



## ENHANCING BIM-BASED QTO USING VISUAL PROGRAMING

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### **ABSTRACT**

Cost estimation relies on the correctness of the material QTO, but human inclusion and limitations of the 2D environment reduce the accuracy of QTO results. Hence, BIM-based QTO has been playing a prominent role in the construction industry. Nevertheless, the quality of BIM models affects the accuracy of quantities. Even the software features somehow hinder the quantification process. Therefore, this research proposes a framework for quantifying architectural cladding materials using visual programming for contractors. It is consequently verified that the accuracy of QTO results is significantly increased, and the benefits and limitations of the proposed strategy are discussed in detail.

### **INTRODUCTION**

Cost estimation during the initial phase of a construction project traditionally relies on the experience of estimators and their assumptions based on the data of the previous projects having a similar scope of works (Jrade and Alkass, 2007). In later stages, cost calculation requires understanding the design details and differences between consecutive design revisions and their unexpected ramifications on the project budget (Lawrence et al., 2014). Hence, specifications and, more importantly, construction drawings play a more critical role as the design develops since information on these documents increases in time and is subject to change. On the other hand, visualization and interpretation of 2D drawings take a significant amount of time to calculate labor, material, and equipment quantities for cost calculation (Shen and Issa, 2010). Thus, cost estimation becomes slower since the conventional quantity take-off (QTO) process gets iterative and ineffective due to time constraints and lags during design reviews and developments (Cheung et al., 2012). In other words, human inclusion and time limitations are the main drawbacks of the traditional QTO, hindering the accuracy of cost estimations.

In this regard, Building Information Modeling (BIM) is a good and rapidly advancing environment for increasing efficiency in terms of cost and time to design and manage construction projects in high quality (Ahn et al., 2016). However, sharing construction data with project stakeholders is crucial and difficult even with BIM

because there are many different BIM tools with their distinctive data structure making interoperability unfeasible. BIM workflow, therefore, requires a neutral and open format, named Industry Foundation Classes (IFC) by buildingSMART, to share and exchange construction information in the building sector (Bonduel et al., 2018). In this case, the IFC standard is a conceptual data schema and an exchange file format for BIM data facilitating information sharing among various software to elevate the functionality of computer-aided design (CAD) for structural analysis, 4D planning, and 5D cost calculation (Pauwels and Terkaj, 2016). IFC can be effectively utilized for cost estimation and QTO since it is an open and transparent format. For example, Akanbi et al., (2020) developed a data-driven reverse engineering algorithm to obtain QTO using IFC geometric data. More specifically, BIM tools and IFC schema are significantly advantageous in material quantification in terms of automation, reducing human errors and process time while increasing the efficiency in the cost calculation. It is because BIM models include intelligent 3D building components that can be accessed in various formats to examine, group, and sort accurate material information when required (Masood et al., 2014).

However, Sattineni and Bradford (2011) stated that time reduction and quality increase for cost estimation for the contractors could not be achieved only with BIM adoption since there are different departments for cost estimation and BIM in construction companies. It results in an uncoordinated process between estimation and BIM departments, which in reality should share the same project data and feed each other. Besides, contracts are generally signed before the design completion, and eventually, estimation is performed conceptually (Sattineni and Bradford, 2011). It causes BIM implementation left behind for the cost estimation process. There could also be an inconsistency in QTO due to the lack of measurement standards in software products (Abanda et al., 2017). Besides, the quality of BIM models hampers BIM-based QTO because of nonessential and missing building data and not correctly representing building elements in the design stage. Therefore, this study is structured to suggest a workflow for calculating the architectural quantities using a visual programming tool for contractors who generally suffer from having a 3D

model with insufficient modeling detail. It is important to note that even owners, designers, and contractors utilize internal ad-hoc frameworks and strategies for QTO per their specifications and situations and do not share their measurement standard but rather hide for competitive reasons (Monteiro and Martins, 2013). Hence, the lack of measurement standards should be investigated in further research. Here, this research addresses the difficulties of QTO extraction from BIM software apart from IFC implementation, Autodesk Revit, for the area-based compound elements such as floors, walls, and ceilings. Compound elements are challenging for QTO due to various material layers with different dimensions on the same model component (Khosakitchalert et al., 2019a). The designer models generally do not meet the needs of contractors and model layers do not arranged for material QTO.

The proposed method includes some manual work to prepare the building data for the automated process. The research aims to link building data tabulated in a spreadsheet to a structural 3D model and classify the material quantities for each building room. Besides, architectural model components, including floors, walls, wall bases, and ceilings, are automatically generated for each room of the building. The overview of the data flow among software tools is shown in Figure 1. Accordingly, room data organized in a spreadsheet is imported to Autodesk Revit using the visual programming tool. Dynamo is automatically processing the room geometries and associate the extracted geometric information with room data. Calculated results are later exported to the spreadsheet again, and new building components are created for quantified elements. This approach facilitates using the structural BIM model with the externally stored room information by getting the room dimensions from the model and material types from a spreadsheet. Eventually, the contractor does not need to rely on the designer's model for QTO but instead modifies the structural model, which requires less time comparing the detailing of architectural models and obtains material quantities faster and more accurately. A four-story reinforced concrete (RC) building implementation is done as a case study, and floor, wall, wall bases, and ceiling quantities are checked in terms of accuracy. In the end, results are verified with the results obtained from a correctly modeled building. The following sections explain the background studies and details of the overall process.

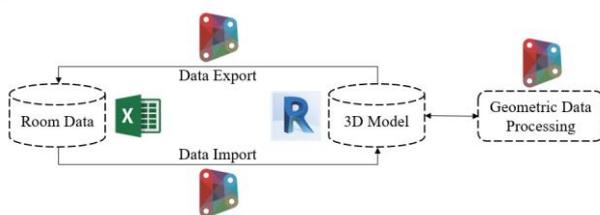


Figure 1: Data flow among software tools

## LITERATURE REVIEW

### **BIM-based quantity take-off and its limitations**

BIM is mainly utilized in the construction industry for photorealistic renderings, virtual design reviews, analysis of different design options, building and construction operations, document management and production, bid package preparation, and cost estimation (Hartmann et al., 2008). Hence, 3D information models are appropriate tools for design and construction management, and also implementing BIM tools and processes positively affects cost management due to increased productivity and manageability (Bryde et al., 2013). It is because geometric and non-geometric cost data is encapsulated and attached to BIM models reducing erroneous information and its misinterpretation while being automatically updatable (Ashcraft, 2008). Besides, BIM increases the effectiveness of bill of quantities (BQ) in construction projects since it improves the conventional error-prone process based on detailed 2D drawings and specifications (Nadeem et al., 2015).

In general, cost estimation comprises the evaluation of various construction conditions, including challenging wall conditions and unique assemblies in the project affecting the project budget (Lawrence et al., 2014). Measurement and assessment of these conditions should be accurate and consistent for successful construction projects. However, the accuracy of cost and quantity data obtained from 3D models needs to be critically assessed because BIM-based QTO may not provide or miss the essential information for cost calculation due to modeling mistakes and approaches (Monteiro and Martins, 2014). At this point, the implementation of BIM in QTO and cost estimation is generally obstructed because of the cost and time requirements for detailed model development (Franco et al., 2015). This is because design teams usually cannot provide an accurate model that can be used for estimating purposes by the contractors, and the contractor needs to improve the model for estimation (Sattineni and Bradford, 2011). Hence, there is still a need to improve BIM-based QTO processes for the contractors so that they can benefit from models obtained from design teams to increase the accuracy of material quantification for the cost calculation process.

### **BIM-based estimation for architectural components**

Architectural building elements are generally difficult to quantify in the BIM environment due to overlaps among different components such as floor and wall claddings and modeling limitations. Cheung et al. (2012) introduced a knowledge-based tool for early design cost estimation to assess the changes in building mass and types in Google SketchUp environment and update the quantities for walls, floors, doors, and windows simultaneously. Monteiro and Martins (2013) stated that the surface coatings, which require a delicate measurement process, can either be modeled for the same material QTO or surfaces of 3D structural elements can be utilized with a

presumed error margin. Accordingly, the former approach increases the model size significantly, while the latter results in a considerable amount of measurement errors requiring in-depth analysis (Monteiro and Martins, 2013). Liu et al. (2016) suggested a construction-oriented QTO framework specifically focusing on light-frame building construction with an ontology-based semantic approach to obtain the material quantities not explicitly modeled in Autodesk Revit. Kim et al. (2019) revealed the quantity discrepancies in interior materials, including masonry, wood, thermal and moisture protection, insulation, and finishes due to model representation and unnecessary modeling and provided suggestions for the BIM modeling process to reduce inconsistencies in material take-offs. Khosakitchalert et al. (2019a) developed a visual programming algorithm to extract surface area information by eliminating modeling mistakes for architectural wall and floor elements from erroneous models using the Autodesk Revit Dynamo tool. Khosakitchalert et al. (2019b) also suggested a wall framing quantification method for general and sub-contractors by enhancing the power of the visual programming tool Revit Dynamo. Khosakitchalert et al. (2020) later proposed a visual programming algorithm to automatically separate wall and floor elements into their layers and convert each layer to an individual model component so that material quantities for each wall and floor layer can be accurately obtained. Their study focuses on BIM models having architectural components and separation of those components for individual material quantification, but models without architectural elements should also be investigated with externally linked building data. It is important because the contractors need to get most out of 3D models they have during the construction.

According to previous studies, there is still ongoing research to improve BIM-based QTO in terms of architectural elements, and visual programming tools are increasingly helpful and essential for more efficiency and automation in BIM-based estimations. Although previous studies address the most challenging architectural quantification problems, there are still some gaps to incorporate available building data existing in project documents with BIM models even the data is created using BIM. In particular, there is limited research focusing on integrating building data in spreadsheets and 3D information models for material QTO using visual programming tools. Thus, this study presents a cluster of visual algorithms for general and sub-contractors so that they can integrate tabulated spreadsheet data with BIM models and use the geometry of buildings for accurate material estimations. Following the previous research, there are also problems in creating architectural components with different layers of materials in terms of the modeling effort. Hence, even though accuracy is the primary concern, this study also aims to automate the modeling of architectural components, especially floors, walls, wall bases, and ceilings, for an RC building having no architectural building component at the beginning.

## **PROPOSED METHOD**

General contractors and sub-contractors are the main stakeholders in construction projects, and they need to have detailed and structured information regarding the project they execute. In an ideal case, where BIM is utilized from the beginning of the project with high-quality standards, the contractors can reach the organized building data, specifically materials quantity, in information enriched 3D models. However, in general, BIM models contain limited information, and construction drawings and schedules may be manipulated in the 2D environment even if they are produced using BIM tools. Therefore, contractors face situations where they have some data on schedules and spreadsheets, and models provided by the design team, but they cannot benefit effectively from BIM. Therefore, this study proposes a framework to draw advantage from BIM model geometry and tabulated spreadsheet data using the visual programming tool Revit Dynamo.

Firstly, the proposed method aims to calculate accurate surface area information for floor, wall, and ceiling materials and total length for wall base materials in a building room. The second goal is to create 3D model elements for these building components automatically. The method includes both manual and mostly automated processes, as shown in Figure 2. Processes inside the dashed rectangle include manual works, and Revit Dynamo automatically performs operations inside the bold rectangle. The manual part is about preparing and organizing building data, such as placing room elements into the BIM model, creating project parameters to store data, and sorting and grouping room information in a spreadsheet accordingly. The automated process includes transferring room data between spreadsheet and Autodesk Revit and manipulating building geometry to obtain correct surfaces and lines for floor, wall, wall base, and ceiling elements.

According to Figure 2, the process commences with the room placement in the 3D model, and room data based on the room numbers assigned by Revit are simultaneously organized in a spreadsheet. Some project parameters, named *base material height*, *ceiling area*, *material extension above the ceiling*, and *room number for doors*, are also defined for the later stages. The base material height and material extension above the ceiling parameters are utilized to determine wall base offsets and wall heights. The room number for doors parameter is to distinguish which floor finish is required at door sills. This parameter is manually filled for each door element. The ceiling area parameter is created to automatically store the calculated area of ceiling materials for each room.

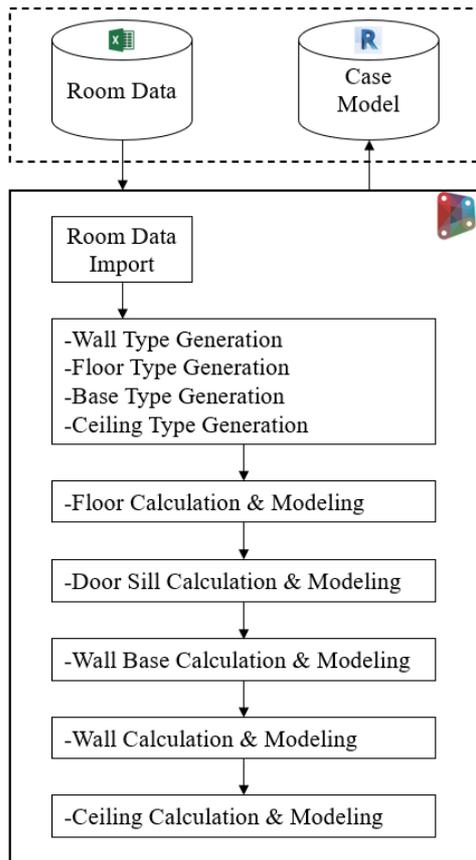


Figure 2: Workflow for material QTO and 3D modeling

Highlighted parameters in Figure 3 are automatically populated with the room data in the spreadsheet. Revit Dynamo does these import operations, and it creates a dynamic and updatable link between Revit and MS Excel, meaning that whenever something changes in the spreadsheet, non-geometric room data also changes in the 3D model. The Limit Offset parameter is utilized for ceiling elevation. Material Extension Above Ceiling and Base Material Height parameters are considered to locate top and bottom offsets for wall elements. Base, ceiling, wall, and floor finish parameters are associated with room surfaces for material quantification. Hence, Dynamo is also utilized to manage and manipulate building geometry to extract the surface area and length information and associate these geometric data with the finish parameters. Besides, new wall, floor, ceiling types are created for 3D model generation using the materials assigned for each room. For example, a floor family is created for the rooms with stone cladding using the previously imported floor finish name and thickness from the spreadsheet. The code takes one of the existing floor types and duplicates it for the new type with the required thickness.

| Rooms (1)                        |                       |
|----------------------------------|-----------------------|
| <b>Constraints</b>               |                       |
| Level                            | Level 1               |
| Upper Limit                      | Level 1               |
| Limit Offset                     | 4000.0                |
| Base Offset                      | 0.0                   |
| <b>Text</b>                      |                       |
| Material Extension Above Ceiling | 150                   |
| Base Material Height             | 100                   |
| <b>Dimensions</b>                |                       |
| Area                             | 27.830 m <sup>2</sup> |
| Perimeter                        | 21300.0               |
| Unbounded Height                 | 4000.0                |
| Volume                           | Not Computed          |
| Computation Height               | 0.0                   |
| <b>Identity Data</b>             |                       |
| Number                           | 2                     |
| Name                             | Room                  |
| Image                            |                       |
| Comments                         |                       |
| Occupancy                        |                       |
| Department                       |                       |
| Base Finish                      | Rubber Skirting       |
| Ceiling Finish                   | Gypsum                |
| Wall Finish                      | Gypsum Board          |
| Floor Finish                     | Stone                 |
| <b>Phasing</b>                   |                       |
| Phase                            | New Construction      |

Figure 3: Room parameters manipulated in Autodesk Revit

Figure 4 presents the primary operations inside Revit Dynamo. The process continues with the extraction of building geometry and filtering of individual room elements. Besides, room element geometries are exploded to obtain top surfaces and room perimeters. Top surfaces are used for ceiling calculation and modeling, while room perimeters are utilized for floor, wall, wall base calculation and modeling.

For floors, room perimeters are directly converted to floor elements according to floor finish material previously assigned to rooms. The challenging activity is to get floor surfaces at door sills since room boundaries do not extend inside the door openings and underestimate floor material. Thus, door elements are filtered, and the bounding box, which encloses the door opening using the maximum and minimum point coordinates of the opening, for each door is extracted, then all surfaces of these boxes are eliminated except the bottom face. The boundary curve of the bottom surface is later converted to floor elements. The floor type for door sills is determined using the previously assigned room numbers for the doors parameter. Consequently, floor claddings for rooms and door sills are calculated and modeled.

For the wall base calculation and modeling, the total length and area of the base are calculated after deducting door opening widths from the total room perimeter since there is no base material at door locations. Hence, door bounding boxes are extracted, and they are scaled to larger geometries at their original coordinates so that doors and room perimeters are intersected with each other. Later, overlapped parts of room perimeters with scaled bounding boxes are removed from the calculation, and then wall base material is located on the curves along the room perimeter. In the end, wall base length, area, and 3D model geometry are attained.

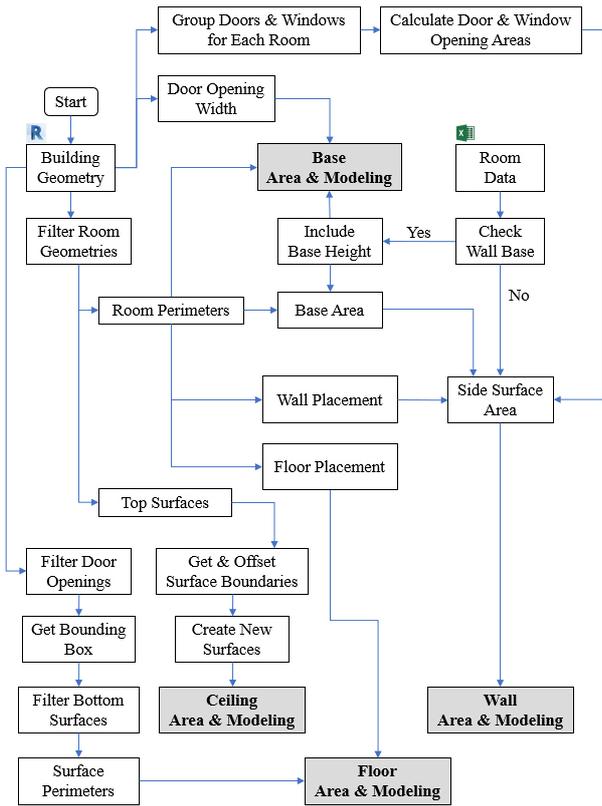


Figure 4: Framework for material QTO and 3D modeling

Like floors, room perimeters obtained from the BIM model directly converted to wall elements. During the wall placement along with the rooms, previously created base material height and material extension above ceiling parameters for rooms are included in wall properties. Therefore, the base material is checked to determine base offset values for the wall elements. Moreover, doors and windows are grouped for each room, and width and height parameters are obtained for each window and door element. The area is then calculated for windows and doors, and these areas are deducted from the overall wall surface area. Eventually, wall material area and 3D wall models are obtained for each room of the building.

For ceilings, room solid geometries are exploded into surfaces, and top faces are filtered. Perimeter curves of these surfaces are obtained, and they are shifted towards to center of the room by the thickness of wall cladding, considering the ceiling installation is to be done after wall cladding. New surfaces are generated by using new curves, and surface area is calculated. Since Revit Dynamo does not support ceiling creation, generic models are utilized to model ceilings. Surface area information for ceilings is saved in the previously created ceiling area parameter.

Figure 5 shows the specific nodes integrated into visual scripts. The *Room.Windows* and the *Room.Doors* nodes are obtained from the clockwork package to group the windows and doors for each building room (figure 5a). The *FamilyType.SetCompoundLayerWidth* from the clockwork package is also integrated while creating new

family types (figure 5b). This node is used to modify the material thicknesses in compound elements like walls and floors. The *Level.ByName* node from the wombat package is utilized at several locations to get the project levels using their names (figure 5c). Converting the ceiling surfaces to generic models is performed using the *FamilyInstance.ByGeometry* node from springs package library (figure 5d). Additionally, in-house nodes from Dynamo library like the *Floor.ByOutlineTypeAndLevel* and the *Wall.ByCurveAndHeight* nodes are utilized to place 3D floor and wall components (figure 5e and 5f). Figure 5g is to show strings searched in the spreadsheet and Revit model. These strings are only coded once, and they are precisely written the same in the spreadsheet, Revit, and Dynamo to prevent coding errors.

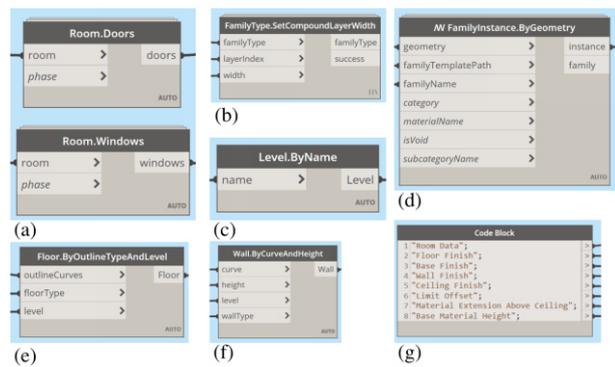


Figure 5: Specific nodes integrated into visual scripts

Furthermore, figure 6 presents some parts of visual codes. Bounding box generation for door elements to quantify and model the materials at door sills is shown in figure 6a, and the shifting room perimeter curve for ceilings and regenerating ceiling boundaries are illustrated in figure 6b. Figure 6c demonstrates some steps for filtering, grouping room data, and removing nonessential information from the lists.

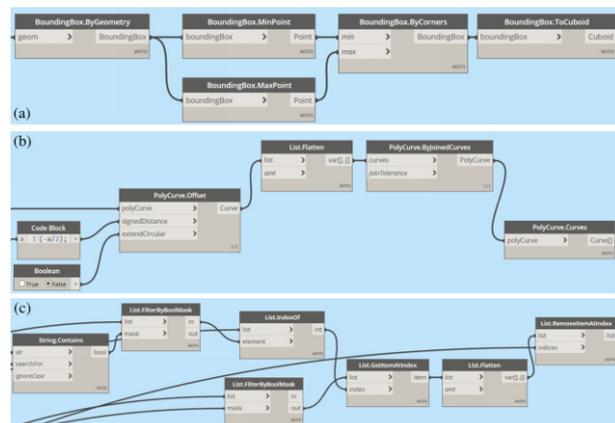


Figure 6: Some part of visual codes

## RESULTS AND DISCUSSIONS

The proposed algorithm is tested on a hypothetical case study building created by the authors. The model is generated in Autodesk Revit 2021, and visual codes are

prepared in Revit Dynamo. Although the building data could be in any other format, it is assumed that room data is tabulated in MS Excel in this study. Figures 7a and 7b show the 3D model of the case study. It is a four-story RC building with a stair shaft at the center. The building does not have any architectural component at the beginning of the study, and only structural elements are modeled. For the verification of results, another project is created later, and all architectural elements are manually modeled according to the same data used in visual scripts. Hence, figure 7 is the combination of manually created structural and architectural models. Figures 7d, 7e, and 7f point out specific details like door sill, wall base, and window opening. Dimension “A” shown in figure 7e represents the previously mentioned material extension above the ceiling. Similarly, dimension “B” indicated in figure 7d stands for the wall base height.

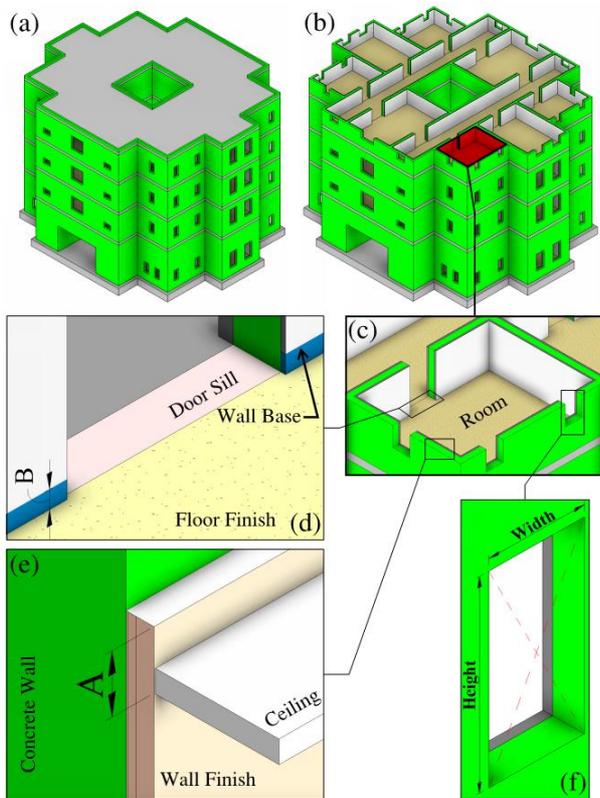


Figure 7: Sample 3D view of case model and some details

In general, this study investigates the material QTO for architectural floors, wall bases, walls, and ceilings in terms of accuracy using the visual programming tool. The concept is to integrate 3D models and spreadsheet data dynamically and automatically to reduce human inclusion in the takeoff process, thereby increasing QTO accuracy. Comparison between Revit takeoff and Dynamo takeoff with proposed strategy is tabulated in table 1. The comparison is made between the manually and automatically detailed models. Table 1 shows that floor and ceiling quantities extracted from Revit using software features are similar to those obtained from Dynamo.

However, wall base and wall takeoff results differ from each other. The reason is examined, and it is observed that some wall bases and wall heights are not correctly created in the manually detailed model. Hence, material quantities deviate from each other. When the manually generated model is corrected, quantities for walls and wall bases obtained from Revit also match Dynamo results.

Table 1: Result comparison for material QTO

| Building Component | Revit Takeoff (m2) | Dynamo Takeoff (m2) |
|--------------------|--------------------|---------------------|
| Floor              | 1146.11            | 1146.11             |
| Wall Base          | 69.98              | 71.24               |
| Wall               | 3093.32            | 3072.36             |
| Ceiling            | 1126.47            | 1126.47             |

Other than quantification, the visual script is also utilized for creating 3D architectural elements. Even though floors, walls, wall bases, and ceilings are generated with Dynamo, there are some problems in the modeling process (figure 8). For example, floors and walls are generated using the ready families in Revit, but ceiling components could not be modeled with ceiling families due to software limitations. Hence, ceiling elements are modeled with generic components. Besides, walls are created with the correct height and length, but the window and door openings could not be created automatically (figure 8b). To do so, newly created walls should be manually joined with the original 3D model walls. Lastly, wall bases cannot be placed in correct locations such that half of the cross-section interferes with the original 3D wall element (figure 8c).

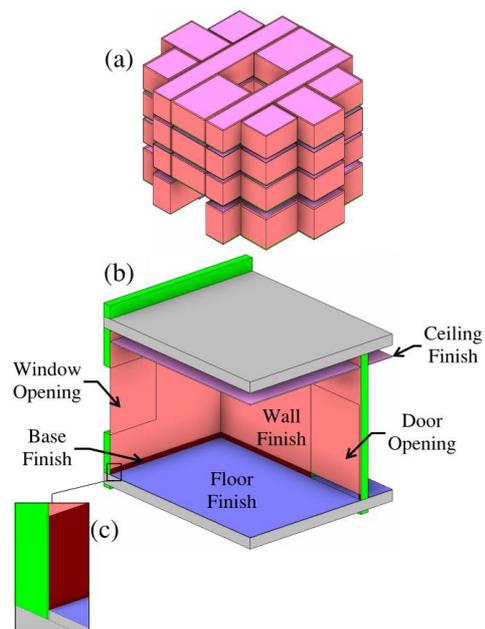


Figure 8: Automatically modeled BIM components

It is verified that the proposed framework facilitates material quantification for architectural floors, walls, wall bases, and ceilings. Moreover, 3D model elements are generated, and model development processes are facilitated using visual programming. Compared to previous studies stated in the literature review section, this study suggests a framework for contractors to use spreadsheet data, and 3D model geometry effectively. Previous studies are focusing on the extraction of information only from building information models. However, contractors might need additional information from other sources, and they might need to link 3D models and their spreadsheets using visual programming tools. For example, information related to government agencies or vendors' prices might be needed to link to 3D models and be used in conjunction with QTO results from BIM.

Even though the framework is appropriately applied in this study, it needs further improvement. For example, all wall surfaces in a room only take one type of wall finish and wall base material. It is considered that building orientation according to project north direction can be implemented in visual scripts to distinguish materials on east, west, south, and north walls of a building room. Moreover, this study can also be performed using other visual programming tools such as Rhino Grasshopper to evaluate the performance of visual programming platforms in quantification.

## **CONCLUSIONS**

Contractors are responsible for executing construction projects within a limited time and budget. Thus, cost management paves the way for the successful completion of projects. Since quantity take-off (QTO) comprises a considerable amount of cost estimation activities, this paper describes a visual programming approach to calculate quantities for architectural building components for the benefit of contractors. Hence, the accuracy of material QTO obtained from Revit and Dynamo are compared based on a four-story RC case building. Results extracted with automated strategy are accurate for the case study, and 3D architectural model elements are also generated automatically with minor problems. Even though human inclusion still exists while organizing building data, this study reduces human inclusion using 3D model geometry, so the dimensions are automatically extracted with Revit Dynamo, and it increased accuracy. In future studies, this strategy should be tested with a real complex building with actual building data. The limitations like preparing room spreadsheets manually and adding parameters for doors to determine materials at door sills can be organized using artificial intelligence or machine learning techniques to reduce human inclusion. This industry problem should definitely be investigated with open-source format IFC to prevent vendor dependency for a standardized approach. For example, IFC models extracted from other BIM tools with required IFC attributes can be investigated by linking into another

software, and IFC schema can be explored with visual programming tools like Dynamo and Rhino Grasshopper or with an IFC viewer enabling code implementation.

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