Computational BIM-based Framework for Sustainable Material Assessment in Green Building Projects

Taki Eddine Seghier
Department of Architecture, FAB, Universiti Teknologi Malaysia (UTM)
Johor Bahru, Malaysia
segatakieddine@gmail.com

Yaik-Wah Lim
Department of Architecture, FAB, Universiti Teknologi Malaysia (UTM)
Johor Bahru, Malaysia
limyaikwah@gmail.com

Mohd Hamdan Ahmad
Department of Architecture, FAB, Universiti Teknologi Malaysia (UTM)
Johor Bahru, Malaysia
drmedan@gmail.com

***Abstract*— Building materials selection process become dependent on many variables related to sustainability. These variables are often correlated and require complex calculation to be assessed. Material reuse, recycled materials, regional materials and Concrete Usage Index (CUI) are the common sustainability criteria related to building materials that have been adopted by the different green rating tool available in Malaysia. Currently, sustainable material assessment is achieved either by manual calculations or semi-automated methods based on material take-off functionalities provided by the BIM tools. Both of these methods require repetitive and manual inputs which make them relatively time-consuming. Therefore, this paper aims to tackle the current challenges by developing a computational BIM-based framework for sustainable material assessment (SMA-Framework) in green building projects specifically for the Malaysian context. The development of the SMA-framework started by interpreting the sustainability criteria of building materials available in the green building rating tools to BIM-based rules. Then, based on these rules, the functionalities of Revit and Dynamo are explored to extract the required data from the BIM model. Based on these findings, a tool for Concrete Usage Index (CUI) assessment is developed and tested in case study building. The developed framework and tool are designed to support project team in the assessment of sustainable materials with more flexibility and automation compared to the conventional methods. This study serves as proof of concept that sustainable building material assessment can be automatically processed through customized workflows developed using computational BIM technologies.**

Keywords*— *Dynamo, automation, green building rating, Green BIM, material selection

I. INTRODUCTION

The building industry has been heavily criticized for being one of the largest contributors to the environmental degradation and global warming [1]. As a result, it is urgent for building stakeholders to act against these environmental impacts by adopting sustainable practices in building design [2]. In light of this issue, several terms have become increasingly adopted by architects to describe their projects and design approaches such as "green building" and "environmentally friendly building" [3].

Green building rating systems consist of quantitative and qualitative criteria created for the evaluation of building performance and the guidance of green buildings design and construction [4]. Building Research Establishment Environmental Assessment Method (BREEAM) is the first green building rating system which was founded in the U.K in the 1990s followed by several other rating systems such as Haute Environmental Quality (HQE) in France in 1996 and the Leadership in Energy and Environmental Design (LEED) in US in 2000 [5]. Nowadays, numerous new green rating systems have been adopted in many other countries. For instance, Singapore has developed Green Mark in 2005, while GreenRE and Green Building Index (GBI) have been established in Malaysia in 2009 and 2013 respectively.

Design decision-making in green building projects is often very time consuming due to the fact that collecting, managing and documenting the relevant data is a very labour process [4,6–9]. For instance, materials selection in green buildings become dependent on several new sustainability criteria and regulations, such as materials embodied energy, carbon emissions, Concrete Usage Index (CUI), regional material, etc. It is not easy to predict the effects of material choices on the overall building sustainability, especially in the early stages of building design [10]. For example, one material choice could achieve a good thermal performance of the building indoor environment. However, the same choice could have a huge impact on the environment. Therefore, building practitioners need more sophisticated methods and tools to assist them in material selection and grip the complexity of design decision-making under the criteria of sustainability.

A remarkable investment and effort have been devoted by many countries around the world including Malaysia for the adoption of Building Information Modelling (BIM). With the advent of BIM technology, the automation of building sustainability compliance checking according to the rating criteria becomes achievable [9]. Thanks to the BIM software and its parametric capabilities that can be manipulated through visual programming tools (VPL). Accordingly, many repetitive tasks in the BIM-based design process can be automated by developing scripts that are able to interact with the BIM authoring tool via its Application Programming Interface (API). Therefore, a framework that supports the assessment of building sustainability using computational BIM could automate the assessment and rating process. This research focuses only on materials criteria and requirements under GBI and GreenRE rating tools. Hence, it aims at developing a computational BIM-based framework for sustainable material assessment (SMAF).

A. *BIM for Sustainability Analysis*

Previous studies have argued that BIM technologies are able to support compliance with building sustainability rating criteria [4,9,11]. Kriegel and Nies [3] claimed that BIM can support sustainable design in many aspects which include building orientation optimization, daylighting analysis, energy modeling and sustainable materials selection. By using BIM technologies, building model is constructed digitally and loaded with different type of information that can support design decision making and analysis through building lifecycle. Various BIM-based Frameworks, models, and tools have been developed as a part of integrating BIM technologies to support green building performance assessment and rating. For instance, [8], [12] and [13] have developed a Revit-based green template to support the assessment of the different sustainability analysis such as the embodied energies of building materials and the Overall Thermal Transfer Value (OTTV). In these studies, "Material take-off" of Revit is the main functionality that has been used to develop the green template. This method is efficient in term of accuracy, however, it is not flexible because schedules in Revit cannot be combined in Revit, moreover it is relatively time-consuming because it is not fully automated.

Lim [14] developed a BIM-based framework for sustainable building design process and decision-making support. The framework covers the main criteria related to building design process (building massing, building envelope, building structure, and building interior). It guides the user through the design process in making a design decision based on BIM model Level of Development (LOD), design variable/objective(s) and the BIM tool. On the other hand, [7] and [9] proposed two BIM-based tools for building sustainability assessment which are integrated to BREEAM and BEAM plus certifications respectively. Both these tools extract the required data from the BIM model and then, the data is processed through several steps to reach the final score of specific sustainability criteria.

Table I shows the main sustainable material criteria adopted by two widely used green building rating tools in the Malaysian building industry namely: Green Building Index (GBI) and GreenRE.

TABLE I. THE MAIN SUSTAINABLE MATERIAL CRITERIA IN GREEN BUILDING INDEX (GBI) AND GREENRE

<table>
<tr><th>Green building Rating Tools</th><th>Sustainable Material Criteria</th><th>Objective</th></tr>
<tr><td rowspan="5">Green Building Index (GBI)</td><td>(M-1) Materials reuse and selection</td><td>To reuse building materials and products, hence, to reduce demand for virgin materials and waste.</td></tr>
<tr><td>(M-2) Recycled content materials</td><td>To increase demand for building products that incorporate recycled content materials.</td></tr>
<tr><td>(M-3) Regional materials</td><td>To increase demand for building local materials and products.</td></tr>
<tr><td>(M-4) Sustainable timber</td><td>To encourage environmentally responsible forest management.</td></tr>
<tr><td>(M-5) Storage & collection of recyclables</td><td>To facilitate the reduction of waste, generated during construction and during building occupancy</td></tr>
<tr><td rowspan="2">GreenRE And Green Mark (Singapore)</td><td>(M-6) Sustainable and recycled materials usage</td><td>To encourage the use of Green Cements with approved industrial by-product to replace Ordinary Portland Cement (OPC).</td></tr>
<tr><td>(M-7) Concrete Usage Index (CUI)</td><td>To encourage the use of environmentally friendly materials in concrete such as ash, etc.</td></tr>
</table>

B. *Computational BIM*

Computational Building Information Modelling (BIM) is a design paradigm grounded on the use of algorithms and BIM-based rules for data extraction and management to meet design objectives and user needs. Often computational design is performed in building design using visual programming languages (VPL) tools such as Grasshopper and Dynamo to mention few. Taking Dynamo example, this tool allows the user to manipulate the geometric and metadata embedded in BIM model within Revit. Hence, automates repetitive tasks, and create efficient workflows to solve complex design problems.

Kensek [15] argued that using VPL in green building design would support sustainability analysis in the early stages of the design process. Several studies [15–20] implemented

Visual Programming tools to create frameworks and workflows for building performance analysis. For instance, Konis et al [18] have developed a framework for building passive performance optimization in the early design stage. The framework implements a simulation-based parametric modeling workflow able to optimize several variables of building envelop configuration according to predefined design objectives. In this workflow, Grasshopper has been used as the visual programming tool to manipulate design variables and run the optimization. Several other studies have implemented Visual Programming tool for building performance analysis such as Energy Efficiency and daylighting optimization [19], structural analysis [21], acoustical analysis [22] and building envelope performance assessment [20].

II. METHODOLOGY

A research methodology of three main stages has been adopted for the development of the computational BIM-based framework for sustainable material assessment (SMAF). Firstly, the requirements of sustainable building material assessment were collected from green building rating tools, mainly GBI and GreenRE. Then, these requirements were interpreted to logics for credit allocation (design objective) and variables which will support the development of the BIM-based rules for data extraction process. The second stage consisted of the exploration of possible workflows for automation through Revit Material Take-off functionality and Dynamo scripting along with the preparation of Revit by adding the necessary parameters according to each sustainable material criteria. By combining the finding of the previous two stages, a computational BIM-based framework of sustainable material assessment (SMAF) was developed. Finally, a part of the developed SMA-Framework was further developed as a tangible tool for Concrete Usage Index (CUI) assessment, then tested on a case study building for preliminary validation purpose.

III. COMPUTATIONAL BIM-BASED FRAMEWORK FOR SUSTAINABLE MATERIAL ASSESSMENT (SMAF)

A. Sustainable Material Requirements Interpretation

A key step in the development of the SMA-framework is the interpretation of the requirements related to materials criteria to BIM-based rules. Several scholars adopted this approach in similar researches related to BIM application in sustainability such as Wu [4] and Kasim [23]. Thus, the relevant green building certification and guides are reviewed and the required data related to material assessment is extracted. As shown in Table II, Seven sustainable material criteria (M1, M2, M3, M, 4, M5, M6, and M7) have been selected and interpreted to two key elements as follows:

- Credit allocation logics/Design Objective;
- Required variable for data extraction

The required variables consist of the data that should be extracted from the BIM model in order to perform the necessary calculations. Whereas, credit allocation logics are the rules that will be applied to weigh a given assessment result by the relevant credit points.

B. SMA-Framework Development

Based on the interpretation of material requirements illustrated in Table II, the BIM authoring tool (Revit) was prepared to host the required parameters and relationships between the variables and logic were identified. As shown in Table III, several new parameters (Shared parameters) have been added to each materials using Revit Material browser. All the new parameters are assigned as Boolean (yes/no) type, this will help in the filtration of the unnecessary data during the assessment process.

Data extraction can be proceeded using material take-off functionality of Revit (Semi-automated method) or by using Dynamo to create costume scripts (Automated method). By implementing the second method, the user has to create several scripts using Dynamo for each material criteria. These scripts should be created based on data extraction process described in the SAM-Framework (Table III). More details about this method are explained in the SAMF validation part.

C. SMA-Framework Application

The SMA-Framework responses to the complexity of gathering the information related to sustainable materials within building components through BIM technologies capabilities. It can be used to guide the project team during the assessment of sustainable materials criteria. This BIM-based framework shows the required data and variables of each material sustainability criteria and the required steps to perform the relevant data extraction process from the BIM model. For instance, in order to assess the local material usage in the project, the user will create a material take-off schedule, then, only local materials are ticked using the new Boolean parameter (yes/no) assigned for them, hence, only their data will be included in the calculation process. The main BIM functionality used in this framework is "Material Take-off" of Revit. This functionality is not fully automated, hence it is relatively time-consuming and requires manual input to be accomplished, such as filtering, grouping, etc. The second option, the SAM-Framework can be used as a guide for the development of Dynamo scripts to automate the different tasks related to the assessment of each material criteria.

Table II. SUSTAINABLE MATERIAL REQUIREMENT INTERPRETATION

Sustainable Material Criteria	Credit allocation logic/ Design objective	Required variables for calculation
Green Building Index (GBI-Non Residential Building)		
M-1	V1 ≥ 2%V2; score: 1 credit point V1 ≥ 5%V2 ; score: 2 credit points	(V1) Reused products/materials total cost (RM) (V2) Project's total material cost value (RM)
M-2	V1+½V2 ≥ 10%V3; score: 1 credit point V1+½V2 ≥ 30%V3 ; score: 2 credit points	(V1) Post-consumer recycled materials total cost (RM) (V2) Pre-consumer content total cost value (RM) (V3) Project's total material cost value (RM)
M-3	≥ 50% of V2 satisfy (V1); score: 1 credit point ≥ 75% V2 satisfy (V1) ; score: 2 credit points	(V1) Local material (V2) Total material cost (RM)
M-4	Credit allocation logic: V2/V1≥ 50%; score: 1 credit point V2/V1≥ 75%; score: 2 credit point	(V1) Wood-based material total cost (V2) Certified* Wood-based material total cost *Certified by Forest Stewardship Council (FSC), OR Malaysian Timber Certification Scheme (MTCS).
M-5	V1/ V2 ≥ 50%; score 1 credit point V1/ V2 ≥ 75% ; score 2 credit point	(V1) Recycle and/or salvage material volume (m^3) (V2) Volume of non-hazardous construction debris (m^3)
GreenRE & Green Mark (Non Residential Building)		
M-6	V2/V1= 10%; score 1 credit point V2/V1= 30%; score 2 credit point V2/V1= 50%; score 3 credit point V2/V1= 70%; score 4 credit point V2/V1= 80%; score 5 credit point	(V1) Ordinary Portland Cement (OPC) volume (m^3) (V2) Green cement volume (m^3)
M-7	0.6 < CUI ≤0.7; score 1 credit point 0.5 < CUI ≤0.6; score 2 credit point 0.4 < CU I ≤0.5; score 3 credit point 0.35 < CUI ≤ 0.4; score 4 credit point CUI ≤ 0.35; score 5 credit point	(V1) Total Concrete Volume (m^3) (V2) Constructed Floor Area (CFA) (m^2)

IV. SMA-FRAMEWORK VALIDATION

For validation purpose, a part of the SMA-framework is further developed as a tool for the automation of Concrete Usage Index (CUI) assessment. This tool is then tested on a case study building and the generated results are analyzed and discussed. Even though CUI represents only one requirement of the SMA-Framework, yet it is argued that similar tools can be developed and tested using the same approach implemented for the CUI tool.

A. Concrete Usage Index (CUI) Tool Development.

Based on the finding of the SMA-framework related to CUI requirements (M-7), several BIM-compatible rules for data extraction and management were created along with the preparation of the design environment of Revit to host the new required parameters. Then, two scripts for CUI assessment were developed using Dynamo to streamline the data extraction from the BIM model (See *Fig 1:*). The first script is designed to run a quick assessment of CUI, hence provide the user a quick feedback on the current CUI value and rating score. Based on these results, the user is free to choose between testing another design option and executing the second script to generate automatically the CUI report.

The CUI assessment tool workflow is designed to track the concrete volume within the building elements of the BIM model. These scripts are designed to track concrete material

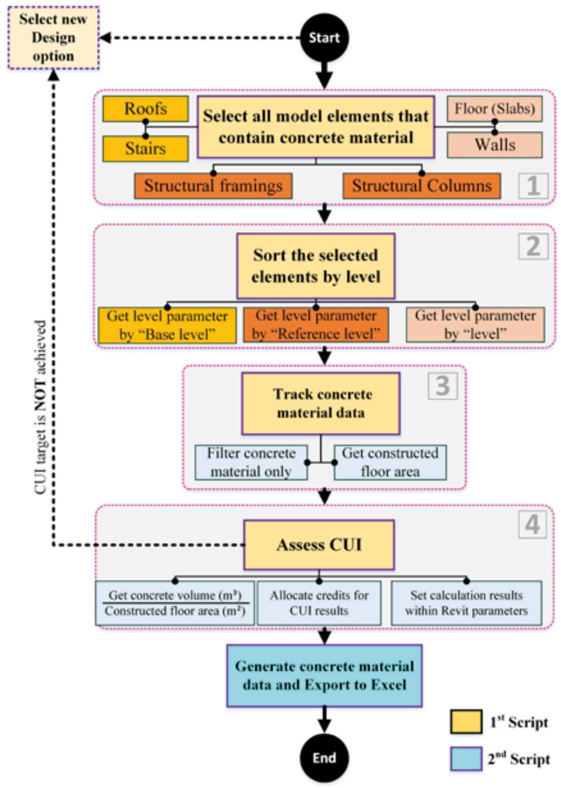

Fig 1: The logic workflow of the developed Dynamo scripts for automated CUI assessment

quantities in each building element and then generate the CUI score and rating in a very short time. This step is essential because it supports decision making regarding concrete use within building elements. Once the CUI target is achieved (e.g. GreenRE Gold certification, CUI ≤0.5) the second script is executed to generate automatically the CUI report. The information related to each building element that contains concrete are exported to an excel spreadsheet ready to be submitted. This tool was tested on case study building that consists of an existing office building of four (4) levels and an area of 7500 m². This building is located in the faculty of built environment at the University of Technology Malaysia

TABLE III. COMPUTATIONAL BIM-BASED SUSTAINABLE MATERIAL ASSESSMENT FRAMEWORK (SMAF)

Criteria	**Variable**	**New Required Parameters**		**Output data type**	**Data extraction process through: Revit Material take-off / Dynamo scripts**
		Parameters Name	**Parameters type**		
M-1	V1	Reused material?	Boolean (Yes//No)	Calculate Cost if Yes	1. Input cost data for each material in the project 2. Calculate the total material cost value used in the project 3. Filter by Boolean only the reused materials and calculate its cost 4. Apply the logic conditions to allocate the scored credits (M1-TABLE II)
	V2	N/A	N/A	Calculate Cost	
M-2	V1	Post-consumer recycled material?	Boolean (Yes//No)	Calculate Cost if Yes	1. Input cost data for each material in the project 2. Calculate the Post-consumer recycled materials cost and Pre-consumer material cost. 3. Filter by Boolean both the Post-consumer recycled materials and Pre-consumer material, then calculate its cost 4. Apply the logic conditions to allocate the scored credits (M2- TABLE II)
	V2	Pre-consumer material?	Boolean (Yes//No)	Calculate Cost if Yes	
	V3	N/A	N/A	Calculate Cost	
M-3	V1	Local Material?	Boolean (Yes//No)	Calculate Cost if Yes	1. Input cost data for each material in the project 2. Calculate the total material cost value used in the project 3. Filter by Boolean only the local materials and calculate its cost 4. Apply the logic conditions to allocate the scored credits (M3- TABLE II)
	V2	N/A	N/A	Calculate Cost	
M-4	V1	N/A	N/A	Calculate Cost	1. Input cost data for each material in the project 2. Filter by Boolean only the Wood-based material and calculate its cost 3. Filter by Boolean only the Certified Wood-based material and calculate its cost 4. Apply the logic conditions to allocate the scored credits (M4- TABLE II)
	V2	Certified Wood-based material?	Boolean (Yes//No)	Calculate Cost if Yes	
	V2	N/A	N/A	Recycling bins/ area	
M-5	V1	Recycle and/or salvage material?	Boolean (Yes//No)	Calculate Volume if Yes	1. Calculate the recycle and/or salvage material volume (m³) 2. Calculate the volume of non-hazardous construction debris 3. Apply the logic conditions to allocate the scored credits (M6-TABLE II)
	V2	Non-hazardous construction debris?	Boolean (Yes//No)	Calculate Volume if Yes	
M-6	V1	Ordinary Portland Cement (OPC)?	Boolean (Yes//No)	Calculate Volume if Yes	1. Filter the Ordinary Portland Cement (OPC) material used in the project, then, calculate its volume (m³) 2. Filter the green cement material used in the project, then, calculate its volume (m³) 3. Apply the logic conditions to allocate the scored credits (M7- TABLE II)
	V2	Green cement?	Boolean (Yes//No)	Calculate Volume if Yes	
M-7	V1	N/A	N/A	Calculate Concrete Volume	1. Filter by name the concrete material used in the superstructure of the project, then, calculate its volume (m³) 2. Calculate the some of the Constructed floor area (m³) (CFA) 3. Apply the logic conditions to allocate the scored credits (M7-TABLE II)
	V2	N/A	N/A	Calculate CFA	

(UTM). The structure of the building is mainly constructed with column and beam system with concrete material. The floor slabs and stairs are mainly built of concrete material as well. In contrast, most of the exterior and interior walls are built using a brick material. The assessment results using the developed tool generated a CUI = 0.255 m^3/m^2 which is equal to the CUI calculated using Material take-off method. This proofs the workability and accuracy of the developed tool considering its additional advantages that consist of a higher level of automation and short calculation period.

V. Conclusion

This paper has presented the development of a computational BIM-based framework for sustainable material assessment (SMAF) in green building projects. The SMA-Framework supports sustainable material assessment through computational BIM functionalities (Material Take-off and Dynamo scripting). By using this framework, project teams are able to develop their own tools to automate the repetitive tasks during the assessment process of sustainable materials.

A tangible example of a tool for CUI assessment is developed based on the SMA-Framework, then tested on a case study building as proof of concept and for validation purpose. The CUI assessment tool is capable of assessing CUI automatically in a very short time compared to "Material take-off" method. This will support design decision making regarding concrete usage in building design, by allowing the project team to test several design options and check if the intended CUI target has been achieved.

Similar workflows to this study can be adapted to automate different tasks related to building sustainability assessment during the design stage such embodied energies, Co2 emissions, etc. This study serves as a proof of concept that building practitioners are able to automate their design assessment workflows, besides developing their own tools using computational BIM functionalities instead of completely relying on commercial tools which are often very expensive.

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