Automation of Concrete Usage Index (CUI) assessment using computational BIM

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ABSTRACT

Concrete Usage Index (CUI) is one of the very used sustainability criteria related to building materials available in the Malaysian and the Singaporean building standards. Often, CUI assessment is achieved either by manual calculation or semi-automated methods based on Material Take-off functionalities provided by the BIM tools. Both of these methods are relatively time-consuming, error-prone, and require much human intervention. The purpose of this paper is to develop a computational BIM-based tool for the automation of Concrete Usage Index (CUI) assessment and rating, called Auto-CUI. This tool takes advantage of the data embedded in the BIM model and the automated CUI compliance-checking which is developed using a Visual Programing Language (Dynamo for Revit). For validation purpose, this tool has been tested on a BIM model of an existing building and the results were compared with Revit Material Take-off method. Thus, Auto-CUI tool automates the process of data collection, calculation and the generation of the CUI report. In addition to that, the generated results are as accurate as the material take-off method. Auto-CUI will support design decision-making during the design stage by providing an interactive feedback of CUI actual score and rating. Thus, the project team will be able to compare different design options according to the concrete usage. Furthermore, it will allow designers to avoid CUI's cumbersome calculations and inaccurate outputs. Even though, the usage of this tool does not require programming skills, developing this tool further as a plug-in for Revit would be helpful in reducing computation time as well as enhancing the generation of CUI report.

1. Introduction

Building and construction sector has been heavily criticized for being a major contributor to the environmental degradation and global warming (Stadel et al., 2011). As a consequence, it is now believed that building professionals and stakeholders should act in order to alleviate these environmental impacts by adopting sustainable practices in building design (Dixon et al., 2012). The push forward to embrace sustainable practices in the building industry is supported by the establishment of several green building rating systems around the world. These green building rating systems consist of quantitative and qualitative metrics designed to evaluate building performance and guide the design and construction of green buildings (Wu, 2010). 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 (Stephanie Vierra, 2014). Nowadays, numerous new green rating systems have been adopted in many other countries. For instance, Singapore has developed Green Mark in 2005, while GreenRE (GreenRE, 2015) and Green Building Index (GBI) (GBI, 2010) have been established in Malaysia in 2009 and 2013 respectively.

Design decision-making under the green rating system requirements is often very time-consuming due to the fact that collecting, managing and documenting relevant data is a very labour process (Wu, 2010; Wong and Kuan, 2014; Jalaei and Jrade, 2015; Ilhan and Yaman, 2016; Lim et al., 2016). For instance, materials selection in green buildings become depended on several new sustainability indicators and regulations, such as the material's embodied energy, carbon emissions, and Concrete Usage Index (CUI). It is not easy to predict the effects of material choices on the overall building sustainability, especially in the early stages of building design (Trusty, 2003). For example, one material choice could achieve a good thermal performance of the building indoor environment. However, the same choice may have a huge impact on the environment in term of concrete usage index. 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.

Building Information Modelling (BIM) is a recently emerged digital concept and it is considered as one of the most promising developments in Architecture, Engineering, and Construction (AEC) industries. With the advent of BIM technology, the automation of building sustainability compliance checking according to the rating criteria becomes achievable (Wong and Kuan, 2014). Thanks to the BIM software that have opened their Application Programming Interface (API), hence, the user has access to their systems. Accordingly, many repetitive tasks in the BIM-based design process can be automated by developing rules and codes that are able to interact with the API of the BIM tool.

Concrete Usage Index (CUI) is one of the sustainability criteria related to building materials that have been adopted by Green Mark (Singapore) and GreenRE (Malaysia) rating systems. Currently, CUI 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 are relatively time-consuming and require much human intervention. Thus, this paper aims to develop a computational BIM-based tool capable to assess the CUI of a building design and generate the CUI report automatically in a very short duration.

2. Literature review

2.1 BIM for Sustainable Materials Selection

In the past few years, many studies have argued that the application of BIM technologies for green building design has a great potential to support design -making (Wong and Kuan, 2014). By using BIM technologies and tools, building model is constructed digitally and loaded with different type of data that can support design decision-making and analysis through building lifecycle. Kriegel and Nies (2008) claimed that BIM can support sustainable design in various aspects which include building orientation optimization, daylighting analysis, energy modeling, and sustainable materials selection (Krygiel and Nies, 2008). 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, (Kim and Jun, 2013; Lee et al., 2015; Lim et al., 2016) have developed Revit templates to support the assessment of different sustainability indicators such as the embodied energies of building materials and the Overall Thermal Transfer Value (OTTV). On the other hand, (Wong and Kuan, 2014; Ilhan and Yaman, 2016) proposed BIM-based tools for building sustainability assessment integrated to BREEAM and BEAM plus certifications respectively. Both these tools extract the required data from the BIM model and then, this data is processed through several rules and functions to reach the final score of specific sustainability indicators.

2.2 Computational BIM and Visual Programing Language (VPL)

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 construct programmatic relationships using a Graphical User Interface (GUI) (Vandezande and Krygiel, 2015). Thus, rather than writing 'code' from scratch, the user is able to assemble custom relationships by connecting pre-packaged nodes together to make a custom algorithm. This can support project teams in manipulating the geometric and metadata embedded in the BIM model within Revit. Hence, automates repetitive tasks, and create efficient workflows to solve complex design problems. Kensek and Noble (2014) argued that capability of Dynamo in manipulating the parameters of Revit added an extra level of associativity and created new opportunities for cross-platform and cross-discipline collaboration (Kensek and Noble, 2014). Recently, new promising functionalities such as "Dynamo Player" have been included in Revit 2017.1 (Autodesk, 2017). Dynamo Player is designed to allow users without programming skills to execute Dynamo scripts with a click of a button.

Kensek (2015) claimed that Visual Programming Languages (VPL) can support sustainable building design analysis in the early stages of the design process (Kensek, 2015). Several studies (Asl et al., 2011; Kensek and Kahn, 2013; Kensek, 2015; Kim et al., 2015; Konis, Gamas and Kensek, 2016) implemented Visual Programming tools to create frameworks and workflows related to building performance analysis. For example, (Konis, Gamas and Kensek, 2016) developed a framework for building passive performance optimization for the early design stage. The framework implements a simulation-based parametric modeling workflow able to optimize several variables for building envelop configuration. 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 (Asl et al., 2011), Overall Thermal Transfer Value (OTTV) assessment (Seghier et al., 2017), Structural analysis (Makris et al., 2013), Acoustical analysis (Andrea Vannini, 2015) and more. In this area, Edwin Guerra (2014) proposed a simplified problem-solving workflow for Dynamo which covers 3 key steps: identify the problem to explore, develop Dynamo script and explore (Edwin Guerra, 2014). Nevertheless, there is still no comprehensive VPL based model or workflow for building sustainability analysis. In addition, only a few of these studies integrate computational BIM concept into their workflows.

2.3 Concrete Usage Index (CUI)

The reduction of concrete quantities in buildings has many benefits that include cost-benefit, structure weight reduction and cleaner construction site. Building and Construction Authority of Singapore (BCA) has developed Concrete Usage Index (CUI) criteria, which aims at increasing the awareness regarding concrete usage in building projects. Several green rating tools have adopted CUI as a sustainability requirement in order to encourage the project team to use different materials and look for alternative design options. In both Green Mark and GreenRE rating tools, CUI weights up to 5 credit points. This number may seem to be insignificant compared to the total credit points of a rating tool. Nevertheless, CUI is considered as a prerequisite requirement for buildings seeking for gold or platinum certification. This means any project team targeting for these two certifications must achieve a CUI ≤ 0.50m³/m² and ≤ 0.70 m³/m² for gold and platinum certification respectively. In this context, achieving CUI requirement could be even more challenging.

Based on the CUI guide (Keung, 2012), the calculation of CUI consider only the superstructure elements which include structural and non-structural elements. It does not include the concrete used for external works and sub-structural works such as basements and foundations. As shown in Equation 1, CUI is defined as the volume of concrete in cubic meters to cast a square meter of constructed floor area.

$$CUI = \frac{Concrete\ Volume\ (m^3)}{Constructed\ Floor\ Area\ (m^2)}$$

Equation 1 *Concrete Usage Index (CUI) equation (Keung, 2012)*

3. Potential of Full Automation of CUI Assessment

Traditionally, CUI is computed by collecting the relevant data manually from 2D drawings, then, inputting this data into an excel template created for this purpose. This method could be very time consuming especially if the building in question is very large or has complicated forms. Chandra and Zhou (2014) argued that because the collection of data related to concrete quantities is very complicated, this method required design/engineering consultants to spend a week or more on the calculation process. The second method for CUI assessment is based on the use of Material Take-off functionality of the BIM tools such as

Revit. This method is able to extract the relevant quantities of concrete and the Constructed Floor Area (CFA) which are needed for the computation of Concrete Usage Index (CUI), hence it eases the complication of computing the CUI value manually. Nevertheless, this method is still not fully automated. Since most of the BIM software have opened their programming interfaces, tasks such as CUI can be automated by developing a tool able to extract the relevant data from the BIM model according to the CUI compliance (Chandra and Zhou, 2014). Often, BIM-based tools are developed using sophisticated languages such as C# and C++. However, this study explores and implements a visual programing language workflow using Dynamo for Revit for the development of the Auto-CUI assessment tool.

4. Methodology for automated CUI compliance checking

In order to streamline the compliance of CUI requirement and develop a computational BIM-based tool capable of assessing and rating the CUI automatically, a methodology that consists of three stages has been developed as shown in Figure 1. Wu (2010), Lim et al. (2016) and Kasim (2015) have adopted similar approaches in their studies related to the integration of BIM and green building certifications.

Firstly, the requirements of CUI were interpreted based on the sustainability-related regulations available in the relevant literature. In this step, the required parameters for CUI computation and the relationship between them are identified. Then, BIM-compatible rules for data extraction and management were created along with the preparation of the design environment of Revit to host the new parameters. Finally, Dynamo scripts for CUI assessment was developed to streamline the data extraction from the BIM model. The scripts are developed using a mix of Dynamo built-in nodes and several other nodes which are available in the custom packages of Dynamo library such as "Clockwork" and "Archi-lab". For validation purpose, the developed Auto-CUI tool was tested on a case study building and the results were compared with the conventional Material Take-off method.

It is worthy to mention, that there is various BIM software in the market capable to manage the information related to building materials in the BIM model. Though, in this study, Autodesk® Revit® is used as the BIM authoring tools and Dynamo as the Visual Programming tool. Both tools are linked together, hence, all the data in the BIM model can be extracted and managed by developing specific Dynamo scripts.

5. Findings

5.1 Limitations in the current method of CUI assessment

CUI assessment using Material Take-off can be considered as a semi-automated method. Although this method is more efficient compared to
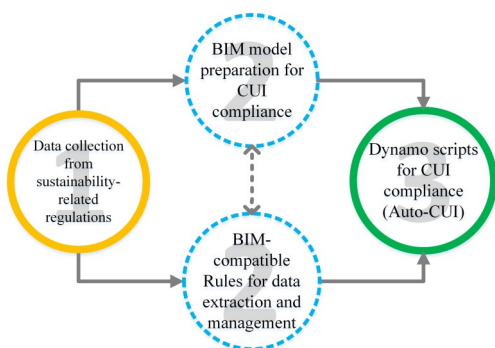

Figure 1 Computational BIM-based workflow for the development of Auto-CUI tool

the manual calculation method, it still requires manual preparation of material quantities schedules of each building component separately. This preparation process includes the execution of filtering, grouping and sorting commands, then concrete quantities are summed up in each building element according to the floor level using an excel spreadsheet. Based on our observation, the Revit® Material Take-off tool has some limitations which are considered as an obstacle for the automation of CUI assessment. These limitations are as fellow:

Material Take-off schedules in Revit are created separately for each building element category. Although its consolidation does not take as long as the modeling process, it is still contributing to the time of the assessment process.

By using Material Take-off functionalities, the calculation results of different schedules cannot be combined between the different element categories. For example, in CUI case, the concrete volume in each elements category has to be summed manually from the relevant schedules to get the total concrete in the project.

The scheduling method is still not suitable for decision-making regarding CUI, because when the project team changes to a new design option, CUI calculation must be carried out again by going through the above tasks (limitations).

Thus, developing Dynamo scripts to overcome the above-stated limitations would increase the automation level and support project team in CUI assessment and rating.

5.2 Auto CUI tool development

5.2.1 CUI requirement interpretation

After reviewing the relevant literature related to the CUI requirement, a coding system that contains the most important quantitative and qualitative items has been developed as shown in Table 1. The outcome of this content analysis will consist the fundamental reference that will enable the development of the required rules for data extraction, which in turn will be used to develop Dynamo scripts for CUI automated-compliance checking. Yet, these required rules have to be developed by taking consideration of the limitation/capability of the BIM authoring tool Revit. Hence, the compliance of Revit and CUI is investigated in the next sub-heading.

5.2.2 Revit-CUI compliance

One of the critical issues to consider in the automation of CUI assessment is that the BIM model must be modeled correctly in order to extract data properly. According to the CUI guide (Keung, 2012), CUI report should contain the quantities of concrete in each level of the building. Technically speaking, this can create an issue related to the elements that span across multiple levels in the design such as columns and stairs. This issue can be solved if all building elements are modeled in each level (elements should not span to more than one level). Another issue that may create errors during data extraction is the naming of the assigned materials in building elements. For instance, a material as concrete should be spelled correctly in the material editor otherwise the volume of this material will not be taken into consideration in the calculation process and this may lead to erroneous results.

In order to provide the user a quick feedback of the building's design CUI value and the rating score during the design stage, three shared parameters have been added to the design environment of Revit namely; CUI (m³/m²), GreenRE/ Green Mark credit points and exclude from CUI calculation (see Figure 2). Shared parameters are the definition of parameters that can be added to families or projects. These

Table 1 *The interpretation of CUI requirement*

| Coding system	Content	Comments/ Rules for CUI automation
Keywords	Concrete Volume, include only superstructure elements (structural and non-structural elements), exclude concrete used in external works and substructural	All concrete of the superstructure should be included in CUI calculation (using grouping and filtering functions)
Equation	$$CUI = \frac{\text{Concrete Volume (m}^3)}{\text{Constructed Floor Area (m}^2)}$$	Concrete has to be tracked in each building element, "Element Material" node from Clockwork package may be used for this purpose.
Requested data	Concrete quantities in building elements, total Constructed Floor Area (CFA)	Both of these data can be extracted from the BIM model.
Considered Building elements	Walls, Floors (Slabs), Roofs, structural Columns, beams, and stairs	Gather these elements using "All element of category" node, then filter the irrelevant elements.
Credit allocation logic	$0.6 < CUI \leq 0.7$ $0.5 < CUI \leq 0.6$ $0.4 < CU I \leq 0.5$ $0.35 < CUI \leq 0.4$ $CUI \leq 0.35$	These logics will be used to automate the rating of building CUI within the BIM authoring tool (Revit).
Prerequisite requirements	GreenRE Gold $\geq$ 3 credits GreenRE Platinum $\geq$ 5 credits	A quick assessment of CUI can be useful in supporting decision-making regarding CUI.
Documentary Evidences	Calculation showing the quantity of concrete used for each floor level.	Two Dynamo script has to be created one for quick CUI assessment (to support Decision-Making) and the second for CUI report generation.
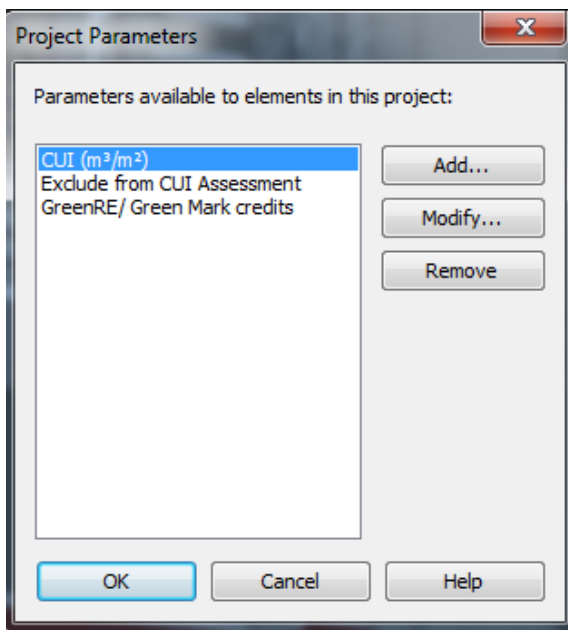
Figure 2 *New shared parameter for CUI assessment workflow*

parameters are stored in a text file independent of any family file of Revit project. Shared parameters file can be imported and used in multiple families or projects (Autodesk, 2015). The first and the second parameters are created to host the assessment result of CUI while the 3rd parameter is to exclude building element that should not be considered in CUI calculation such as substructure elements.

5.2.3 Dynamo scripts for Auto CUI tool

As shown in Figure 3 and Figure 4, Auto-CUI tool contains two main scripts developed using Dynamo for Revit. The first script (Quick CUI

assessment) is developed to provide the user with a quick assessment of the Concrete Usage Index (CUI) of the building design. This script is designed to track concrete material quantities in each building element and then generate the CUI score and rating in a very short period. During the design stage, a project team could run this script to investigate and compare the impact of several design options on the CUI value. This step is essential because it supports decision-making regarding concrete usage in the building. Once the CUI target is achieved (e.g. GreenRE Gold certification, CUI ≤ 0.5) the second Dynamo script (Export CUI Report) is executed to generate automatically the CUI report. This script is very similar to the first one, however, it contains additional nodes to export the relevant data to an excel template designed for that purpose.

In more details, the scripts are developed to conform to the rules and elements categorization in Revit. Thus, the first script task is executed in order to select the relevant building elements existing in the BIM model, namely: structural framings (Beams), Structural columns, Floor (slabs), Walls, stairs and roofs (See Figure 3 and Figure 4). Then, the level of each selected element is defined based on its Level parameter. This parameter varies based on each element category in Revit, for instance, the level parameter for beams is 'Reference level', however, for stairs and roofs is 'Base level'. Next, the data of concrete material is gathered from each element using functions such as filtering, sorting, and grouping. Finally, the CUI is calculated by dividing the total concrete volume by the constructed floor area (CFA), and credit allocation logic (see Table1) are used to score the CUI value. At this stage, if the CUI target has been achieved the user is able to execute the second Dynamo script to generate the CUI report.

5.3   Testing and validation

For validation purpose, the developed 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
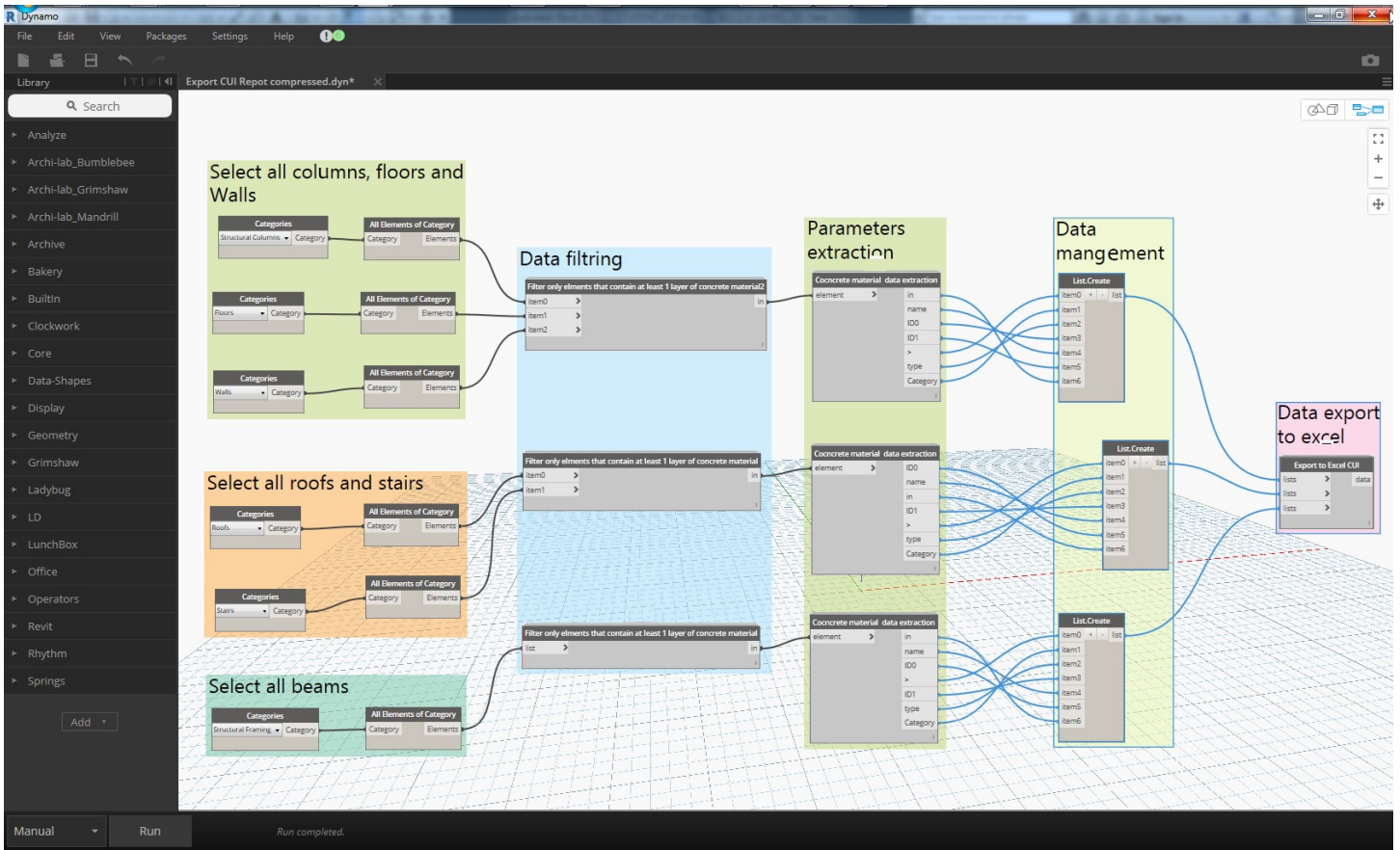
Figure 3: Script for the automation of CUI assessment developed using Dynamo
(For visualization purpose, some nodes in the above script contain several sub-nodes grouped together)
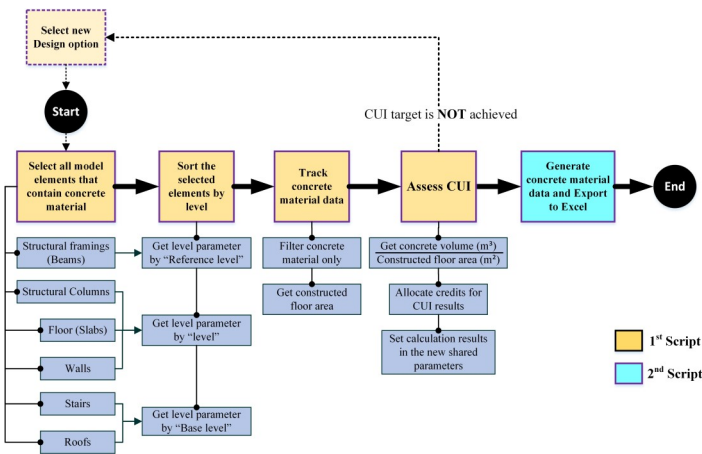

Figure 4 *The logic workflow of the developed Dynamo script for automated CUI assessment*

environment at the University of Technology Malaysia (UTM). The BIM model of this building was modeled by several undergraduate students from the department of architecture based on CAD drawings. It was noticed that the building model was not accurate compared to the existing building. However, it is believed that this will not affect the validation process of Auto-CUI tool. The structure of the building is mainly constructed with a 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 demonstration of the workability of the Auto-CUI tool is implemented to this existing case study building. Though, the same process can be used during the design stage.

The assessment process of CUI using the developed tool is very straightforward. When Revit project is open and building materials are assigned to the building elements, the user needs first to run Dynamo Player (Figure 5). When the first script ("Quick CUI Assessment") is executed, the results of CUI and its rating are calculated automatically and shown in the propriety palette in all the views under "Green Building Proprieties"(Figure 5). According to the results, the user is free to take the decision between doing modification in building design to decrease concrete quantities or generate the CUI report in the case where CUI results are acceptable (see Figure 6). This process can be repeated until achieving the targeted CUI score.

Based on the results of Auto-CUI tool, the CUI of this building equals to $0.255 m^3/m^2$. This value explains a very low concrete
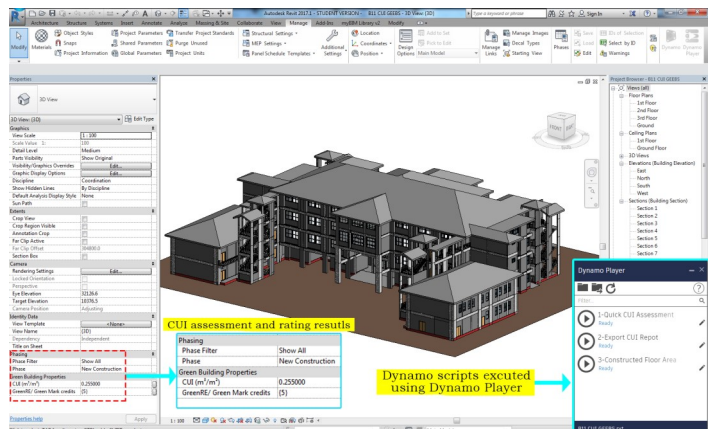

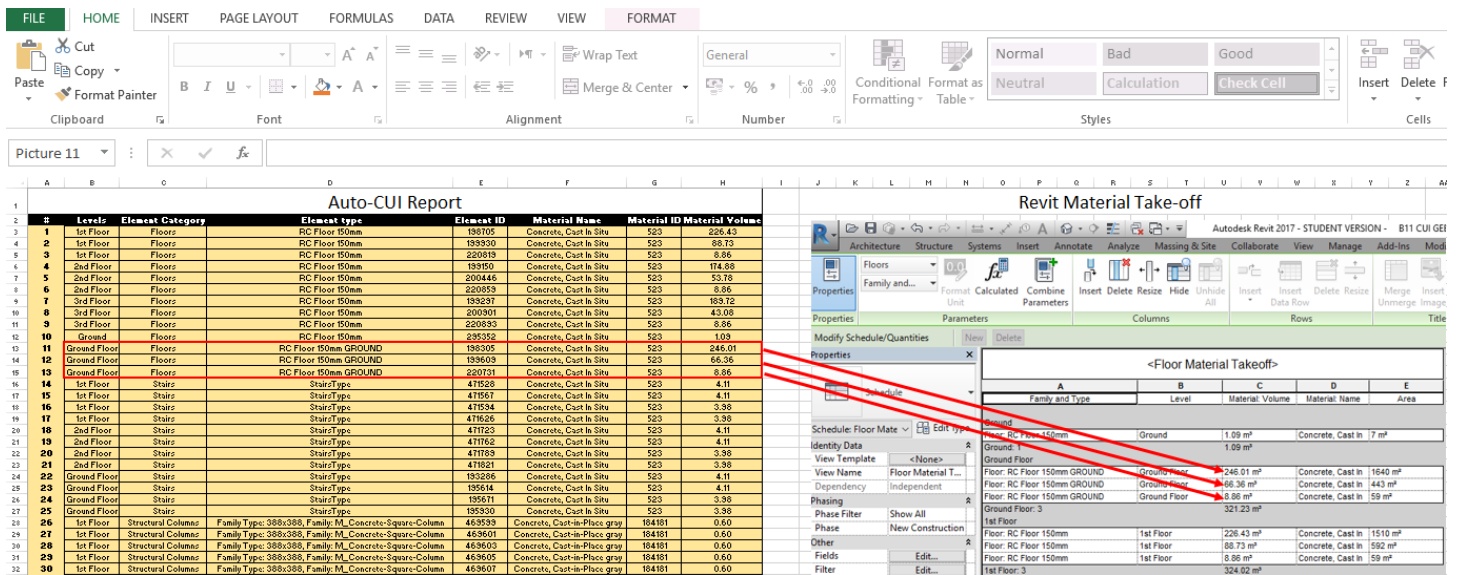***Figure 5*** *BIM model of the case study building in Revit*

Figure 6 Sample of detailed comparison of CUI results generated using Auto-CUI report and Revit Material Take-off

usage in this building which scores 5 credit points (CUI requirement for Platinum certification). In order to validate the results, a Revit Material Take-off based calculation is compared with the results of Auto-CUI tool (see Table 2). The comparison results of each method turn out to be consistent. However, it can be seen that concrete in walls slightly differs in the 2nd floor level of the building. This occurred because one material type could not be filtered by the Material Take-off in Revit. The comparison results of the concrete volumes of the developed tool and Revit Material Take-off are very similar. This is considered natural since Dynamo scripts are designed to handle the same data and rules within Revit API as Material Take-off functionalities do.

CUI assessment using Material Take-off method requires taking extra steps to prepare the schedules (filtering, grouping and sorting functions). Furthermore, the final results of each schedule should be combined manually because in this method building materials are scheduled according to each element category (walls, Floors, stairs…

etc.). However, by using the Auto-CUI, the user needs only to run the Dynamo scripts by a click of a button. Data processing in this method may take a few seconds or several minutes depending on the project size, yet, no manual process is required.

During the development and the validation of the tool, some observations have been noticed which may affect the accuracy of the output results. These remarks will be considered as predefined modeling rules for the CUI assessment. Hence before running Auto-CUI tool, the user must follow the following instructions:

- split in each level the elements that span across multiple levels such as walls, columns, and stairs.

- exclude substructure elements from CUI calculation. This can be done using the relevant parameter "Exclude from CUI calculation"
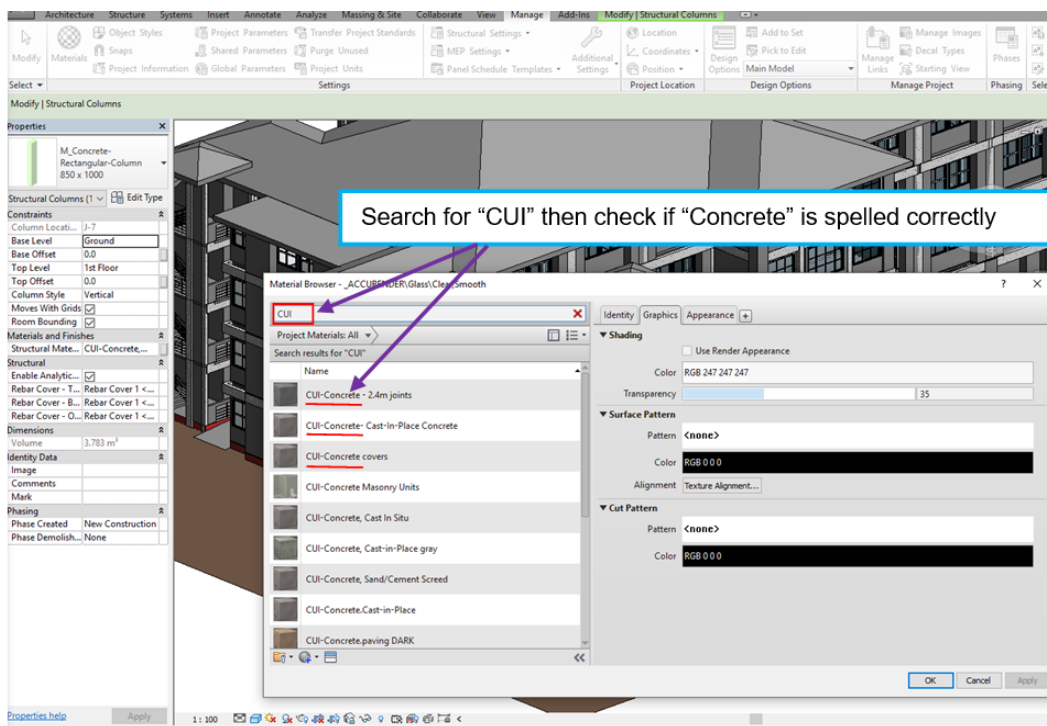

Figure 7 Using Revit Material Browser to check the spelling of the assigned material in the BIM model

Table 2 *Overall comparison between the results generated using Revit Material Take-off and Auto-CUI tool of concrete volume based on the building element category and level*

Building Level	Building Elements	Concrete Volume (m³)		Building Level	Building Elements	Concrete Volume (m³)	
		Revit Material Take-off	Auto-CUI Tool			Revit Material Take-off	Auto-CUI Tool
Ground + Ground floor	Floors	322.32	322.32	2nd Floor	Floors	237.52	237.52
	Roofs	0	0		Roofs	0	0
	Stairs	16.17	16.17		Stairs	16.17	16.17
	Columns	133.5	133.5		Columns	59.09	59.09
	Beams	0	0		Beams	110.56	110.56
	Walls	23.77	23.77		Walls	4.92	5.65
	Total Concrete Volume	495.76	495.76		Total Concrete Volume	428.26	428.99
1st Floor	Floors	324.02	324.02	3rd Floor	Floors	241.66	241.66
	Roofs	0	0		Roofs	0	0
	Stairs	16.17	16.17		Stairs	0	0
	Columns	94.81	94.81		Columns	52.4	52.4
	Beams	143.03	143.03		Beams	115.66	115.66
	Walls	0	0		Walls	0	0
	Total Concrete Volume (m³)	578.03	578.03		Total Concrete Volume (m³)	409.72	409.72

- check the spelling of the assigned materials in the Revit material editor (one solution is porposed in Figure 7)

- assign building material to the loadable families such as columns in the family editor and not in the project.

- model the Constructible floor area as floor element and not as plate roof.

- check if there are overlapping elements in the project.

6. Discussion

Building designers and architects tend to be just as consumers of many tools that support design workflows and design decision-making. However, nowadays technologies such as computational BIM and visual programming tools have created more opportunities by allowing project teams without programming skills to develop their own tools for design decision support. Auto-CUI tool development is one example showing how the user can become a prosumer instead of a consumer during the design process.

Auto-CUI is easy to use and it requires no coding experience. It will allow the project team to focus more on design ideas instead of hesitating about the concrete usage and its rating score. The developed scripts can be used on many projects and shared with the project team members. This study is a first step in automating sustainability analysis criteria under green building rating tools requirements.

At this level of development, the tool has some technical limitations. For instance, ramp elements are not supported. Hence if a building project contains ramps constructed with concrete material, they will be ignored, thus, their relevant data must be added manually. In addition, in the case where there is more than one type of concrete in the same building element, this may cause errors in the generation of CUI report. All these limitations depend on the capability of Dynamo to interact with Revit API. However, since Dynamo supports Python scripting, it is believed that these limitations can be overcome through code-based scripting within Dynamo scripting environment or by developing a plug-in for Revit.

7. Conclusion

Sustainability analysis related to construction materials require often complex procedures for data collection and assessment. The power of the parametric modeling of BIM tools and the customization capability of visual programming tools have made the automation of repetitive task achievable.

This paper has presented a computational BIM-based workflow for CUI automated compliance-checking. The developed tool is capable of assessing CUI automatically in a very short time and with high accuracy compared to Material Take-off method. This will support design decision-making regarding concrete usage in the building by allowing the project team to test several design options and check if the intended CUI target has been achieved. Moreover, when the CUI goal is reached, the user is able to export the CUI report which clarifies the concrete usage of each building element by floor level. The workflow implemented in this study can be adapted to automate different tasks related to building material usage and impacts during the design stage. For instance, tools for the assessment of materials embodied energy or recycled materials could be developed using similar workflows. Furthermore, this study is considered as a proof of concept that building practitioners are able to develop their own tools using computational BIM and visual programming languages instead of completely relying on commercial tools which are often very expensive.

Acknowledgment

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