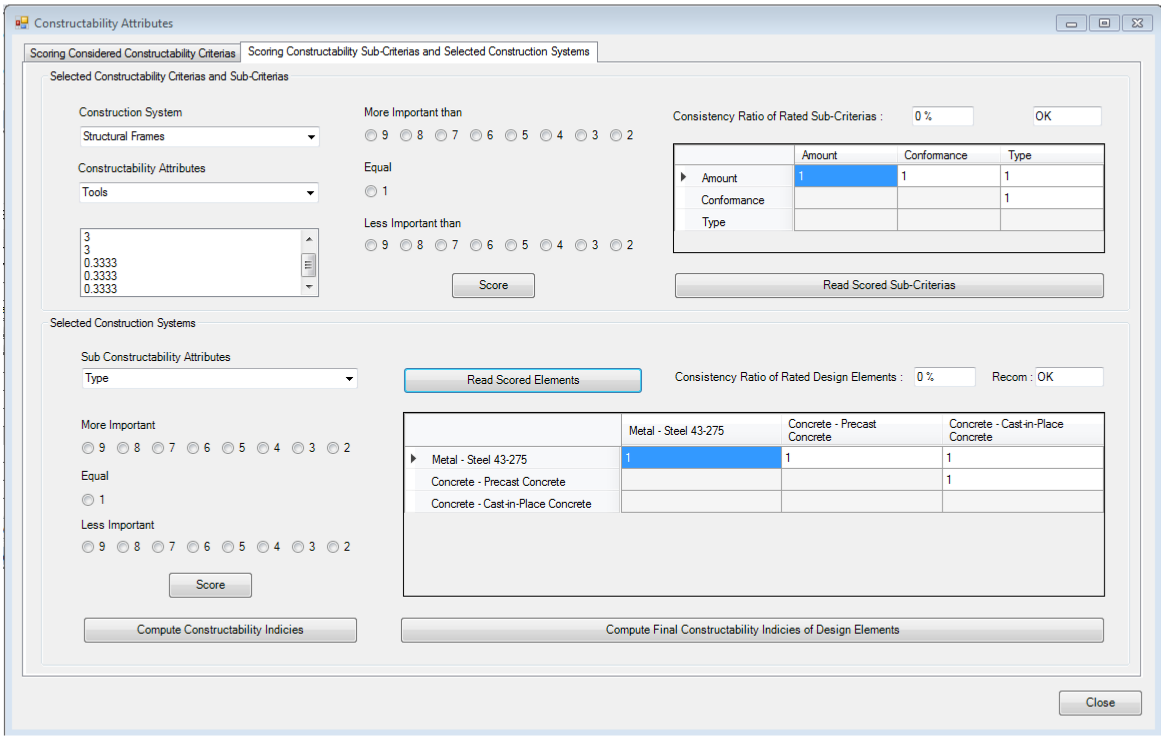

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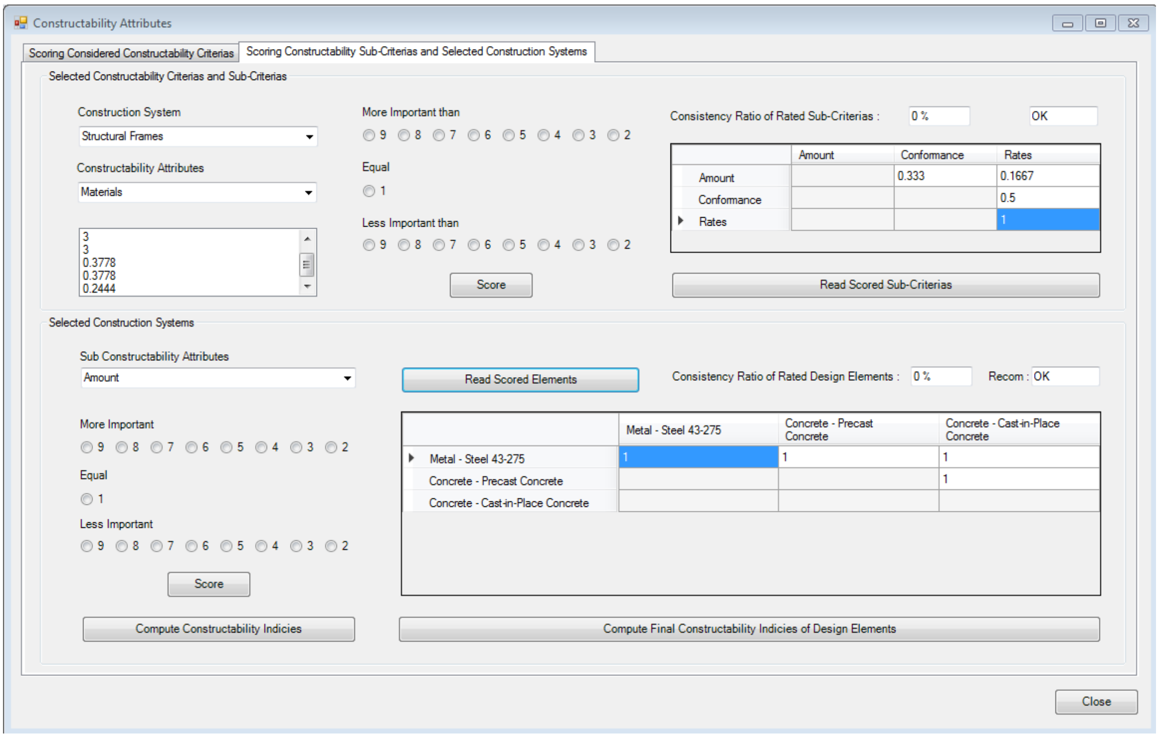
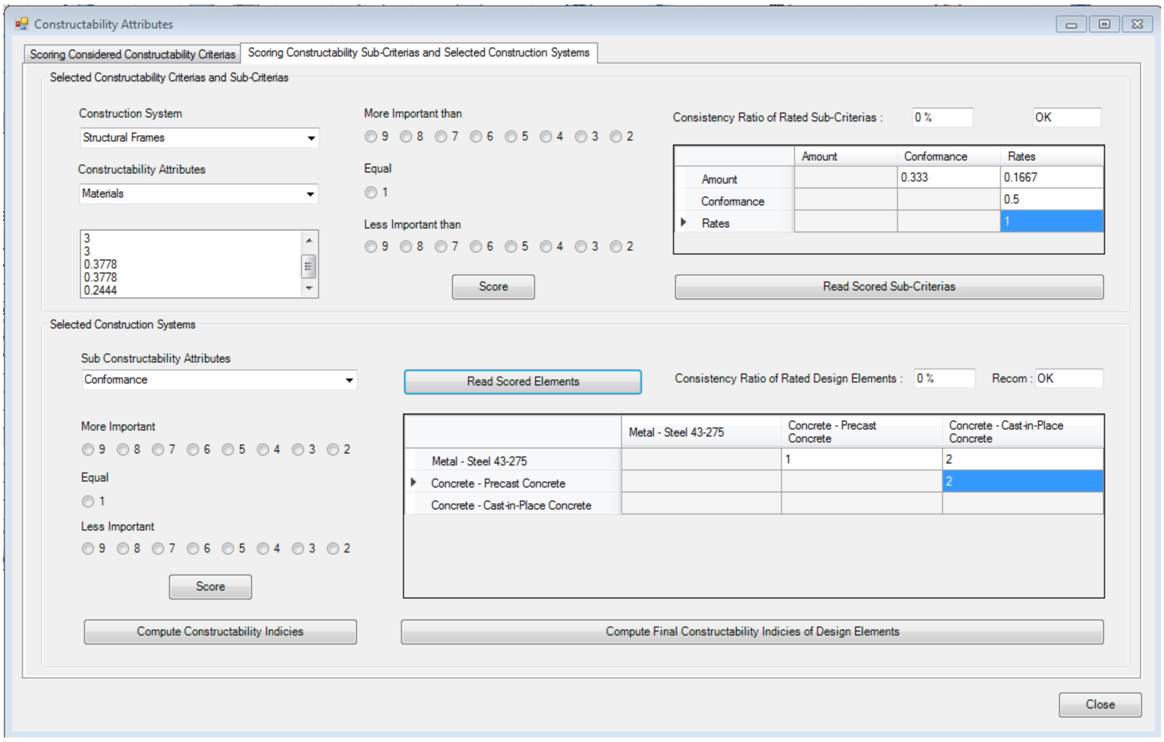
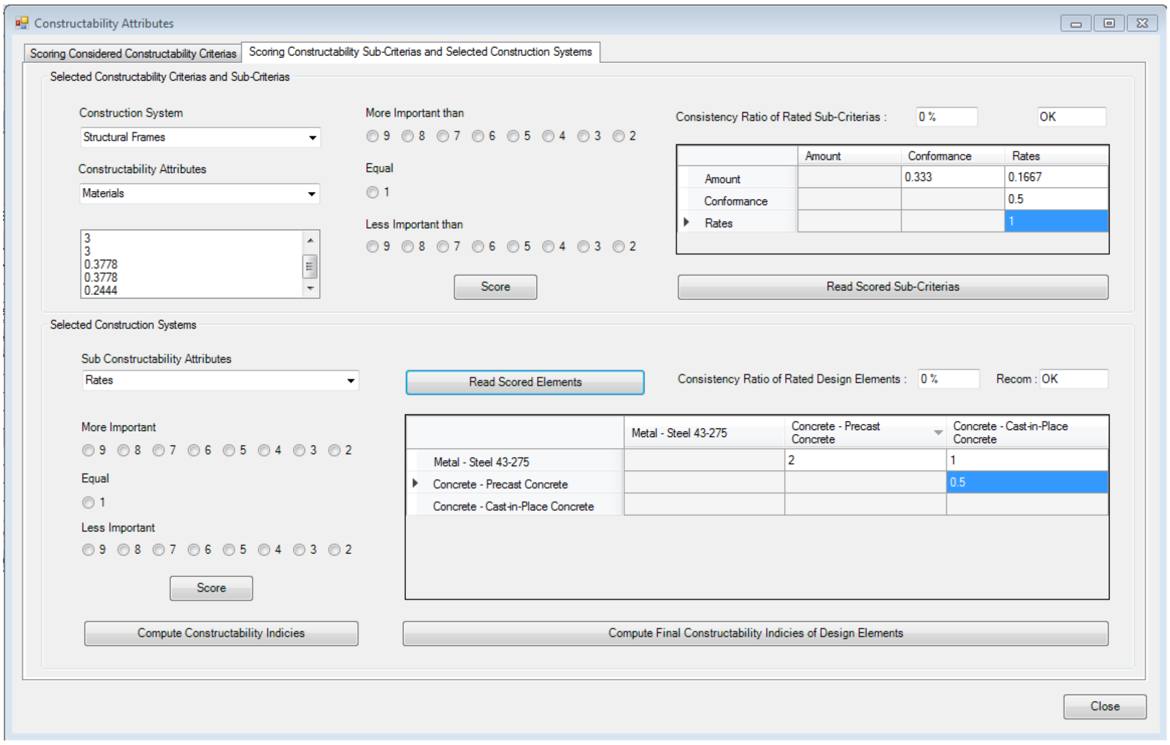


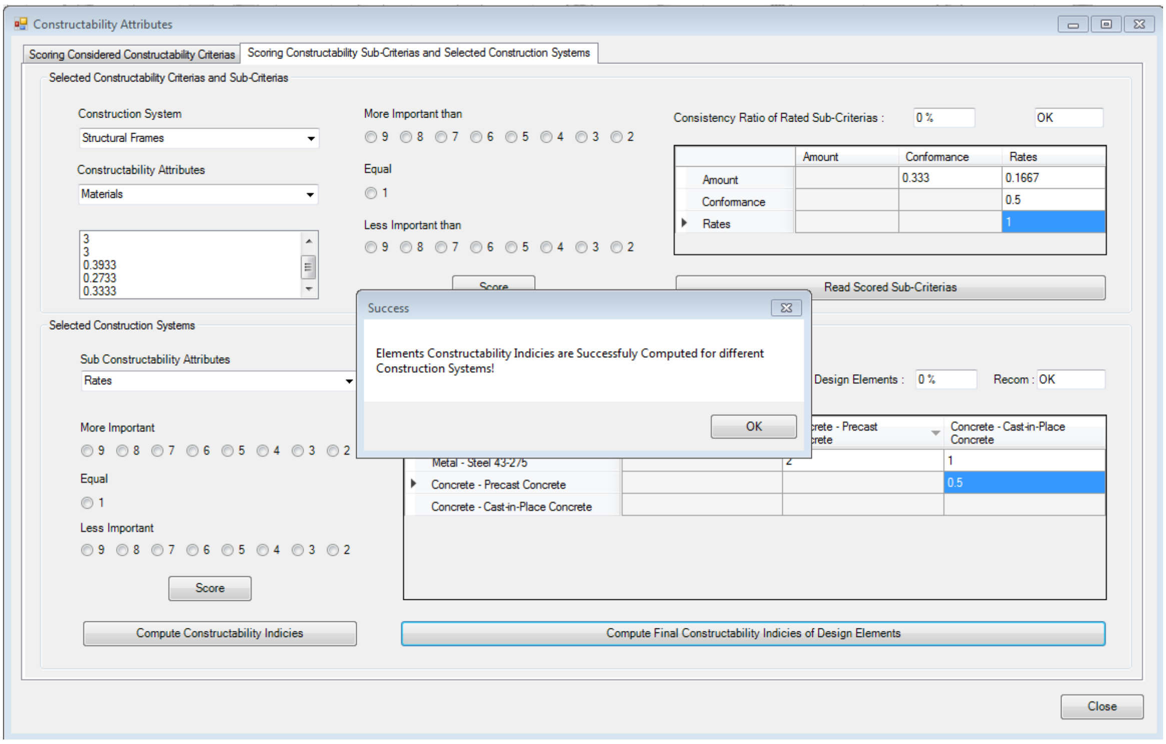
Scoring ***Structural Frame options*** *with respect to* ***Amount*** *branch sub-criteria clustered under* ***Materials*** *criteria*



Scoring ***Structural Frame options*** *with respect to* ***Conformance*** *branch sub-criteria clustered under* ***Materials*** *criteria*



*Scoring **Structural Frame options** with respect to **Rates** branch sub-criteria clustered under **Materials** criteria*



Success message confirming calculation of Constructability Indices for construction systems alternatives

Appendix 3: Focus Group Meeting

Focus group meeting: Issues arising from the use of the BIM-based constructability model.

Issues raised during the meeting	Responses
In a typical project, where you have multiple designers, each of them with their different priorities, how does the tool factor in such differences and priorities when using the AHP to ensure the alternatives meet the criteria objectives, which sometimes have conflicting views?	The system is meant to provide the design team with the means to objectify their subjective views. Ideally, the team should be working together to establish a representative model for their requirements. As mentioned by one of the practitioners, it should prompt discussion among the team where there is a disagreement in specific matters and establish a consistent practice to resolve such disagreements.
When customising a new constructability model, one participant commented on the initially provided information, particularly concerning the type of building the model is suitable to assess. They were concerned that typical designs involve a combination of materials rather than only one option to be decided.	This information is just a description of the model and does not impact the assessment outcomes. It is intended to facilitate the reusability of the model by establishing a tagging system or using keywords. Specific to the type of building, whether it is concrete or steel, etc., this should describe the main structural system used in the majority of the building in terms of slabs, beams, and columns. However, if users find it difficult to assign a specific category, they can always come up with a categorisation approach to distinguish the building from others, beside those already included (name, location, etc.)
Can the tool operate on other platforms apart from Revit Software?	The assessment framework is built upon extracting its inputs directly from BIM models. This requires BIM authoring tools that support object-based modelling features. For this study, Autodesk Revit software was employed to host the implemented prototype, because of its popularity compared with other BIM tools in the UK. However, the proposed framework is valid to be implemented with other BIM tools due to its generic conceptualisation and design.
Is the scope of using the tool just during the design stage?	The model can be utilised during the design stage as well as to support activities that take place prior to the construction phase. As highlighted in Table 4-4, this could include contractors and sub-contractors using the tool to measure their capability to build a specific design and establish the feasibility to bid for

	it, or to identify critical aspects in the project to develop contingency plans and avoid risks, if they are already selected to build it.
In the complexity part, are the developed descriptive equations embedded within the implemented system, or should they be established by the design team?	The current formulas have been developed based on common knowledge and best practice with regard to constructible design as a test of how subjective constructability attributes can be objectified to produce tangible indicators. The users are also provided with the opportunity to amplify the importance of specific aspects which they see as more important by overriding the weighting factors.
The relation between the BIM model and the knowledgebase.	Relationship is the BIM model is used to extract the features that are relevant for the constructability assessment. The CM AHP tables require quantities and types of used construction system to establish the score of AEC Systems module. The CM rules and constraints extract related parameters values within the model (sizes, dimensions, weights, etc.) to validate their satisfaction. The CM complexity formulas extract properties of design elements (e.g. columns type and numbers, connections, etc.) to establish the design complexity. The CM location constraints extract values of restricted parameters (e.g. limitations in components dimension due to transportation requirements) to establish their satisfaction.
One participant mentioned that the sustainability aspect is not included in the scope of the assessment.	The featured design objectives in the demonstrated example are only examples of what criteria the user can define to enable the decision-making. In fact, this query was answered by one of the participants during the session. He mentioned that sustainability is considered among the attributes when scoring various construction systems, instead of being a design objective.

Appendix 4: Evaluation Questionnaire

EVALUATION QUESTIONNAIRE: A BIM-BASED APPROACH FOR CONSTRUCTABILITY ASSESSMENT OF BUILDINGS DESIGN

1. Your role:

2. Work experience in years:

3. General impression:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The system takes reasonable efforts to conduct the assessment	○	○	○	○	○
The system is capable of informing decision on constructability:	○	○	○	○	○
The system enables to compare constructability of design alternatives:	○	○	○	○	○
The time spent on constructability assessment is acceptable	○	○	○	○	○

4. Satisfaction for implementation requirements:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The system is easy to use	○	○	○	○	○
The system is generic and valid for various prospective users:	○	○	○	○	○
The system displays a good degree of flexibility in operation	○	○	○	○	○
The system is comprehensive in assessing various constructability aspects	○	○	○	○	○
The system is scalable in considering various buildings size, shape and dimensions	○	○	○	○	○
The delivered assessment outcomes reflect design constructability status	○	○	○	○	○
The delivered assessment outcomes lead to improve designs constructability	○	○	○	○	○

5. Will the proposed system affect design decisions for constructability considerations?

6. What are the potential challenges to adopt the proposed system?

7. Will the proposed system have impacts on improving the construction industry performance?

8. Which features of the system did you find particularly useful?

9. What features do you recommend being added to the proposed system?

10. Any other comments?

Thank you