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Doctoral Dissertation

Development of Quantity Takeoff Methods for Compound Elements Based on Building Information Modeling (BIM)

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Abstract

Quantity takeoff, a process in which building materials or work tasks are measured and calculated, is traditionally performed based on 2D construction drawings. This traditional quantity takeoff requires manual work and human interpretation, which are time-consuming and error-prone. The emergence of Building Information Modeling (BIM) allows a new approach for quantity takeoff, called a BIM-based quantity takeoff. All building elements are represented as digital models with data attributes, and hence the quantities of them can be obtained directly from a BIM model. The BIM-based quantity takeoff is more reliable, accurate, and rapid than the traditional quantity takeoff approach. However, the quality of BIM models affects the quality of BIM-based quantity takeoff. Incomplete details and inappropriate modeling methods cause deviations in extracted quantities. Compound elements, such as walls and floors, always face this issue because they contain multiple material layers, which can have different sizes and compositions, and they also contain sub-components, such as wall framings, that are usually absent from the BIM model transferred from the design phases. Furthermore, overlapping regions of compound elements with other building elements result in excess material quantities. Therefore, the compound elements must be inspected and edited after the design phases for quantity takeoff and other construction tasks. Nevertheless, manual inspection and modification of each compound element are time-consuming, cost-intensive, and error-prone.

This study developed three methods to improve BIM-based quantity takeoff for compound elements. The first method improves the accuracy of the quantities of compound elements, which are walls and floors, by integrating the concept of BIM-based clash detection to automatically subtract the overlapping quantities and add the missing quantities of each layer of compound elements. The second method extends the first method to automatically modify compound elements in BIM models by separating each layer of compound elements into an individual model element and eliminating the overlapping regions of the compound elements. Accurate material quantities for compound elements can then be obtained from the modified BIM models. The last method proposes an alternative way to obtain the correct material quantities from compound elements in a BIM model without modifying the BIM model. This method calculates quantities of sub-components, which are wall framings of drywalls, and embeds them into the drywall properties in the BIM model. The quantities of sub-components can then be extracted directly from the BIM model that does not contain these sub-components.

The prototype system for each method is developed using Autodesk Revit 2018.2 and Dynamo 1.3.3.4111. The methods were validated by actual construction projects. All methods can improve the accuracy of material quantities from the incomplete or incorrect compound elements in the BIM models. The execution time of the prototype systems is much less than the manual modification time of the BIM models and the calculation time of the traditional methods. Therefore, these methods can reduce the working time, cost, and human error associated with the manual works. This research contributes to the understanding of the deviations of BIM-based quantity takeoff when extract quantities from the incomplete or incorrect compound elements and to develop the methods that can improve the accuracy and efficiency of the BIM-based quantity takeoff for compound elements.

Preface

This dissertation is the original work by Chavanont Khosakitchalert under the supervision of Professor Nobuyoshi Yabuki. Three journal articles and two international conference proceedings that relate to this dissertation have been submitted or published and are listed below.

Journal articles:

1. Khosakitchalert, C., Yabuki, N., and Fukuda, T. (2019). Improving the accuracy of BIM-based quantity takeoff for compound elements. *Automation in Construction, 106*, 102891. https://doi.org/10.1016/j.autcon.2019.102891
2. Khosakitchalert, C., Yabuki, N., and Fukuda, T. (2020). Automated modification of compound elements for accurate BIM-based quantity takeoff. *Automation in Construction, 113*, 103142. https://doi.org/10.1016/j.autcon.2020.103142
3. Khosakitchalert, C., Yabuki, N., and Fukuda, T. Development of BIM-based quantity takeoff for light-gauge steel wall framing systems. *Journal of Information Technology in Construction (ITcon)*, Under review.

International conference proceedings:

1. Khosakitchalert, C., Yabuki, N., and Fukuda, T. (2018). The accuracy enhancement of architectural walls quantity takeoff for schematic BIM models. *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)*, 768–775. https://doi.org/10.22260/ISARC2018/0108
2. Khosakitchalert, C., Yabuki, N., and Fukuda, T. (2019). BIM-based wall framing calculation algorithms for detailed quantity takeoff. *Proceedings of the 4th International Conference on Civil and Building Engineering Informatics (ICCBEI)*, 251–258. http://iccbei2019.com/proceedings/iccbei2019_proceedings.pdf

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Chapter 1
Introduction

1.1 Background and problem statements

Quantity takeoff, a process of measuring and calculating quantities of building elements or work tasks, is one of the fundamental tasks in construction projects (Holm et al., 2005; Monteiro and Martins, 2013). Generally, it is performed after the design development phase to prepare a bill of quantity of the project (Holm et al., 2005). The measured quantities are then used for several purposes, including cost estimation, cost management, procurement, construction schedule planning, and material purchasing (Firat et al., 2010; Liu et al., 2016; Olanrewaju and Anahve, 2015).

Traditionally, the process is done manually based on 2D construction drawings and human interpretation (Monteiro and Martins, 2013). Quantity surveyors have to interpret a set of drawings, which include floor plans, elevations, sections, and detail drawings, from design teams and measure each building element by its element-specific measurement rules. Furthermore, if the set of drawings does not have sufficient information owing to the project being in the schematic or development phases of design, knowledge and experience have to be used to infer the missing information. Therefore, traditional quantity takeoff is a time-consuming and error-prone process, and the results can differ among quantity surveyors (Holm et al., 2005; Juszczyk et al., 2014; Monteiro and Martins, 2013).

The development of computer technologies improves the ease and efficiency of quantity takeoff (Brook, 2017). Computer-aided design (CAD) software provides digital tools for creating construction drawings and measuring lengths, areas, and volumes from those drawings. However, the overall process is still time-consuming and error-prone because it requires manual work and human interpretation when measuring quantities.

The emergence of Building Information Modeling (BIM), a digital modeling approach that represents physical and functional characteristics of a built asset (National Institute of Building Sciences, 2007; D. Smith, 2007), provides a new method for quantity takeoff, called a BIM-based quantity takeoff. All building elements in a BIM model consist of computable graphics and data attributes; therefore, the quantities of building elements can be obtained directly from a BIM model (Sacks et al., 2018). This method provides more reliability, accuracy, and speed than the traditional quantity takeoff method (Bečvarovská and Matějka, 2014; Nadeem et al., 2015; Sacks et al., 2018; Sattineni and Bradford, 2011). However, if the BIM model is incomplete or incorrect, the quantities extracted can be insufficient or deviate from actual values. In order to obtain accurate quantities, a BIM model must contain appropriate details for a quantity takeoff purpose (Andersson et al., 2016; Hardin and McCool, 2015).

In principle, a BIM model is a centralized model that is shared, exchanged, developed, and integrated among stakeholders from the building design phase to the facility management phase (ISO, 2018; Underwood and Isikdag, 2009). However, in practice, the development of different models for different purposes is a better approach to deal with model complexity and file size (Kensek and Noble, 2014). For example, designers make BIM models for the visualization and production of building drawings, while contractors make BIM models for cost estimation and construction planning. This fragmentation of BIM models causes incomplete information when models are transferred from one phase to another phase in a project life cycle (Kensek and Noble, 2014). Therefore, the BIM model from the design phases must be inspected and modified or sometimes recreated for quantity takeoff purposes not only with respect to the information in the model elements but also the geometry of the model elements (Sattineni and Bradford, 2011; P. Smith, 2014).

Compound elements are one of the building element categories that usually have issues when performing a quantity takeoff. A compound element is a building element that consists of multiple material layers (Autodesk Knowledge Network, 2018). Examples of compound elements include walls, floors, ceilings, and roofs. Quantity takeoff for compound elements is complicated in both traditional and BIM-based methods because each material layer is found in a different location and may differ in size. In the traditional method, each material layer must be measured separately (Packer, 2016). In the BIM-based method, each layer of compound elements must be modeled to represent the exact dimension of the actual construction in order to obtain accurate quantities (Zima, 2017). Furthermore, some layers of compound elements must contain sub-components for quantity takeoff, such as wall framings in a structural layer of drywalls. However, in practice, these sub-components are usually absent from the BIM model given to contractors (Olsen and Taylor, 2017). Also, the compound elements in a BIM model are generally treated as single model elements with defined material layers (Monteiro et al., 2014). In this modeling method, the size and composition of each layer are not freely controlled or adjusted so deviations in material quantities are possible if each layer must have a different size and composition (S. Kim et al., 2019; Monteiro et al., 2014; Monteiro and Martins, 2013; Zima, 2017). For example, the interior finish layer of a wall might reach the height of the ceiling, while the core structural layer of a wall reaches the soffit of the beam or the floor above. In addition, the compound elements in a BIM model could be modeled by overlapping with other elements causing excess material quantities (Khosakitchalert et al., 2019a, 2020, 2018). For example, the walls may penetrate beams without subtraction, and the floor finish may overlap with columns and walls.

The recent solutions to solve these issues are to manually separate each layer of the compound element as an individual model element identical to the actual construction and eliminate the overlapping regions element by element. Besides, the sub-components must be modeled to obtain their material quantities. However, these solutions are a time-consuming and cost-intensive process. The complexity of 3D models also increases the risk of human error. Therefore, BIM-based quantity takeoff methods for compound elements would be proposed and validated in this research.

1.2 Research objectives

BIM can deliver accurate quantity takeoff if the geometries and data in the BIM model represent the actual construction. Compound elements always have complications when performing BIM-based quantity takeoff because they consist of multi-material layers that have different sizes and compositions. Generally, the compound elements in the BIM models from the design phases are single model elements with defined material layers, and some sub-components are not yet modeled, which leading to the deviation or missing of the material quantities extracted from the BIM models. Therefore, the objectives of this research are as follows:

(1) To study the discrepancy of inaccurate quantities of compound elements in BIM models caused by modeling methods.
(2) To improve the accuracy of the quantities of compound elements extracted from BIM models that are incomplete or incorrect.
(3) To reduce the working time and cost of editing or recreating BIM models, which will improve the performance of BIM-based quantity takeoff and cost estimation.
(4) To develop a method that can automatically modify compound elements in BIM models for accurate quantity takeoff.
(5) To develop a method that can embed the correct quantity results into the compound elements in BIM models.

1.3 Research significance

The research will provide an understanding of BIM-based quantity takeoff issues when extract quantities from the compound elements that are modeled using different modeling methods. The proposed methods in this research are beneficial for both professional practice and the research community. For professional practice, accurate material quantities of compound elements can be achieved from BIM models. The working time, cost, and error associated with editing BIM models to include accurate details of compound elements can be reduced. For the research community, the proposed methods are platform-independent, and hence they are applicable to develop the automatic quantity takeoff systems in any BIM software product.

1.4 Research scope

The focal compound elements in this research are architectural walls and architectural floors (or floor finishes) because they are major architectural components in which each material layer usually has its own distinction. Architectural walls and architectural floors are non-structural elements that are not served as the main structure of a building. Layers of compound elements that are reinforced concrete, such as concrete slabs and concrete walls, are excluded from the scope of the study because these layers are structural elements.

The BIM software used to develop prototype systems in this research must have modeling tools for architectural works, quantity takeoff tools, and an application programming interface (API). Hence, Autodesk Revit 2018.2 and Dynamo 1.3.3.4111 are chosen. Autodesk Revit is one of the BIM platforms for architectural works that has modeling tools, quantity takeoff tools, and an API, which is suitable for developing the prototype systems (Autodesk, 2020a). Dynamo is a user-friendly visual programming extension in Autodesk Revit requiring no programming background to develop and visualize results (Autodesk, 2016). Dynamo scripts can also be run directly in Autodesk Revit using the Dynamo Player feature, which is faster and easier than opening the Dynamo extension. Other BIM platforms for architectural works that have modeling tools, quantity takeoff tools, and an API can also be used to develop the systems. However, Autodesk Revit has the Dynamo extension that is easy and convenient for non-programming background users to use.

1.5 Overview of the dissertation

This dissertation consists of six chapters as follows:

Chapter 1 Introduction:

This chapter introduces the background information, problem statements, research objectives, research significance, research scope, and overview of all chapters in this dissertation.

Chapter 2 Literature review:

This chapter reviews the concepts, issues, and recent research that relates to this study. It is divided into five sections. The first section describes the brief definition of the traditional quantity takeoff, rules of measurement, and issues of traditional quantity takeoff in the current practice. The second section presents the focal compound elements used in this research and quantity takeoff methods of each element. The third section describes the definition, benefits, and platforms of BIM. The fourth section reviews the tools for extending the capabilities of BIM including API and visual programming language. The fifth section reviews the issues of BIM-based quantity takeoff, level of development (LOD) and its relationship to the BIM-based quantity takeoff, the cause of inaccurate quantities of compound elements, and previous research on the improvement of BIM-based quantity takeoff.

Chapter 3 Improving the BIM-based quantity takeoff for compound elements:

In this chapter, a comparative study to examine the inaccurate quantities caused by the modeling method is presented. Subsequently, a method to improve the accuracy and speed of BIM-based quantity takeoff for compound elements by using clash detection and calculation algorithms is proposed. The development of the prototype system is described. Validation is conducted. The results are discussed and summarized.

Chapter 4 Automatic modification of BIM models:

This chapter extends the proposed method from Chapter 3 to automatically modify the compound elements in BIM models. The corrected BIM models can then be used to extract accurate material quantities. The development of the prototype system is described. Validation is conducted. The results are discussed and summarized.

Chapter 5 Automatic calculation and embedding of quantity results into BIM models:

This chapter presents an alternative approach to obtain the correct material quantities from compound elements in a BIM model. Instead of modifying the compound elements, Chapter 5 proposes a method to calculate material quantities and embed them into the existing compound elements in a BIM model. The development of the prototype system is described. Validation is conducted. The results are discussed and summarized.

Chapter 6 Conclusions:

This chapter presents the conclusions and contributions of the research, then suggests recommendations for future works.

Chapter 2
Literature review

This chapter focuses on the topic of the traditional quantity takeoff, BIM technology, and issues of BIM-based quantity takeoff. It is divided into five sections. The first section reviews the definition, measurement standard, and issues of traditional quantity takeoff. The second section focuses on the compound elements in this research and quantity takeoff method of each element. The third section describes the overview concept of BIM, the advantages of BIM and BIM platforms. The fourth section describes the recent tools that can extend the capabilities of BIM. The fifth section reviews the issues when using BIM for quantity takeoff, the cause of inaccurate quantities of compound elements, and the previous studies that try to improve the BIM-based quantity takeoff.

2.1 Traditional quantity takeoff

Quantity takeoff is a process in which quantities of building materials or work tasks in a construction project are measured (Holm et al., 2005; Monteiro and Martins, 2013). It is a necessary task that is usually done after the design development phase to prepare a bill of quantity, which provides basic information for other tasks in the design and construction process (Farah, 2005; Holm et al., 2005; Liu et al., 2016; Monteiro and Martins, 2013). For instance, in the pre-construction phase, it is used to estimate the project cost for bidding or tendering the project. In the construction phase, it is used for schedule planning, purchasing materials, tracking progress, and calculating change orders and extra work payments. Therefore, the accuracy of quantity takeoff indicates the reliability of the following tasks (Firat et al., 2010; Royal Institution of Chartered Surveyors (RISC), 2012b).

2.1.1 Rules of measurement

In order to perform quantity takeoff correctly, quantity surveyors must follow the rules of measurement or measurement standards. Each building element and sub-element has a different rule of measurement and measurement unit. There are various measurement standards by different organizations used in different countries or companies in the world. Examples of them are (1) the new rules of measurement (NRM) by the Royal Institution of Chartered Surveyors (RISC) (Royal Institution of Chartered Surveyors (RISC), 2012a, 2012b, 2012c), (2) the standard method of measurement for building elements by the Hong Kong Architectural Services Department (Architectural Services Department Quantity Surveying Branch, 2015), (3) the standard method of measurement of building works by Singapore Institute of Surveyors and Valuers (Singapore Institute of Surveyors and Valuers, 1986), and (4) the Malaysian standard method of measurement of building works by The Institution of Surveyors, Malaysia (The Institution of Surveyors Malaysia, 2000).

This research adopted the NRM as the rules of measurement throughout the study because, from the literature reviews, this standard is commonly used in several studies (Abanda et al., 2017; Cheung et al., 2012; P. Smith, 2014). Furthermore, this standard explains the measurement method in great detail.

The NRM consists of three documents:

(1) NRM1: Order of cost estimating and cost planning for capital building works (Royal Institution of Chartered Surveyors (RISC), 2012a).
(2) NRM2: Detailed measurement for building works (Royal Institution of Chartered Surveyors (RISC), 2012b).
(3) NRM3: Order of cost estimating and cost planning for building maintenance works (Royal Institution of Chartered Surveyors (RISC), 2012c).

The NRM2 is mainly used in this research because it provides detailed measurement rules for the preparation of the bill of quantities after the design development phase. The NRM1 and NRM3 are not used because the NRM1 is used for cost estimating and cost planning in the design phases where the details of the buildings are not fully developed and the NRM3 is used for cost estimating and cost planning in the maintenance phase, which is out of the scope of this study. The measurement methods for compound elements will be further described in Section 2.2.

2.1.2 Issues of traditional quantity takeoff

Traditionally, quantity takeoff is performed manually using 2D construction drawings. The procedures of the traditional quantity takeoff are as follows (Holm et al., 2005). Initially, quantity surveyors have to review all construction drawings, including floor plans, sections, elevations, and detail drawings, to understand all project information. If they find any issues, they have to submit the request for information (RFI) to the designers. After that, they will begin measuring each building element from the construction drawings according to the rules of measurement that they adopt. During the measurement, they will mark the items on the drawings that have been quantified using a highlighter or a pen. After the measurement, they have to recheck the marks on the drawings again for any items that have not been quantified. Then they have to check the bill of quantity to verify that all calculations are correct. All in all, the traditional quantity takeoff is a time-consuming and error-prone process because it is based on manual measurements of 2D construction drawings and human interpretations (Holm et al., 2005; Juszczyk et al., 2014; Monteiro and Martins, 2013). The results from quantity surveyors with different experiences and knowledge may not be the same. Furthermore, the low quality of drawings and specifications is a challenge for traditional quantity takeoff (Nani and Adjei-Kumi, 2007).

Advances in computer-aided design (CAD) and spreadsheet software have improved the convenience and efficiency of the calculation process (Brook, 2017). CAD software not only provides the digital tools for drafting construction drawings, but also the tools for measuring lengths, areas, and volumes from those drawings. Some CAD software, such as PlanSwift, CostX, and Bluebeam Revu, is designed specifically for assisting traditional quantity takeoff in a digital way. Spreadsheet software, such as Microsoft Excel, Google Sheets, and LibreOffice Calc, is used for managing bill of quantities (BOQ) and calculating quantity results. However, the overall process is still time-consuming and error-prone. This is because 2D and 3D geometries in a CAD file do not have any semantic information. Quantity surveyors have to do the majority of manual works, such as selecting geometries that represent doors to count items, selecting vector lines that represent walls to measure lengths, and drawing the overlay areas to measure areas or volumes of rooms.

2.2 Compound elements

Compound elements are building elements that are composed of multiple layers of materials (Autodesk Knowledge Network, 2018). Examples of compound elements are walls, floors, ceilings, and roofs (see Figure 2.1). These building elements are complicated in both traditional and BIM-based quantity takeoff because each material layer has unique size and composition. Therefore, they must be measured separately (Packer, 2016).

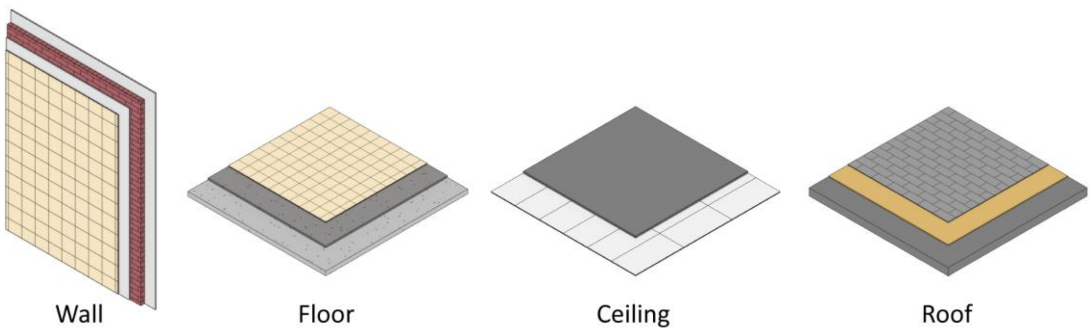

Figure 2.1 Examples of compound elements.

In this research, architectural walls and architectural floors (or floor finishes) are two focal compound elements. They are non-structural elements, which do not bear the weight of a building. The details and the rules of measurement of walls and floors are described in the following sections.

2.2.1 Walls

A wall is a building element that can be either a structural element or a non-structural element (architectural element). A structural wall is a loaded bearing wall that is a part of a building structure. Reinforced concrete walls are the common structural walls in the present day. They are measured as their volume of concrete (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). An architectural wall is a non-load bearing wall that can be constructed between structural frames as an envelope of a building or as a partition that divides interior spaces. Masonry walls and drywalls are the two major architectural walls in the present day. They are measured as their surface area of each material layer (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). This research focuses only on architectural walls. Therefore, all material layers of walls are measured as their surface area.

Architectural walls consist of two major layers: a core structural layer and finish layers.

2.2.1.1 Core structural layer

A core structural layer of a wall is a layer at the center of the wall that is served as the structure of the wall. Based on the construction materials, a core structural layer of a wall consists of masonry units for a masonry wall and wall framings for a drywall.

(1) *Masonry walls*

Masonry units, such as bricks, concrete blocks, and stones, and mixed mortar are materials used to form a core structural layer of a masonry wall (see Figure 2.2). This research focuses on the masonry wall in Chapters 3 and 4.

To prepare a bill of quantity in a pre-construction phase, a masonry layer is measured as its surface area by multiplying the center-line length of the walls by the height of the walls. Subsequently, the areas of wall openings, such as doors, and windows are subtracted from the calculated area to form the net surface area (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). In a construction phase, the number of masonry units and mortar for material purchase can be calculated by multiplying the surface area of the masonry layer by the number of masonry units or mortar per area (Brook, 2017).

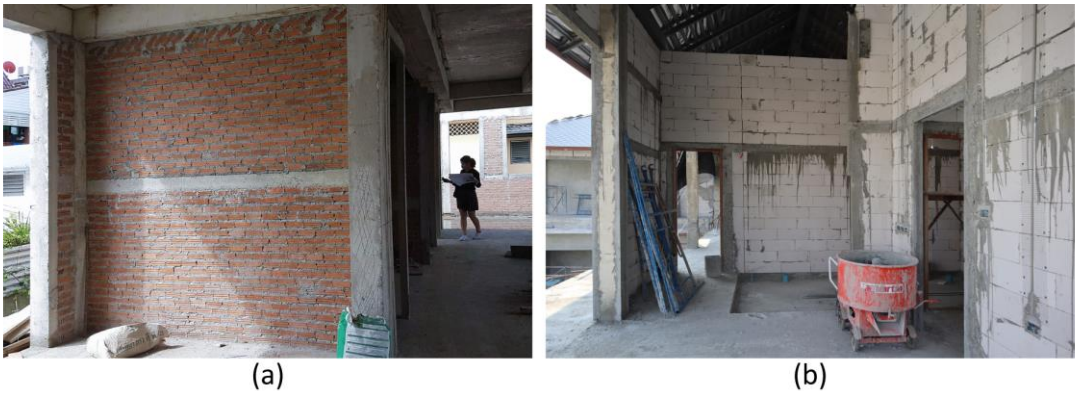

Figure 2.2 Examples of masonry units in masonry walls: (a) brick masonry units and (b) lightweight concrete masonry units.

(2) Drywalls

A wall framing system is a core structural layer of a drywall. The material of wall framing members can be either wood or steel (see Figure 2.3). However, in current drywall constructions, a light-gauge steel framing system is used as an alternative to a wood framing system (Packer, 2016).

Figure 2.3 Examples of wall framings in drywalls: (a) wood wall framings and (b) light-gauge steel wall framings.

This research focuses on a light-gauge steel framing system in Chapter 5. Components of a light-gauge steel framing system in a drywall are more complex than the masonry units in a masonry wall. According to the installation guides for a light-gauge steel framing system for non-load bearing walls from the wall framing suppliers (The Siam Cement Group Public Company Limited, 2016; The Siam Gypsum Industry (Saraburi) Company Limited, 2015; USG Australasia, 2011), the horizontal members have a U-shaped steel section and are called U-tracks, whereas the vertical members have a C-shaped steel section and are called C-studs. The components in a light-gauge steel framing system are illustrated in Figure 2.4. The U-track at the top of the wall attached to a ceiling or a soffit of a floor above is called the top track. The U-track at the bottom of the wall attached to a floor is called the bottom track. The U-track between the top and bottom tracks is called the nogging track. The spacing value of the nogging tracks depends on the need for bracing to prevent studs from rotating and buckling. The U-track at the top of a door or window is called the header track. The U-track at the bottom of a window is called the sill trimmer track. The C-stud installed between the top track and the bottom track is called the common stud. The C-stud installed between the top tracks and the headers or the sill trimmers and the bottom tracks is called the jack stud. The general spacing value of C-studs is a maximum of 600 mm center-to-center. The C-stud at each side of the opening should use two C-studs combined into one boxed stud for better strength. Furthermore, extra C-studs are needed at the intersections and the corners of drywalls. Two possible details, which depend on the construction site, are shown in Figure 2.5 (The Siam Cement Group Public Company Limited, 2016; The Siam Gypsum Industry (Saraburi) Company Limited, 2015; USG Australasia, 2011). Construction detail A has one extra C-stud at a corner and a T-intersection, and has two extra C-studs at a cross intersection. Construction detail B only has one extra C-stud at a cross intersection.

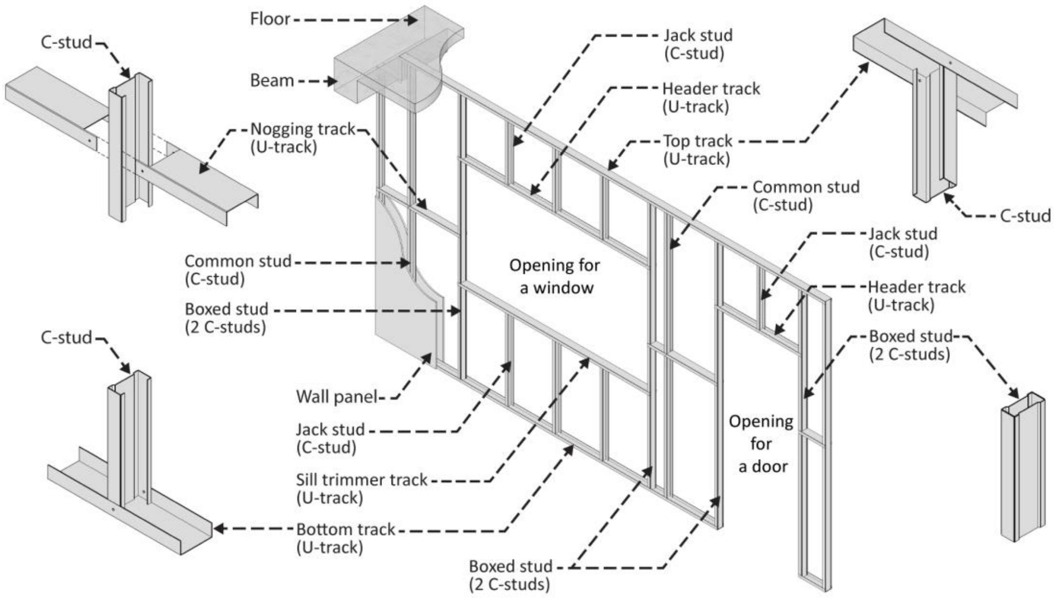

Figure 2.4 Components in a light-gauge steel framing system.

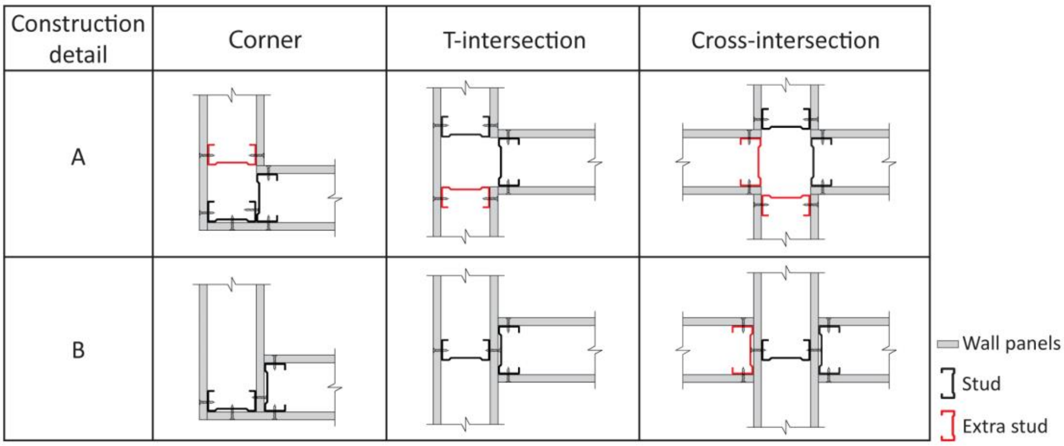

Figure 2.5 Two possible details at intersections and corners of a light-gauge steel framing system.

To prepare a bill of quantity in a pre-construction phase, it is similar to the masonry layer. A wall framing layer is measured as its surface area by multiplying the center-line length of the walls by the height of the walls. Subsequently, the areas of wall openings, such as doors, and windows are subtracted from the calculated area to form the net surface area (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). In a construction phase, light-gauge steel framing members are sold by the linear meter; therefore, their quantity is measured by length. Traditionally, there are two quantity takeoff methods for wall framings: by wall framing spacing and by wall framing per area (Holm et al., 2005). Additional interviews with quantity surveyors in Thailand, where the case study in Chapter 5 took place, gathered more details about both methods.

The first method calculates the lengths of the wall framings from the wall dimensions (lengths and heights) and spacing values of C-studs and U-tracks. The length of the U-tracks is calculated by the following method. The wall height is divided by the spacing of the U-tracks and the result is rounded up to a whole number and one is added for the end track. This yields the number of U-tracks. Finally, the number of U-tracks is multiplied by the wall length to get the total length of the U-tracks. The length of the C-studs is calculated by the following method. The wall length is divided by the spacing of the C-studs, and the result is rounded up to a whole number and one is added for the end stud. This yields the number of C-studs. The number of extra C-studs at the intersections, corners, and openings is counted and added to the number of C-studs. Finally, the number of C-studs is multiplied by the wall height to get the total length of the C-studs.

The second method calculates the lengths of the wall framings from the wall areas and the lengths of the C-studs and U-tracks per square meter. The wall areas should be the net areas with the doors, windows, and other elements that overlap with the walls subtracted. The length of the U-tracks is calculated by multiplying the wall areas by the lengths of the U-tracks per square meter. The length of the C-studs is calculated by multiplying the wall areas by the lengths of the C-studs per square meter. Then, the length of extra C-studs at the intersections, corners, and openings, which is calculated by multiplying the number of extra C-studs by the wall height, is added for more accurate results.

Both methods are estimations; therefore, the results could deviate from the actual values. However, the methods are faster and more practical than counting the actual number of wall framings. Furthermore, most construction drawings contain only typical details of wall framings, not the full details of the wall framings. Therefore, it is impossible to count the actual number of wall framings from the construction drawings.

2.2.1.2 Finish layer

Finish layers of a wall are material layers that cover a core structural layer of a wall. Normally, they cover the core structural layer on both sides and each side may have one or more layers. Materials for wall finish layers can be divided into two major groups: materials for finish layers of a masonry wall and material for finish layers of a drywall.

(1) Masonry walls

Masonry walls usually have a wall plaster as the finish layers (see Figure 2.6a). In some cases, the walls have more than one finish layer. The second layer could be a wall tile layer on top of a tile mortar layer or a wallpaper layer on top of a plaster layer (see Figure 2.6b). Generally, the wall finish layers of the masonry wall not only cover the masonry layer, but also cover the surface of connected structural columns and beams. Furthermore, the interior finish layer and the exterior finish layer may have different heights. The height of the interior finish layer may attach to the ceiling level or may have a specific height while the height of the exterior finish layer attaches to the floor level above.

To prepare a bill of quantity in a pre-construction phase, a finish layer of the masonry wall is measured as its surface area. The surface area of the exterior wall finish of the masonry wall is calculated by multiplying the external girth or the perimeter length of the building by the floor-to-floor height. Subsequently, the areas of wall openings, such as doors, and windows are subtracted from the calculated area to form the net surface area (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). The surface area of the interior wall finish of the masonry wall is calculated by multiplying the internal girth or the perimeter length of the room and the floor-to-ceiling height or the specified height. Subsequently, the areas of wall openings, such as doors, and windows are subtracted from the calculated area to form the net surface area (Packer, 2016; Royal Institution of

Chartered Surveyors (RISC), 2012b). In a construction phase, the number of materials for material purchase can be calculated by multiplying the surface area of the finish layer by the number of finish materials per area (Brook, 2017).

Figure 2.6 Examples of finish layers of masonry walls: (a) wall plaster and (b) wall tiles.

(2) *Drywalls*

Drywalls have drywall sheets (or drywall panels) as the finish layer (see Figure 2.7). Examples of drywall sheets are gypsum boards, particle boards, plywood boards, and fiber cement boards. Unlike the masonry wall, the finish layers of drywalls usually have the same size as the core structural layer.

To prepare a bill of quantity in a pre-construction phase, a finish layer of the drywall is measured as its surface area. The surface area is calculated by multiplying the external girth of the building or the internal girth of the rooms by the wall height. Subsequently, the areas of wall openings, such as doors, and windows are subtracted from the calculated area to form the net surface area (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). In a construction phase, the number of drywall sheets for material purchase can be calculated by multiplying the surface area of the finish layer by the number of drywall sheets per area (Brook, 2017).

Figure 2.7 Examples of finish layers of drywalls: (a) particle boards and (b) gypsum boards.

2.2.2 Floors

A floor is a building element that consists of a core structural layer and finish layers. The core structural layer is a part of a building structure while the finish layers are the material layers that are applied over a core structural layer.

2.2.2.1 Core structural layer

A core structural layer of a floor is also called a structural floor. It is a part of a building structure that supports all loads and transfers them to beams. The most common structural system for a structural floor is a reinforced concrete structure (see Figure 2.8a). Concrete is the main material and it is measured as its volume (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). Another structural system is a floor framing system. Joists and beams are the horizontal structural members in the floor framing system (see Figure 2.8b). They are measured as their length (Packer, 2016; Royal Institution of Chartered Surveyors (RISC), 2012b). However, the core structural layer or the structural floor is excluded from this research because it is a part of the building structure, which is out of the scope of the study.

(a) (b)

Figure 2.8 Examples of (a) a reinforced concrete floor and (b) a floor framing system.

2.2.2.2 Finish layer

Finish layers of a floor are also called floor finishes or architectural floors. They are material layers that are applied over a core structural layer of a floor (see Figure 2.9). They consist of a supporting layer and a top surface layer. Examples of materials for a supporting layer are concrete screed, wood boards, fiber cement boards, foam boards, and waterproof membranes. Examples of materials for a top surface layer are ceramic tiles, marble tiles, granite tiles, rubber tiles, vinyl tiles, wood planks, terrazzo, and carpets.

To prepare a bill of quantity in a pre-construction phase, the floor finishes are measured as their surface area. The surface area of the floor finishes is calculated from the interior perimeter of a room or the surfaces on which the floor finishes are installed (Packer, 2016; Royal Institution of Chartered

Surveyors (RISC), 2012b). The floor finishes are usually installed after structural elements and walls were built. Therefore, if there are walls and/or columns on the floor, the area of the floor finishes will be less than the area of their core structural layer. In a construction phase, the number of finish materials for material purchase can be calculated by multiplying the surface area of the floor finishes by the number of finish materials per area (Brook, 2017).

(a) (b) (c)

Figure 2.9 Examples of finish layers of a floor: (a) wood planks, (b) rubber tiles, and (c) ceramic tiles.

2.3 Building Information Modeling (BIM)

BIM is a technology that represents a physical built asset, such as buildings, bridges, and roads, as a digital model (ISO, 2018; National Institute of Building Sciences, 2007). It is used to facilitate design, construction, and operation processes to form a trustworthy source for decisions (ISO, 2018). Although the term “BIM” was firstly created in 2002 (Laiserin, 2002), the concepts and ideas of BIM were proposed since the eighties and nineties in the terms of “building product modeling” or “product modeling of buildings” (Eastman, 1999; Harfmann et al., 1993). BIM is the next generation of CAD technology that stores building information in a formal and computer-interpretable way (Underwood and Isikdag, 2009). The objective of this technology is to enable users to develop a digital model of a built asset that contains all information of that built asset (Underwood and Isikdag, 2009). This digital model is then used as the centralized source to provide reliable information about a built asset that can be shared and developed among all parties throughout the building life cycle (Sacks et al., 2018; Underwood and Isikdag, 2009).

2.3.1 Benefits of BIM

At present, BIM is increasingly used to assist the design, construction, and operation of the built asset in many countries (Wong et al., 2009). It gives benefits to all phases of a project life cycle as follows (Sacks et al., 2018; Underwood and Isikdag, 2009).

During a design phase, the 3D model created by the BIM software gives the best visualization for designers and owners. It also provides accurate and consistent 2D drawings, which are extracted directly from the BIM model. When the model is changed, all 2D drawings are automatically updated, which reduces the amount of time and the number of errors associated with editing the drawings. The BIM model can be shared among design disciplines to work in a collaborative way, which reduces design errors. Furthermore, the BIM model can be used for analysis, such as extracting total floor areas for budget estimation and linking the BIM model to energy analysis tools for evaluation of energy use.

During a pre-construction phase and a construction phase, the BIM model can be used to detect and fix conflicts between design disciplines through clash detection. Clash detection is an automatic process for checking spatial conflicts between building objects by overlaying building objects from different disciplines and applying solid modeling algorithms to check intersections. Furthermore, when the BIM model is edited or changed, the construction drawings can be automatically updated. The 3D objects in the model can be linked to a construction plan to simulate the construction process, which reveals potential problems and possible improvements. The BIM model can also be used to extract material quantities for cost estimation during a pre-construction phase and material purchase during a construction phase. In addition, some components in a BIM model, such as precast components and curtain wall components, can be developed to be used in an automated fabrication.

During an operation phase, the BIM model provides an accurate source for managing and operating the building. All project information can be linked to the objects in the BIM model and handed to the owner for use in the facility management system when the building is completed.

All in all, the adoption of BIM can make the design and construction industry more efficient, effective, flexible, and innovative (Takim et al., 2013).

2.3.2 BIM platforms

BIM platform is a set of BIM applications that are developed based on the same primary data model (Sacks et al., 2018). Most BIM platforms include tools such as modeling, rendering, drawing production, and clash detection in their platforms. Examples of BIM platforms in the current market are Autodesk Revit, Graphisoft ArchiCAD, Trimble Tekla Structures, Bentley AECOSim, Digital Project, Nemetschek Allplan, and Nemetschek Vectorworks (Bouška, 2016; Sacks et al., 2018). Most platforms are designed to cover tools, functions, and libraries for working in different domains, including architecture; structure; and mechanical, electrical, and plumbing (MEP).

Different companies may use different BIM platforms through different phases of a project. To work collaboratively in a BIM environment, reducing or preventing data loss during the data exchange between platforms is important (Sacks et al., 2018). One approach for data exchange is through a standard data schema such as Industry Foundation Classes (IFC), which is the open BIM data exchange standard (buildingSMART International, 2020).

This research chooses Autodesk Revit as a BIM platform to develop prototype systems and validate the proposed method. Autodesk Revit is a popular and strong BIM platform that has a wide range of supporting applications (Sacks et al., 2018). It has modeling tools, a quantity takeoff tool, and a direct data link through an API, which is suitable for developing the prototype system (Autodesk, 2020a).

2.4 Extending the capabilities of BIM

BIM models are object-based information models that consist of geometric and non-geometric data of a facility (National Institute of Building Sciences, 2007). Therefore, the information in BIM models can be accessed and used for various purposes, such as quantity takeoff, cost estimation, energy analysis, wind simulation, design optimization, and construction planning (Sacks et al., 2018). Applications for particular purposes can be created using programming languages or visual programming languages, and then connect to the information in a BIM model via an API.

2.4.1 Application programming interface (API)

API is used to connect the information in a BIM model and exchange information between two applications (Sacks et al., 2018). It allows users to access the information stored in the BIM database and perform computational tasks on it (Singh et al., 2017, 2016). Furthermore, users can customize all parameters and properties of all building elements in a BIM model. Therefore, applications, custom tools, and plug-ins can be developed using the API (Kensek and Noble, 2014).

Each BIM platform has its own API. This research focuses on the Autodesk Revit platform; therefore, the Revit API is used. Revit API allows users to program with any .NET compliant language including VB.NET, C#, and C++/CLI (Autodesk, 2020b). Autodesk Revit also has a built-in extension called Dynamo, which allows users to use the Revit API via a visual programming language and Python programming language (Autodesk, 2016).

2.4.2 Visual programming language

Visual programming languages are programming languages that allow users to create a program through graphical elements instead of typing texts (Craft ai team, 2015). It allows users with non-programming background, such as architects and engineers, to develop their own custom tools. The well-known visual programming languages for architectural design are Grasshopper used in Rhinoceros and Dynamo used in Autodesk Revit (Boeykens, 2012). However, Grasshopper is developed for Rhinoceros, which is a 3D modeling software, not a BIM software (Davidson, 2020). Therefore, currently, Dynamo is the only visual programming language for BIM.

Dynamo is developed independently from Revit using the Revit .NET API (Boeykens, 2012). It has a stand-alone version and a plug-in version that is integrated into Autodesk products such as Revit (Autodesk, 2016). This research uses the Dynamo and the Revit API to develop prototype systems. Dynamo for Revit allows users to create algorithms to process or manipulate any Revit elements via Revit API. Functions and variables in Dynamo are represented by node elements. Each node has input and/or output ports, which enable users to wire it together to form a custom algorithm (Autodesk, 2016; Kensek, 2014). Furthermore, Dynamo allows users to write Python scripts in Python nodes to replace many nodes with a few lines of code and to extend the capabilities of Dynamo, such as conditional statements and looping (The Dynamo Primer, 2019).

2.5 BIM-based quantity takeoff

Early research attempted to improve the efficiency of quantity takeoff based on the 2D and 3D CAD technology. For example, Jadid and Idrees (2007) proposed a method for automatically calculating quantities of structural elements by recognizing these elements from each layer of 2D CAD drawings. Manrique et al. (2015) proposed an automatic system for generating shop drawings of wood-framing walls in a 3D CAD model as well as extracting material quantities required for wall assembly.

The development of BIM technology introduces a new approach for quantity takeoff called BIM-based quantity takeoff. A BIM model includes computable graphics and data attributes for each model element, meaning quantities can be extracted directly from the objects identified in the model (Sacks et al., 2018). Bečvarovská and Matějka (2014) compared traditional quantity takeoff and BIM-based quantity takeoff using a case study. The study showed that a BIM-based method substantially minimizes time spent and deviations in accuracy when compared to the traditional method. All in all, BIM-based quantity takeoff delivers better reliability, accuracy, and speed compared with the traditional quantity takeoff method (Bečvarovská and Matějka, 2014; Nadeem et al., 2015; Sacks et al., 2018; Sattineni and Bradford, 2011).

2.5.1 Issues of BIM-based quantity takeoff

In principle, a single centralized BIM model is shared, exchanged, developed, and integrated among stakeholders from the building design phase to the facility management phase (ISO, 2018; Underwood and Isikdag, 2009). However, in practice, BIM models are developed through each phase in a building life cycle, and different models for different purposes is a better approach to deal with model complexity and file size (Kensek and Noble, 2014). For example, designers make BIM models for the visualization and production of building drawings, while contractors make BIM models for cost estimation and construction planning. Fragmentation of BIM models causes gaps when models are transferred among parties in the design and construction phases (Kensek and Noble, 2014).

Several studies have reported the issues of the BIM-based quantity takeoff method in practice. Firat et al. (2010) explored a BIM-based quantity takeoff process using two case studies. They concluded that the lack of modeling guidelines obstructs the quantity takeoff process, and the model should be created in a way that is easy and possible for quantity takeoff. P. Smith (2014, 2016) reported that the quality of BIM models and the ability of quantity surveyors to check BIM models are the issues that affect the quality of a BIM-based quantity takeoff. A study by Franco et al. (2015) revealed that the cost and time associated with modeling are the reasons that BIM is rarely used for quantity takeoff and cost estimation. A survey study by Sattineni and Bradford (2011) showed that most of the BIM models that general contractors received from design teams cannot be used for estimating purposes. Olsen and Taylor (2017) reported that BIM models given to general contractors have only up to 50% of the data needed for quantity takeoff. The examples of the insufficient quantities include architectural finishes; temporary structures; mechanical, electrical, and plumbing (MEP); and landscaping. Monteiro and Martins (2013) studied a quantity takeoff feature in ArchiCAD software, finding that some building elements do not have corresponding modeling tools and some modeling tools do not provide the correct material quantities. All in all, similar to the low quality of drawings that limits traditional quantity takeoff (Nani and Adjei-Kumi, 2007), the quality of BIM models is also a challenge in BIM-based quantity takeoff.

2.5.2 Level of development (LOD) and its relationship to the BIM-based quantity takeoff

To ensure that a BIM model transferred from the design phases has a suitable quality for quantity takeoff, the LOD for each BIM model element should be clearly determined (Firat et al., 2010; P. Smith, 2016; Wood et al., 2014). LOD is the degree of geometry detail and attached information for each BIM model element in each design and construction phase (BIMForum, 2019). It directly affects the accuracy of the quantity takeoff (Peansupap and Thuanthongdee, 2016).

The BIMForum has developed a LOD specification based on the LOD definitions by the American Institute of Architects (AIA) (BIMForum, 2019). The LOD specification illustrates clear characteristics of model elements at different LODs (P. Smith, 2016), which are divided into 5 levels: LOD 100, LOD 200, LOD 300, LOD 350, and LOD 400 (BIMForum, 2019). LOD 300, LOD 350, and LOD 400 represent a specific object in terms of quantity, size, shape, location, and orientation (BIMForum, 2019). Therefore, they are commonly used in the design development phase, where specific building elements should be defined. Monteiro and Martins (2013) reported that building model elements at LOD 300 are typically satisfactory for quantity takeoff. However, for compound elements including walls and floors, LOD 350 is better for quantity takeoff because each material layer is separated as an individual model element (see Figure 2.10b), while at LOD 300, the compound elements are single model elements with defined material layers (see Figure 2.10a) (BIMForum, 2019).

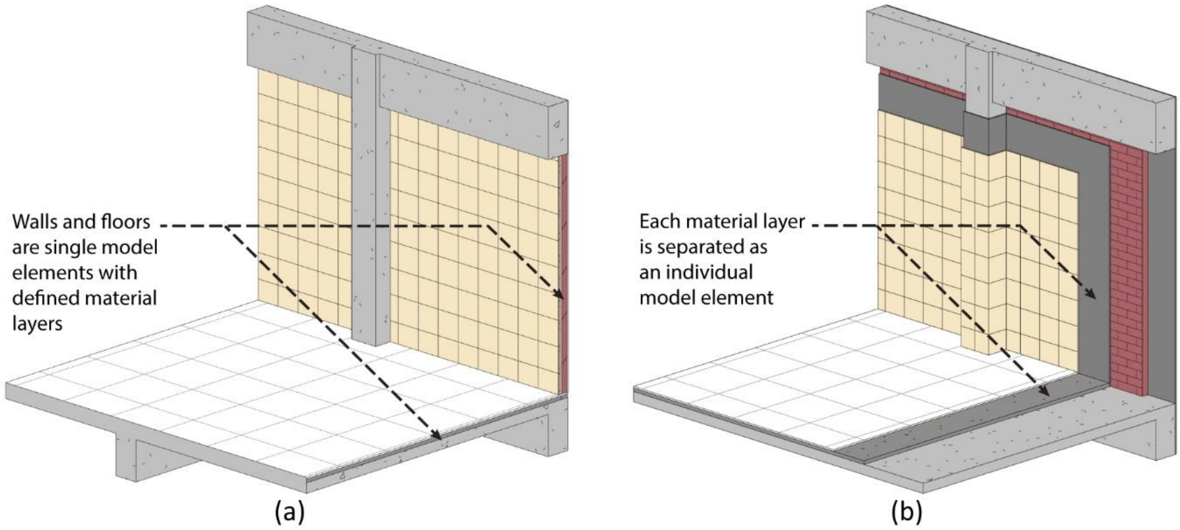

Figure 2.10 (a) A masonry wall and a floor at LOD 300. (b) A masonry wall and a floor at LOD 350.

Furthermore, during a construction phase, some building elements need to be measured their sub-component for material purchase. Examples include wall framings in drywalls and wire mesh and rebar in reinforced concrete slabs (Khosakitchalert et al., 2019b; Peansupap and Thuanthongdee, 2016). Figure 2.11 illustrates a drywall at LOD 300 that does not contain wall framing, while a drywall at LOD 350 contains wall framings, which can be used for BIM-based quantity takeoff. Therefore, some building elements require LOD 350 or higher for material purchase in a construction phase.

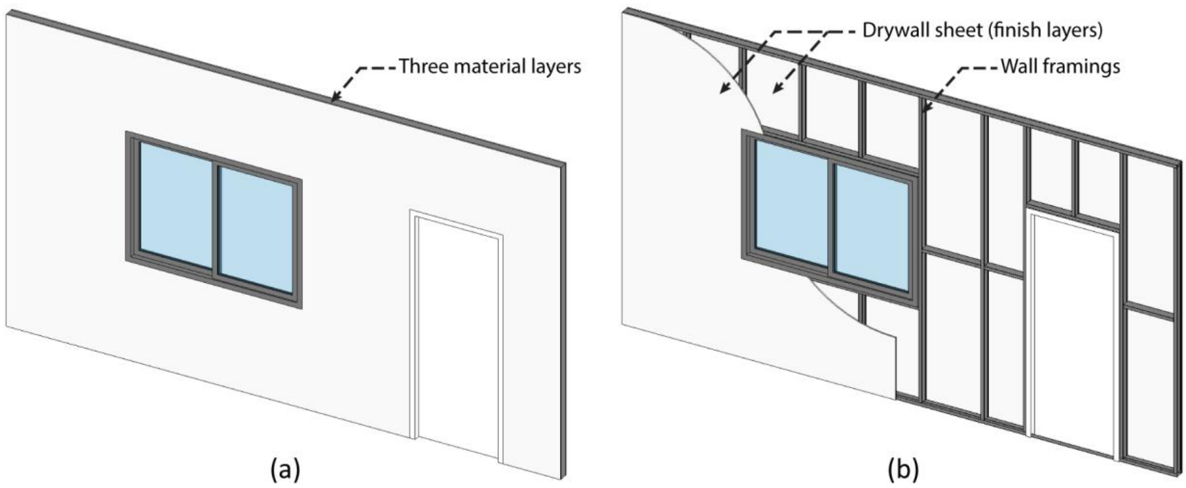

Figure 2.11 (a) A drywall at LOD 300 has defined material layers. (b) A drywall at LOD 350 has details of wall framings.

However, changing compound elements from LOD 300 to LOD 350 or separating material layers into individual model elements requires time, money, and effort. Developing building elements in BIM models from one LOD to another increases the total modeling time by a factor of two to eleven (Leite et al., 2011). This is because each material layer of compound elements must be manually created as an individual model element.

2.5.3 The cause of inaccurate quantities of compound elements

The properly defined LOD must be executed by the correct modeling method, otherwise, quantities extracted from building model elements can deviate from actual values. Modeling methods developed for compound elements can result in inaccurate quantity takeoff. There are two modeling method issues that cause inaccurate quantities of compound elements.

The first issue is that each layer of a compound element is not modeled identically to the actual construction. This issue has been studied using commercial BIM software products, including Autodesk Revit and Graphisoft ArchiCAD, and the open standard for BIM, Industry Foundation Classes (IFC). The studies have shown that when walls and floors are modeled as single model elements, the ability to adjust the size and composition of each material layer is lost, leading to deviations when extracting quantities for each material layer (S. Kim et al., 2019; Monteiro et al., 2014; Monteiro and Martins, 2013; Zima, 2017). Generally, the compound element in a BIM model is created as a single model element in a schematic design phase. Then, the material layers are assigned to the single model element when the designer determines the materials for the compound elements. Thus, these layers have the same size and quantity. However, in the actual construction, these layers do not always have the same size. In the case of floors, the architectural floors or floor finishes are installed after the columns and the walls are built on the structural floors (see Figure 2.9 and Figure 2.13b). Thus, the floor finishes should be created separately from the structural floors. In the case of walls, they are an obvious element in which each layer can have various sizes. For example, the wall finish layers, such as a wall plaster layer, a wall tile layer, and a wallpaper layer, can cover the surface of connected structural columns and beams (see Figure 2.12). Also, the height of each wall layer may vary. To illustrate, the height of the interior finish layers of the walls may attach to the ceiling level or may have a specific height, while the height of the core structural layer is attached to the undersides of beams (see Figure 2.12).

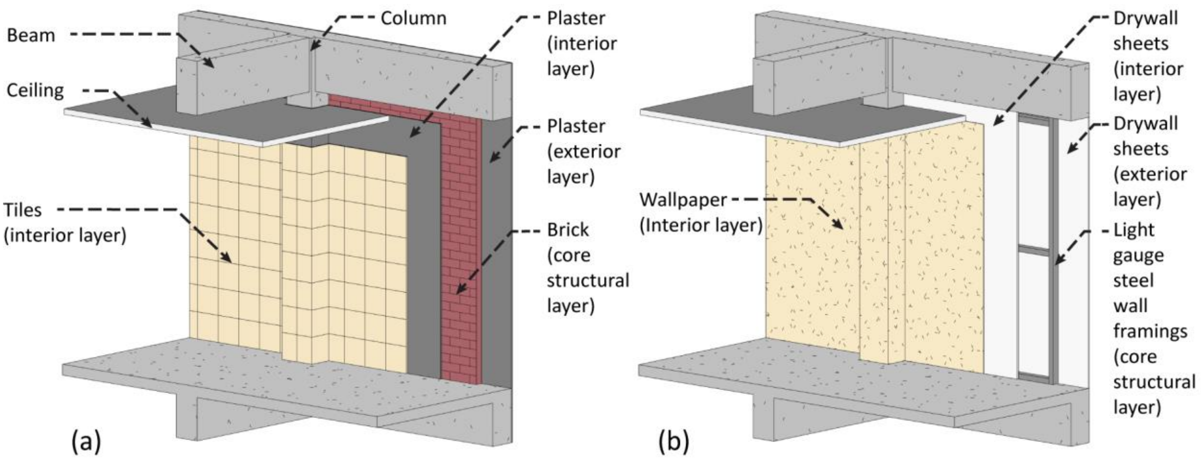

Figure 2.12 Example of (a) masonry wall layers and (b) drywall layers that have various sizes.

The second issue is that the compound elements can be created by the overlap with other building elements, resulting in excess material quantities (Khosakitchalert et al., 2019a, 2020, 2018). In the case of floors, portions of the floor finishes may be under columns and walls. The overlapping regions under the columns and walls thus represent excess quantity because in the actual construction, the floor finishes, which consist of supporting layers and a top surface layer, are constructed after the columns and the walls were built on the structural floors (see Figure 2.13). Moreover, walls should not be built on floor finishes because their weight can damage floor finish materials. In the case of walls, they may be drawn as overlapping with structural columns and beams of the level above. The portions of the walls that overlap inside the structural element represent excess quantity because, in the actual construction, the walls cannot be inside the structural element (see Figure 2.14). However, this modeling approach is intentionally used in some cases, such as producing architectural drawings, because the model is easier to make and edit when compared to a method that separates every element, and the overlapping elements can be hidden by graphic overlays.

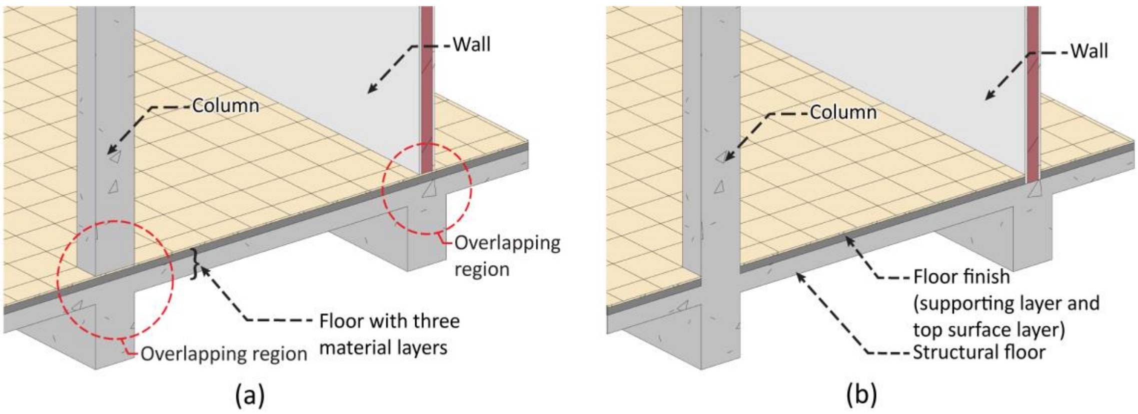

Figure 2.13 (a) The architectural floor (floor finish) is placed under the column and wall, causing excess floor material quantity. (b) The correct modeling method separates the architectural floor (floor finish) from the structural floor to avoid the overlapping regions.

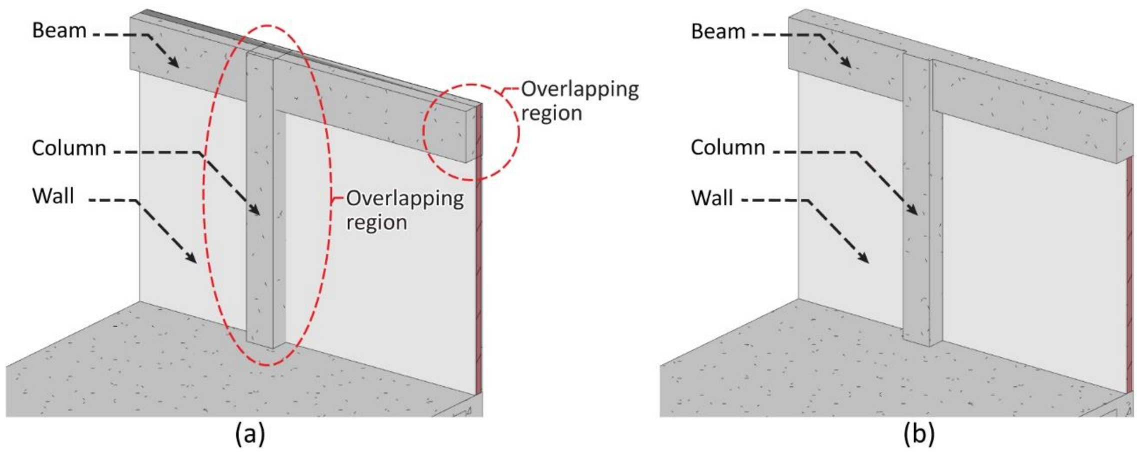

Figure 2.14 (a) The wall that overlaps with the column and beam causes excess wall material quantity. (b) The correct modeling method separates the wall from the structural elements.

In summary, to extract accurate material quantities of walls and floors, each material layer should be created as an individual model element (S. Kim et al., 2019; Monteiro and Martins, 2012; Zima, 2017) and overlapping regions must be eliminated. Figure 2.15a illustrates an example of a BIM model that walls and floors are modeled as single model elements with defined material layers and the walls overlap with columns, beams, and floor finishes (see the circled areas). Figure 2.15b illustrates an example of a BIM model that has been fixed for accurate quantity takeoff. Each layer of walls and floors is separated as an individual model element and all overlapping regions are eliminated (see the circled areas). However, manual separating each layer and removing overlapping regions is a time-consuming, cost-intensive, and error-prone process, especially for complex models.

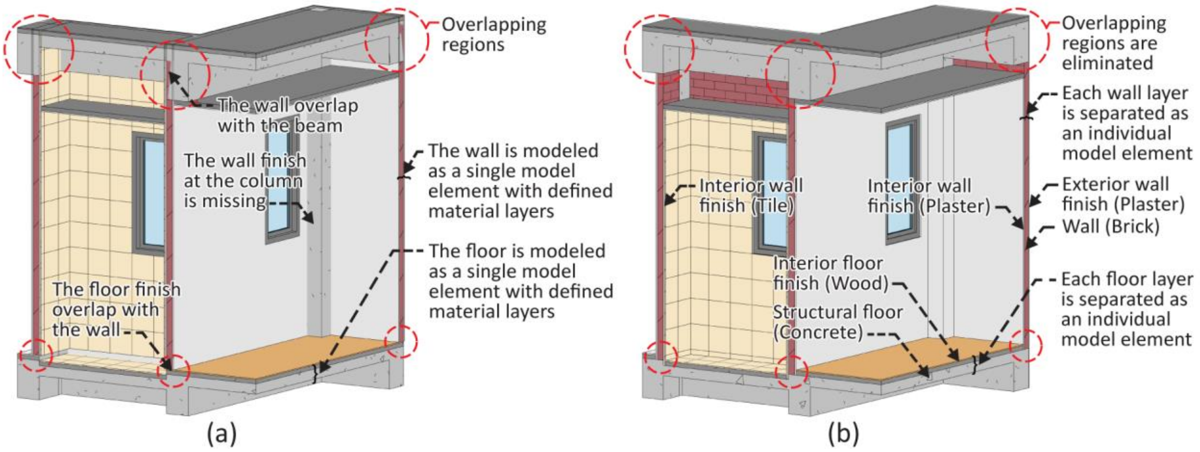

Figure 2.15 (a) Walls and floors are modeled as single model elements with defined material layers. The circled areas indicate the overlapping regions that cause excess material quantities. (b) Wall and floor layers are separated as individual model elements. The circled areas indicate the overlapping regions that are eliminated.

2.5.4 Previous research on the improvement of BIM-based quantity takeoff

Several studies have been conducted to improve the efficiency of BIM-based quantity takeoff and cost estimation. The research papers can be classified into four groups.

The first group studied and suggested BIM modeling methods that can provide accurate quantity results. Monteiro and Martins (2013) suggested using alternative modeling tools to create building elements for which the BIM software cannot extract the correct material quantities. Another study by Monteiro and Martins (2012) proposed four modeling methods for quantity takeoff of walls and floors and compared their strengths and weaknesses in terms of time, cost, and quality. Yun and Kim (2013) studied various modeling methods for reinforced concrete structure and proposed a suitable modeling method for BIM-based quantity takeoff. Peansupap and Thuanthongdee (2016) investigated the LOD for a precast concrete floor to use for cost estimations during bidding and material purchasing. They found that the BIM model of the precast concrete floor for material purchase needed additional details, which are wire mesh and rebar models. Zima (2017) found that walls with separated layers reflected the actual construction better, thus yielding more accurate quantities than walls with integrated layers. S. Kim et al. (2019) examined the deviation of material quantities of building interior components for different modeling methods. They recommended to model each material layer as an individual BIM object for the accurate quantity results.

The second group focuses on quantity takeoff and cost estimation methods from BIM models that do not contain adequate information. S. A. Kim et al. (2009) introduced an automatic modeling system for creating interior wall finishes in a room. Cheung et al. (2012) developed a real-time cost estimation system to calculate the cost of building using floor areas from BIM models in an early design stage. Aram et al. (2014) developed a knowledge-based system for precast concrete quantity takeoff from BIM models. Choi et al. (2015) developed a quantity takeoff system for structural frames of a building. The system has the ability to check the quality of BIM models before calculating quantities. Rajabi et al. (2015) developed a logic system that can estimate quantities of lighting and heating appliances that are not modeled in a BIM model. Cho and Chun (2015) proposed a cost estimation system for reinforced concrete structures that combines BIM-based quantity takeoff and quantity prediction using data mining. Lim et al. (2016) proposed calculation algorithms to estimate rebar from 3D structural models. Manrique et al. (2015) and Abushwereb et al. (2019) developed a CAD-based and a BIM-based system that can automatically generate wood framing models with a bill of quantity.

The third group focuses on linking BIM-based quantity takeoff with various standard databases. This group does not consider the correctness of the quantity extracted from BIM models. Ma, Wei, Song, et al. (2011) studied the possibilities for applying the Industry Foundation Classes (IFC) standard of BIM to the cost estimation standard in China. They then proposed a rule database and semantic database for generating a bill of quantities from the IFC data (Ma, Wei, Zhang, et al., 2011) and developed a semi-automatic system for BIM-based cost estimation (Ma et al., 2013). The proposed system has algorithms that automatically deduct the quantity takeoff results from building elements (columns and beams) that intersect each other. Lawrence et al. (2014) presented a rule-based approach to connect BIM objects with a cost database. Liu et al. (2014) integrated a BIM model with a construction process database for detailed cost estimating and scheduling planning. Furthermore, they developed a prototype system to connect a BIM model with work breakdown structure (WBS) information in Microsoft Access (Liu et al., 2015). Abanda et al. (2017) developed an ontology based on the NRM standard and applied it to BIM-based quantity takeoff.

The last group focuses on querying information and quantities from BIM models. Lin et al. (2013) developed a query system for quantity takeoff using natural language processing (NLP) and the International Framework for Dictionaries (IFD). Lee et al. (2014) proposed an ontology-based system to find tiling work items from work conditions extracted from BIM models. Liu et al. (2016) proposed an ontology-based approach for querying wall framing quantities using a domain vocabulary.

2.6 Summary

BIM-based quantity takeoff outperforms traditional methods, but it still has limitations. Various studies have attempted to improve the efficiency of BIM-based quantity takeoff in many aspects. However, the quality of the BIM model is the key issue, and it has a great impact on the accuracy of the extracted quantities. Previous studies indicate accurate quantities can be extracted from BIM models that are created according to proper modeling methods (Bečvarovská and Matějka, 2014; Firat et al., 2010; S. Kim et al., 2019; Monteiro and Martins, 2012, 2013). Nevertheless, an accurate detailed BIM model with complete information requires more time and higher costs for development (Aram et al., 2014; Monteiro and Martins, 2013). Although some studies proposed improved methods, including mathematical statistic models based on past information and calculation algorithms, to predict insufficient quantities extracted from BIM models (Aram et al., 2014; Cheung et al., 2012; Cho and Chun, 2015; Choi et al., 2015; Lim et al., 2016; Rajabi et al., 2015), no research has focused on using the benefits from BIM models that are incomplete or incorrect. Therefore, this research focuses on improving the accuracy of BIM-based quantity takeoff from the incomplete or incorrect building model elements. The building model elements in this study are compound elements, which are architectural walls and architectural floors (floor finishes), because they consist of multiple material layers and sub-components that can be modeled incorrectly or incompletely for BIM-based quantity takeoff. The proposed methods, the validations, the discussions, and the conclusion will be presented in the following chapters.

Chapter 3

Improving the BIM-based quantity takeoff for compound elements

As described in the previous chapters, the inaccurate quantity of compound elements is caused by the inappropriate modeling method. Manual modifying compound elements identical to the actual construction is time-consuming, cost-intensive, and error-prone. Therefore, the objective of this chapter is to develop a method that can automatically enhance the accuracy of the quantities of compound elements from BIM models that are incomplete or incorrect.

In this chapter, a comparative study to examine the inaccurate quantities is conducted. After that, the overview of the proposed method and the development of the prototype system are described in detail. The proposed method applies the BIM-based clash detection concept to detect the intersection between building elements. The calculation algorithms utilize the intersection information to automatically eliminate the overlapping quantities or add the absent quantities. The prototype system is verified, and the proposed method is validated through four case studies. The results and limitations are discussed. The conclusions are summarized. The calculation algorithms for detecting the intersection between building elements are then extended in Chapter 4 and Chapter 5.

3.1 A comparative study of inaccurate quantities of compound elements

To examine the inaccurate quantities caused by the modeling method, a comparative study was conducted before proposing a new method to solve the problem. Three building case studies are used in the comparison.

In order to test the deviation associated with different settings, three case studies were designed for different building shapes. The first case study is an L-shaped two-story house. The second case study is a U-shaped two-story house. The third and final case study is an I-shaped three-story house (see Figure 3.1). All cases are designed to have different scenarios with respect to the interactions between walls, floors, columns, and beams. For example, the first and second cases have walls attach to a gable roof, and the second case has floors that are raised above the ground level, with walls between the ground and floor levels. However, all cases are designed to have various scenarios of floors placed under columns (see Figure 3.2a), floors placed under walls (see Figure 3.2b), walls overlapping with beams and floors (see Figure 3.2c), walls overlapping with columns at corners (see Figure 3.2d), walls overlapping with other walls at corners (see Figure 3.2e), walls overlapping with columns along their sides (see Figure 3.2f), and walls overlapping with other walls along their sides (see Figure 3.2g).

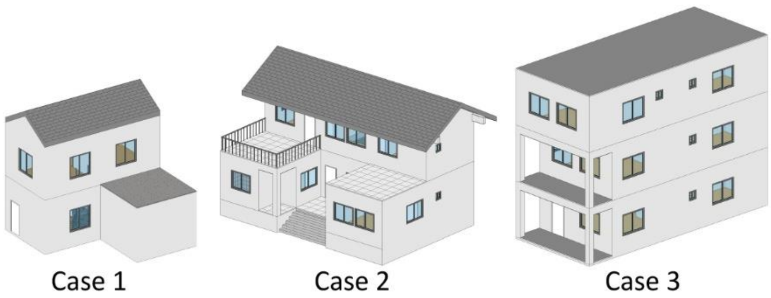

Figure 3.1 Three case studies.

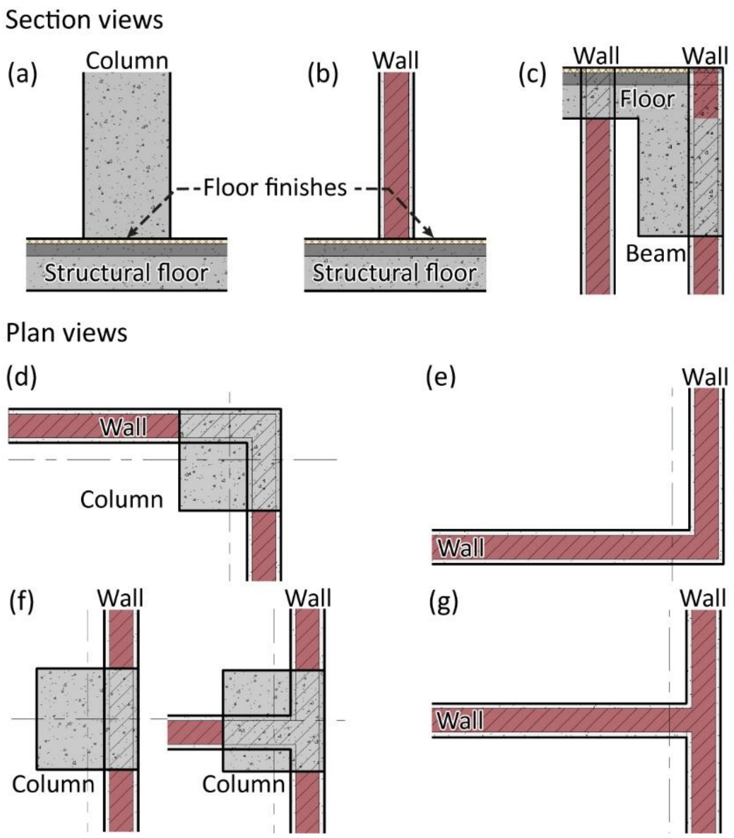

Figure 3.2 Scenarios of interactions between walls, floors, columns, and beams.

The walls in every case have at least three material layers: the core structural layer and the finish layers on both sides. The core structural layer is a brick material. The finish layer is divided into an exterior finish comprising an exterior plaster material and an interior finish comprising an interior plaster material. In addition, the walls that are located in the restroom will have a fourth layer that is a tile material layer. Each combination of the material layers forms one wall type. Each wall type is used for a specific location. For example, the wall that separates the interior and exterior will be of the wall type that has an exterior finish layer and an interior finish layer, while the walls that separate rooms in the interior will be of the wall type that has an interior finish layer on both sides (see Figure 3.3).

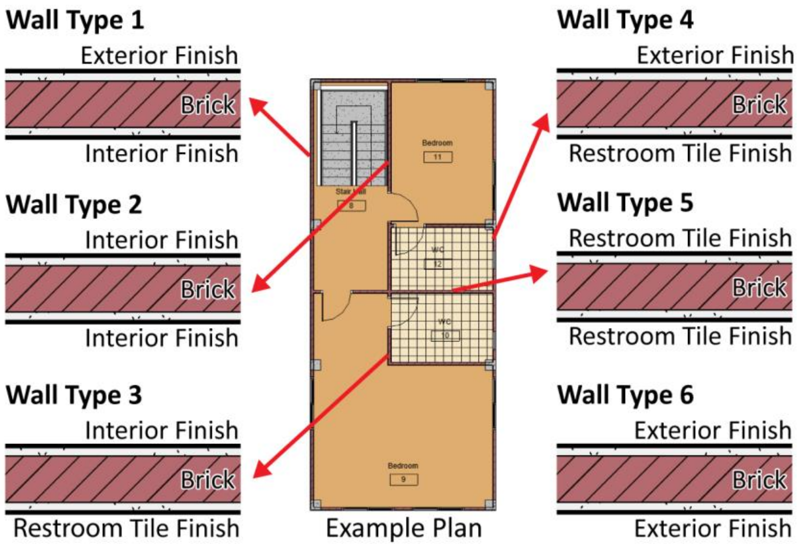

Figure 3.3 Different wall types from the combination of different material layers for specific locations.

The floors in every case have three material layers: the structural layer, the supporting layer, and the top surface layer. The floor finishes in the building usually consist of various materials. However, to simplify the study, the finish layer is divided into three materials for three locations: the exterior floors, the interior floors, and the restroom floors.

In order to compare the quantity results, two groups of BIM models are created. The first group comprises the BIM models that have inaccurate quantities for the walls and floors. This group is named "inaccurate BIM model." These BIM models are created according to the modeling method issues that are explained in Section 2.5.3. The walls and floors are single model elements with layers of materials. The walls are divided into different wall types according to the wall position (see Figure 3.3). They are created by overlapping with structural columns, beams, and floors. The height of each wall layer is not edited. The floor finishes are not separated from the structural floors. The floors are divided into different floor types according to the location, i.e., the exterior floor, the interior floor, and the restroom floor. The floors are placed under the structural columns and walls.

The second group comprises the BIM models that have accurate quantities. This group is named "accurate detailed BIM model." In this group, each layer of walls and floors is created as an individual model element because, according to the NRM, each layer of walls and floors must be measured separately. The walls do not overlap with the structural columns, beams, or floors. The wall finishes cover the walls, structural columns, and beams in the proper places, including the vertical surfaces inside rooms and the exterior surfaces of buildings. The materials and height of each wall layer are defined. The height of the interior finish reaches the ceiling height, and the height of the exterior finish covers the surface of the beams and floors above. In addition, the exterior finish that covers the underside and the top side of the beam is created by using a ceiling element instead of a wall element because the wall element cannot be created in a horizontal position. This ceiling element is composed of the same material as the wall element that represents the exterior finish. The floor finishes are separated from the structural floors. The material of each floor finish is defined. The floor finishes are created inside the boundary of the room, which does not overlap with the walls or structural columns. Figure 3.4 illustrates the differences between the inaccurate BIM model and the accurate detailed BIM model.

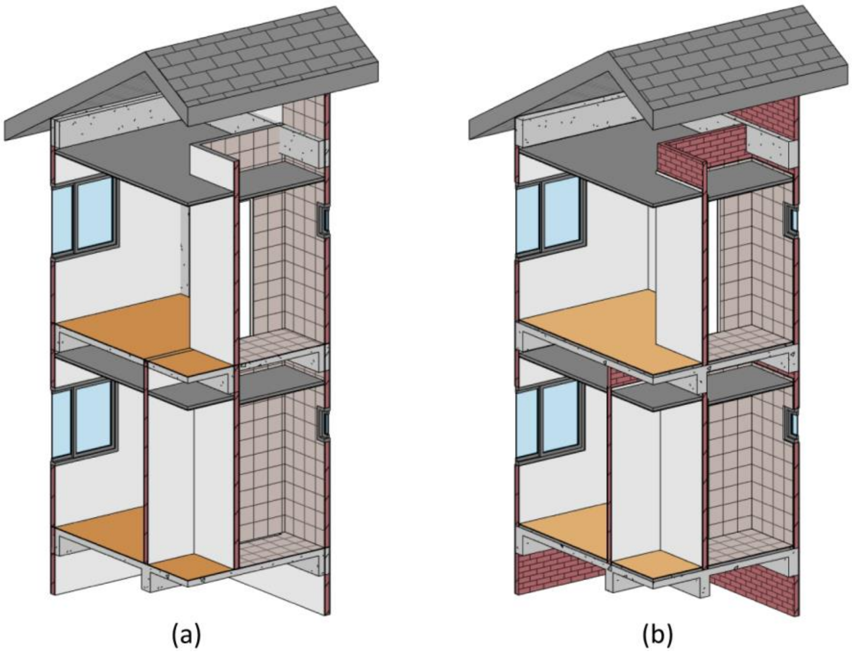

Figure 3.4 Three-dimensional section views of (a) the inaccurate BIM model and (b) the accurate detailed BIM model for case 2.

After the two groups were made, the material quantities were extracted from the BIM model. In Autodesk Revit, material takeoff schedules were created, and the results were compared. The results of the accurate detailed BIM models are the control group or the baseline for the comparison. Table 3.1 shows the comparison of the material quantities between the accurate detailed BIM models and the inaccurate BIM models.

Table 3.1 Comparison of the material quantities between the accurate detailed BIM models and the inaccurate BIM models.

Elements	Layers	Case 1			Case 2			Case 3		
		Accurate Detailed BIM Model	Inaccurate BIM Model		Accurate Detailed BIM Model	Inaccurate BIM Model		Accurate Detailed BIM Model	Inaccurate BIM Model	
		Area (m^2)	Area (m^2)	Deviation (%)	Area (m^2)	Area (m^2)	Deviation (%)	Area (m^2)	Area (m^2)	Deviation (%)
Walls	Core Structure	188.64	232.87	23.45	258.76	339.71	31.28	307.91	379.14	23.13
	Exterior Finish	186.44	180.22	−3.34	262.96	251.59	−4.32	293.45	261.83	−10.78
	Interior Finish	222.75	285.52	28.18	315.18	427.83	35.74	416.39	496.45	19.23
	Restroom Tile	16.56	23.71	43.18	48.50	63.90	31.75	81.72	107.64	31.72
Floors	Exterior Floor	17.20	17.20	0.00	45.20	45.29	0.20	81.79	82.15	0.44
	Interior Floor	74.92	82.60	10.25	107.43	118.90	10.68	130.79	144.90	10.79
	Restroom Floor	2.89	3.38	16.96	9.90	11.79	19.09	20.49	22.13	8.00

Material quantities for the inaccurate BIM model group, when compared to the accurate detailed BIM model group, deviate substantially. Positive deviations indicate the quantities exceed the baseline quantity. Negative deviations indicate the quantities are less than the baseline quantity. For the wall layers, the deviations range from -10.78% to 43.18%. For the floor layers, the deviations range from 0.00% to 19.09%. These deviations vary among each material layer in each building element. The deviations are caused by many factors, including the design, the size of the structural elements, and the ceiling height. Because fixed percentages cannot be used to eliminate the deviations, other methods must be developed to eliminate the deviation.

3.2 Overview of the BIM-based compound element quantity takeoff improvement (BECQTI) method

The BIM-based compound element quantity takeoff improvement (BCEQTI) method integrates the concept of BIM-based clash detection to assist the process of BIM-based quantity takeoff. The BCEQTI method utilizes the advantage of the semantic information embedded in the BIM model to detect the intersection between elements (clash detection). This intersection information is then used to automatically eliminate the overlapping quantities or add the absent quantities. The calculation algorithms were developed for calculating the areas of each material layer in two classes of compound elements: architectural walls and floors.

Figure 3.5 illustrates the overview of the BECQTI method. It comprises three main processes. The first process is to detect intersections between elements. In this process, building model elements are separated into two main groups: the target model elements and the model elements used for testing. The target model elements are walls and floors. The model elements used for testing are structural columns, structural framings (beams), roofs, doors, and windows. All model elements are imported into the system via an API. Subsequently, the target model elements are used to check for intersection with the model elements used for testing. The checking executes by pairing a building element category from each group. The intersection areas of each pair of building element categories are then used in the following processes.

The second process is to eliminate excess quantities when compound elements overlap with other building elements. The calculation method is developed for the walls and floors. As for wall elements, it is used for the case in which the wall layer should not overlap with other building elements. Examples of this wall layer are a core structural layer of masonry walls or drywalls and a wall finish layer of drywalls. As for floor elements, it is used for the case in which some parts of the floor finishes are placed under the columns and the walls, which causes excessive floor area quantities. The areas of the walls and floors are extracted from the model elements. Subsequently, the intersection areas from process 1 are used to subtract from the areas of the walls and floors, yielding the net area of the walls and floors.

The third process is the calculation for the wall finish layers. In actual construction, when the wall elements connect with other building elements, such as columns and beams, the wall finish layers often cover those building elements. The calculation method is developed for the exterior finish layer and the interior finish layer. As for the exterior finish layer, it is used for the case in which the exterior finish layer covers the exterior surfaces of a building. The exterior surfaces are the surfaces of the walls, columns, beams, and floor edges that are exposed to the exterior. The examples of the exterior finish material in an actual construction are wall plaster, wall tiles, wall cladding, and wall paint. As for the interior finish layer, it is used for the case in which the interior finish layer covers the vertical surfaces of each room in a building. The vertical surfaces of each room are the vertical surfaces of the walls and columns that are located between the floors and ceilings. If there are no ceilings, they are located between the floors and the underside of the beams or floors above. Examples of interior finish materials in actual construction include wall plaster, wall tiles, wallpaper, and wall paint. In order to calculate quantities for the wall finish layers, the calculation method integrates the intersection areas from process 1 with the areas of the exterior or interior wall finish layers. The result is the net area of the exterior and interior wall finish.

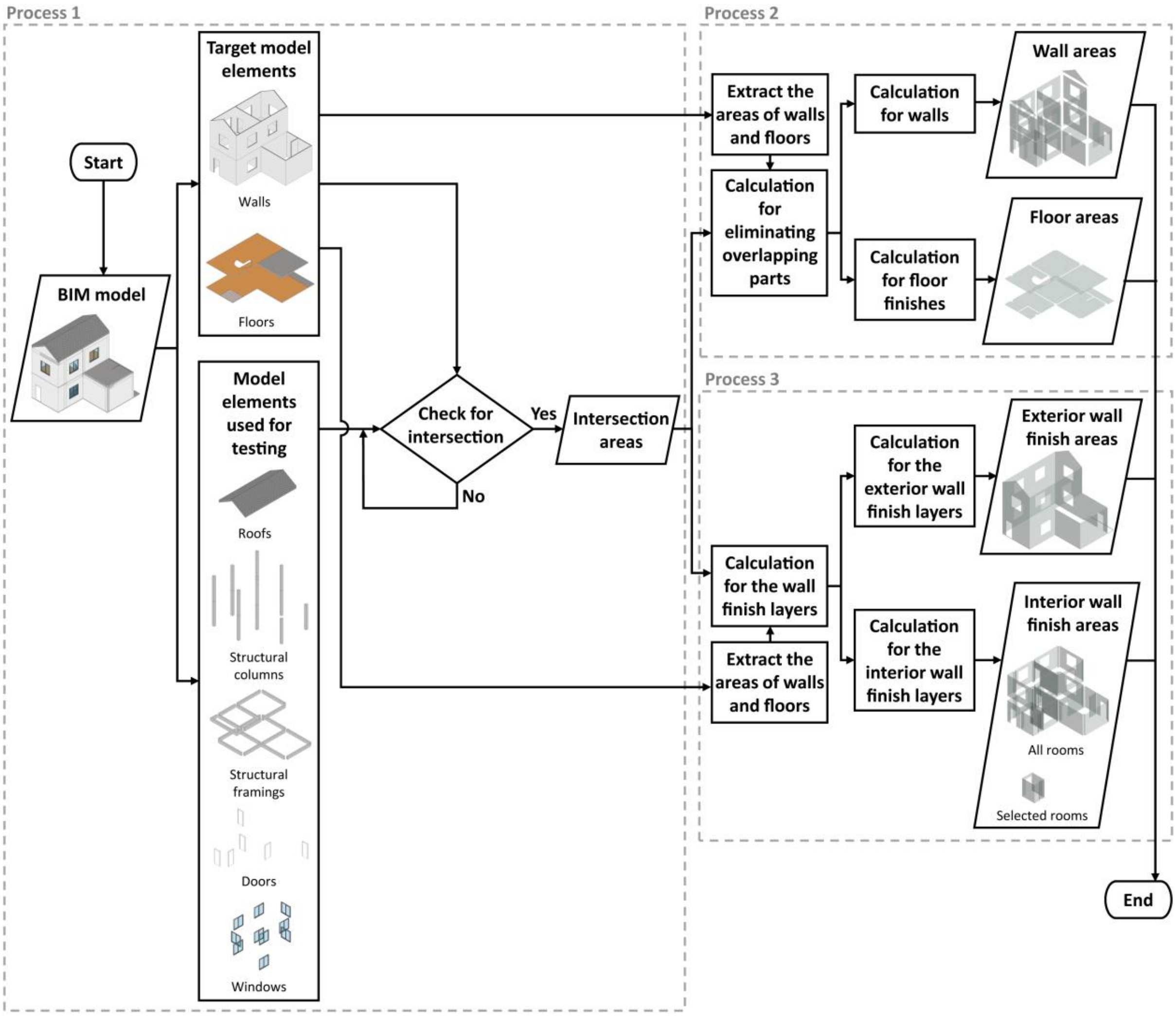

Figure 3.5 Overview of the BCEQTI method.

3.3 Development of the BCEQTI prototype system

To test the concept of the proposed method, the BCEQTI prototype system was developed in Dynamo 1.3.3.4111, a visual programming extension in Autodesk Revit. The BCEQTI prototype system is divided into two sub-systems: the system for eliminating the overlapping parts and the system for calculating the wall finish layers.

3.3.1 The system for eliminating the overlapping parts

The system for eliminating the overlapping parts consists of two main processes for two building element categories: walls and floor finishes.

3.3.1.1 The calculation method for walls

Figure 3.6 illustrates the flowchart of the calculation method for the walls. The building element categories, including walls, structural columns, structural framing, and floors, are input from a Revit model. Subsequently, all elements are extracted from the categories and converted into geometries. The structural columns, the structural framing, and the floors are combined into an integrated geometry. The wall geometries are exploded into surfaces, and the exterior vertical surfaces are then selected. Then, the exterior vertical surfaces are offset to the wall centerlines. These wall surfaces are checked for their intersection with the integrated geometry. The overlapping regions are then subtracted. This process determines the wall surfaces that do not overlap with the structural columns, the structural framing, and the floors. The wall surfaces are then visualized in the 3D view. Finally, the wall surfaces are grouped based on the wall types, and the surface areas for each wall type are calculated (see Figure 3.7).

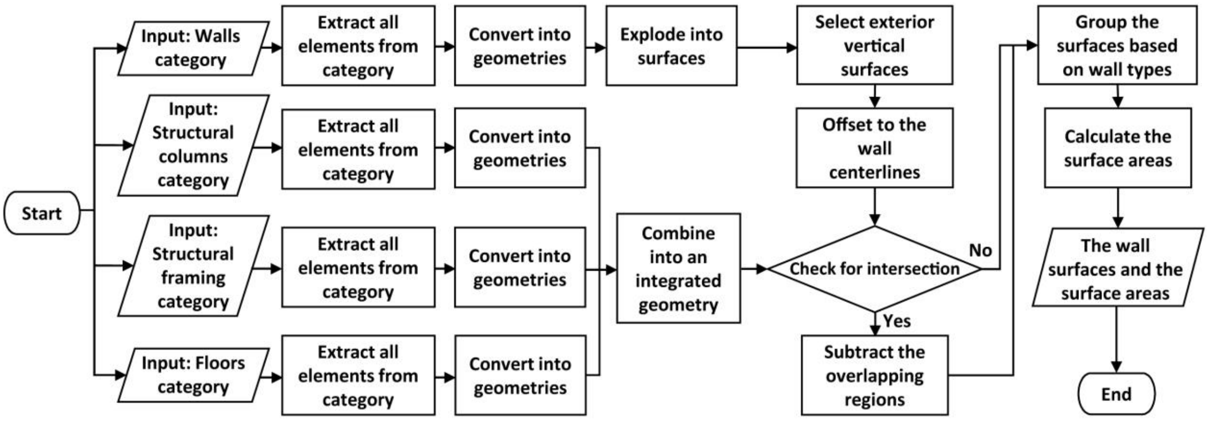

Figure 3.6 Flowchart for the calculation method for walls.

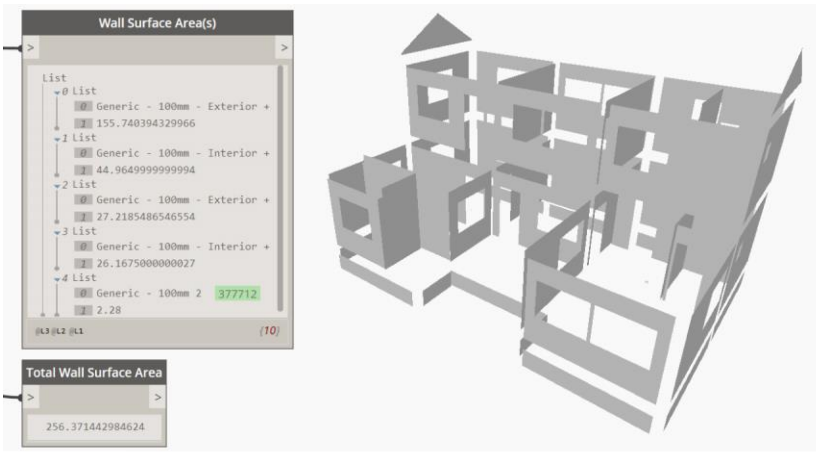

Figure 3.7 Wall surface areas and their visualization.

3.3.1.2 The calculation method for floor finishes

Figure 3.8 illustrates the flowchart of the calculation method for floor finishes. Similar to the calculation method for the walls, the building element categories, including floors, structural columns, walls, doors, and windows, are input from a Revit model. Subsequently, all elements are extracted from the categories. Then, they are grouped by the level parameter and converted into geometries. The structural columns, walls, doors, and windows on each level are combined into an integrated geometry. The floor geometries are exploded into surfaces, and the top horizontal surfaces are selected. The floor surfaces are then checked for their intersection with the integrated geometry for each level. The overlapping regions are then subtracted. This determines the floor surfaces that do not overlap with the structural columns, walls, doors, or windows. The floor surfaces are visualized in the 3D view. Finally, the floor surfaces are grouped based on the floor types, and the surface areas for each floor type are calculated (see Figure 3.9).

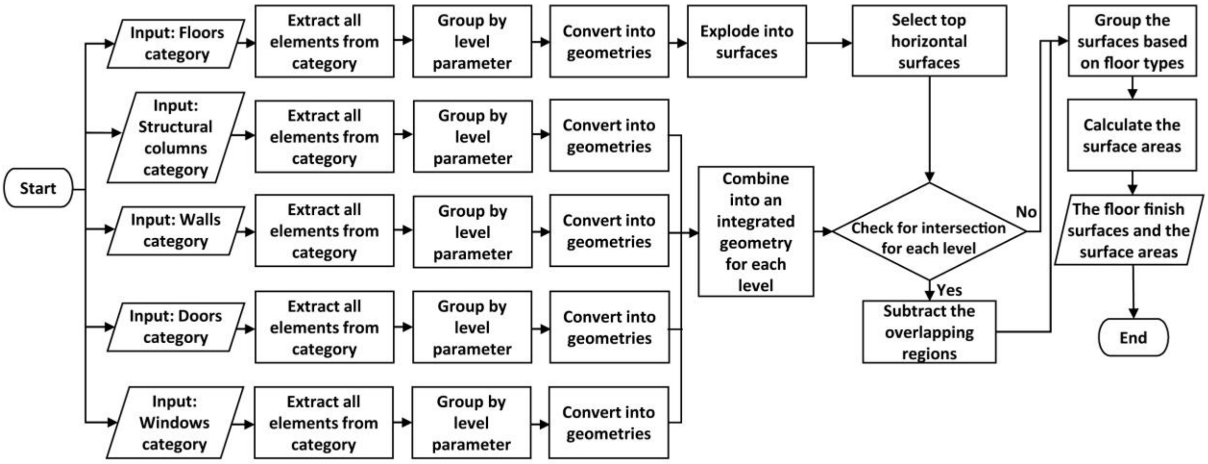

Figure 3.8 Flowchart for the calculation method for floors.

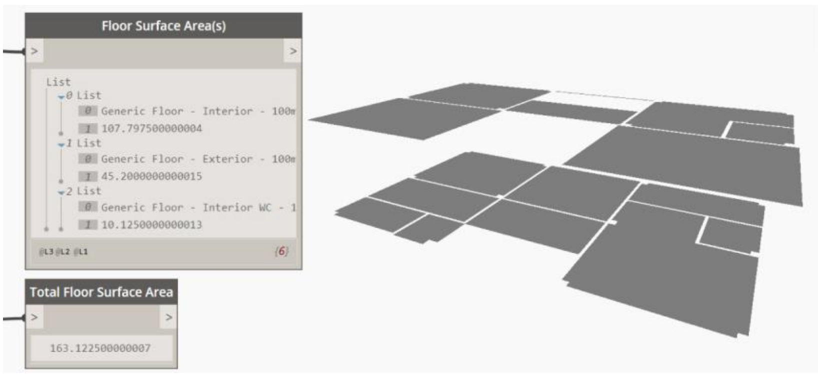

Figure 3.9 Floor surface areas and their visualization.

3.3.2 The system for calculating the wall finish layers

The system for calculating the wall finish layers consists of two main processes for two wall finish layers: the exterior wall finish layer and the interior wall finish layer.

3.3.2.1 The calculation method for the exterior wall finish layer

Figure 3.10 illustrates the flowchart for the calculation method for the exterior wall finish layer. The building element categories, including walls, structural columns, structural framings, floors, and rooms, are input from a Revit model. Subsequently, all elements are extracted from the categories. The calculation process after the input is divided into four main steps.

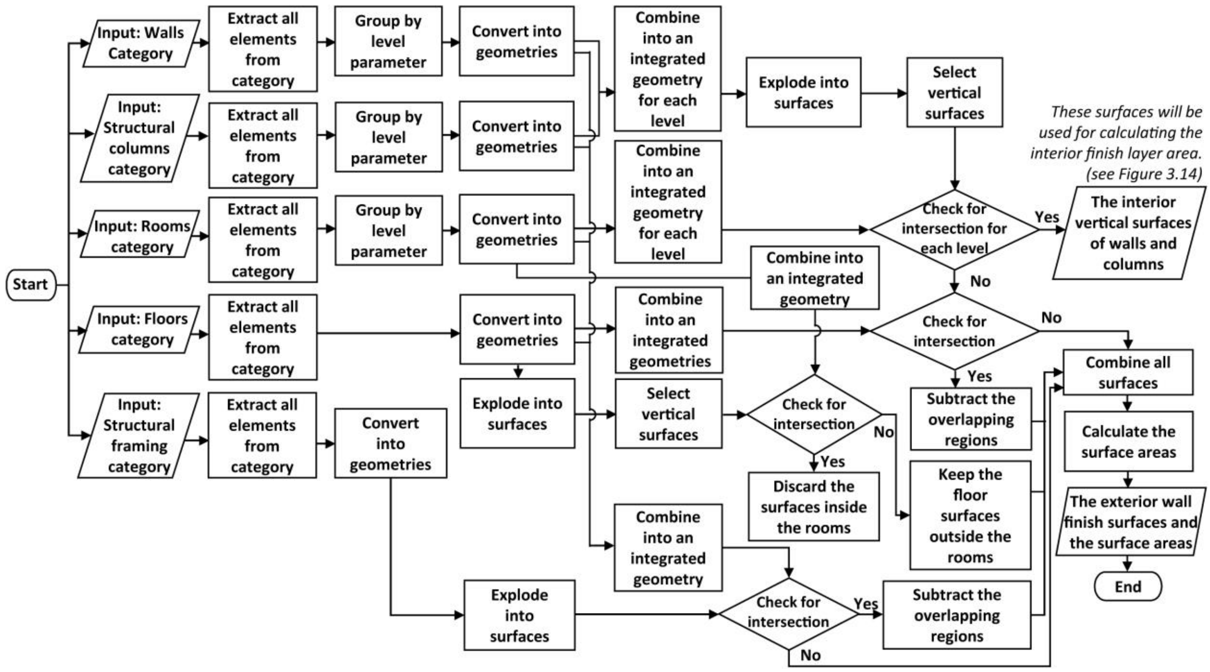

Figure 3.10 Flowchart for the calculation method for the exterior wall finish layer.

The first step is to find the wall and column surfaces that are exposed to the exterior. The walls, structural columns, and rooms are grouped by the level parameter and converted into geometries. The floors are converted into geometries and combined into an integrated geometry. The rooms on each level are combined into an integrated geometry. The walls and structural columns on each level are combined into an integrated geometry and exploded into surfaces. Then, the vertical surfaces are selected. These vertical surfaces are checked for their intersection with the integrated geometry of the room on each level. The surfaces that intersect with the integrated geometry of the room are the interior vertical surfaces, and they are filtered out. The interior vertical surfaces are used in the calculation method for the interior finish layer. The remaining surfaces are the exterior vertical surfaces. These surfaces are checked for their intersection with the integrated geometry of the floor. The overlapping regions are then subtracted, and the resulting surfaces are combined with the other surfaces in the final step.

The second step is to find the exterior surfaces of the structural framing. The wall, structural column, floor, and room geometries are combined into an integrated geometry. The structural framing elements are converted into geometries and exploded into surfaces. These surfaces are then checked for their intersection with the integrated geometry. The overlapping regions are subtracted, yielding the structural framing surfaces that are exposed to the exterior, which are eventually combined with the other surfaces in the final step.

The third step is to find the exterior surfaces of the floor edges. The room geometries are combined into an integrated geometry. The floor geometries are exploded into surfaces, and the vertical surfaces are selected. These surfaces are then checked for their intersection with the integrated geometry of the room. The surfaces that intersect with the integrated geometry of the room are filtered out. The rest of the surfaces are combined with the other surfaces in the final step.

The final step is to combine the surfaces from all steps. The result is the exterior wall finish surfaces that are visualized in the 3D view. Finally, the surface areas are calculated from the exterior wall finish surfaces (see Figure 3.11).

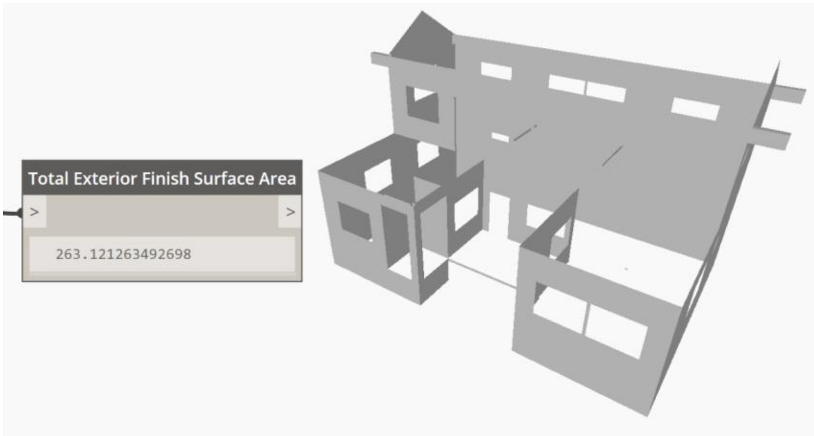

Figure 3.11 Exterior wall finish surface areas and their visualization.

3.3.2.2 The calculation method for the interior wall finish layer

The height of the interior wall finish is the major variable in this calculation. The Limit Offset parameter of the room elements in Revit represents the height of the interior wall finish; therefore, it must be assigned properly before calculation. The Limit Offset parameter can be assigned manually by inputting the value for the parameter. However, this process is error-prone. Therefore, the automatic algorithm for assigning the Limit Offset parameter was developed. Figure 3.12 illustrates the flowchart for the algorithm. In the first step, each room is checked for whether it has a ceiling inside or not. An array of points is created on the bottom surface of each room. Then, the lines are created from the points in an upward direction. The rooms that have lines intersecting with ceilings are separated from the rooms that do not have lines intersecting with ceilings. For the rooms that have ceilings, the ceiling height value is assigned to the Limit Offset parameter. For the rooms that do not have ceilings, the lines are intersected with the beams, floors, and roofs of the level above. Points are then created at the intersections. The distance between these points and the points on the bottom surface of the rooms is calculated. Subsequently, the shortest distance is selected in each room, because the interior finish cannot be higher than the lowest elements in the level above (see Figure 3.13). Then, the distance value is assigned to the Limit Offset parameter. Now, the room elements are ready for the calculation method for the interior wall finish layer.

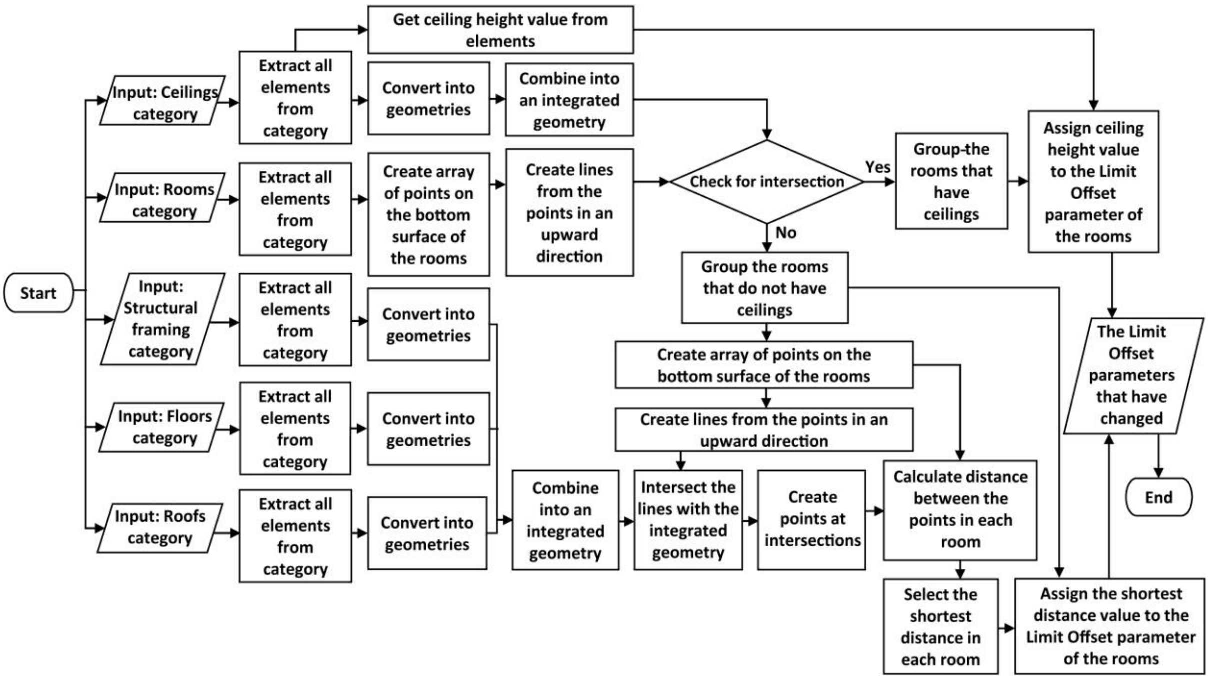

Figure 3.12 Automatic algorithm for assigning the Limit Offset parameter for the rooms.

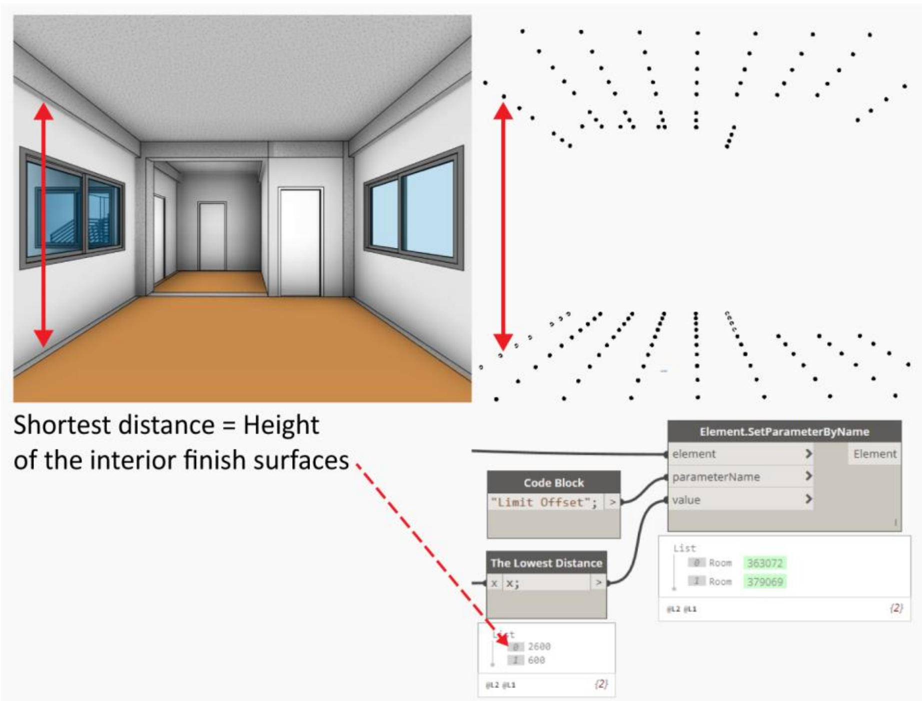

Figure 3.13 The shortest distance between the points used to assign the Limit Offset parameter for rooms without ceilings.

Figure 3.14 illustrates the flowchart for the calculation method for the interior wall finish layer. This calculation method is connected with the calculation method for the exterior wall finish layer. The interior vertical surfaces and the room elements from the first step of the calculation method for the exterior wall finish layer are used in this calculation. The room elements that have the correct Limit

Offset height are converted into geometries and combined into an integrated geometry. The interior vertical surfaces are checked for their intersection with the integrated geometry. The surface regions that do not overlap with the integrated geometry are then subtracted, yielding the interior wall finish surfaces that cover the inside of the rooms. They are then visualized in the 3D view. Finally, the interior wall finish surfaces are grouped based on the room in which they are located, and the surface areas in each room are calculated (see Figure 3.15a).

In addition, the interior wall finish layer may have more than one layer, and its height can be lower than the ceiling height. In order to calculate the area of these specific room finish layers, an extended calculation is added. The room name and the room height are input. The room elements are selected by the input room name. Subsequently, the boundaries of the room are extracted from the selected rooms and converted into surfaces. The surfaces are extruded into 3D geometries. The extrusion height is controlled by the input room height value. However, the room height value is limited by the Limit Offset property of the room. The extruded geometries are then checked for their intersection with the interior wall finish surfaces. The surface regions that do not overlap with the extruded geometries are subtracted, yielding the interior wall finish surfaces of the selected rooms that have the custom surface height. The surfaces are then visualized in the 3D view, and the surface areas are calculated (see Figure 3.15b).

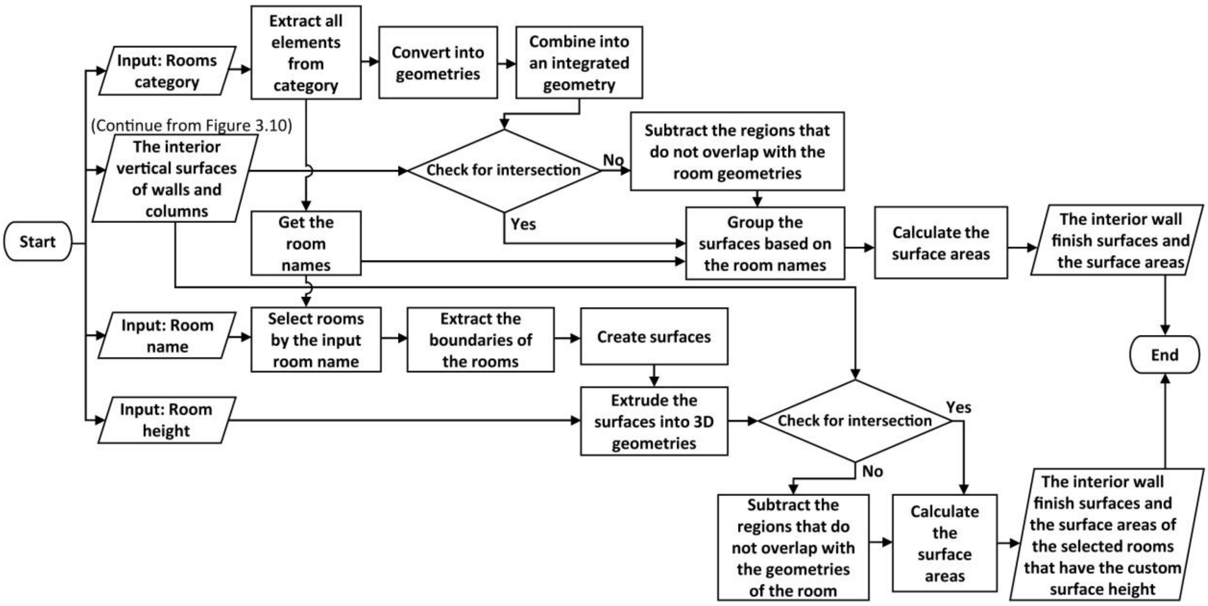

Figure 3.14 Flowchart for the calculation method for the interior wall finish layer.

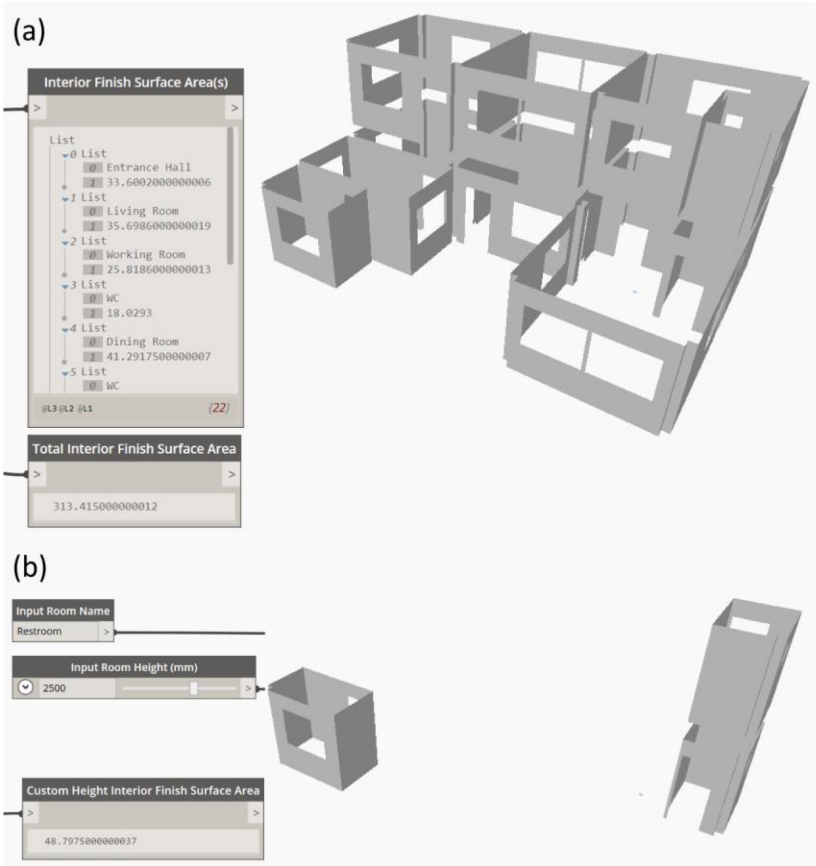

Figure 3.15 (a) Interior wall finish surface areas and their visualization. (b) The interior wall finish surfaces areas of the selected rooms that have the custom surface height and their visualization.

3.4 Validation

3.4.1 Validation with simple case studies

The BCEQTI method was validated with the three case studies described in Section 3.1. In the comparative study before introducing the proposed method, the inaccurate BIM model group is compared with the accurate detailed BIM model group. In this validation, the inaccurate BIM model group is enhanced using the BCEQTI system, and the results are compared with the accurate detailed BIM model group.

The BCEQTI system was developed as three separate Dynamo scripts. The first script eliminates the overlapping parts of the walls using the calculation method for the walls. The second script eliminates the overlapping parts of the floors using the calculation method for the floors. The third script calculates the finish layers of the walls using the calculation method for the exterior finish layer and the calculation method for the interior finish layer.

After the quantity results from each script are automatically exported to Excel files (see Figure 3.16), the quantities are prepared for comparison. The quantities from the element types or the room names that contain the same material are combined. For example, the area of the interior wall finish of each room will be combined except the area of the restroom because the material is different. Figure 3.17 shows the visualization results from the BCEQTI system, and Table 3.2 shows the comparison of the material quantities between the accurate detailed BIM models and the inaccurate BIM models enhanced by the BCEQTI system.

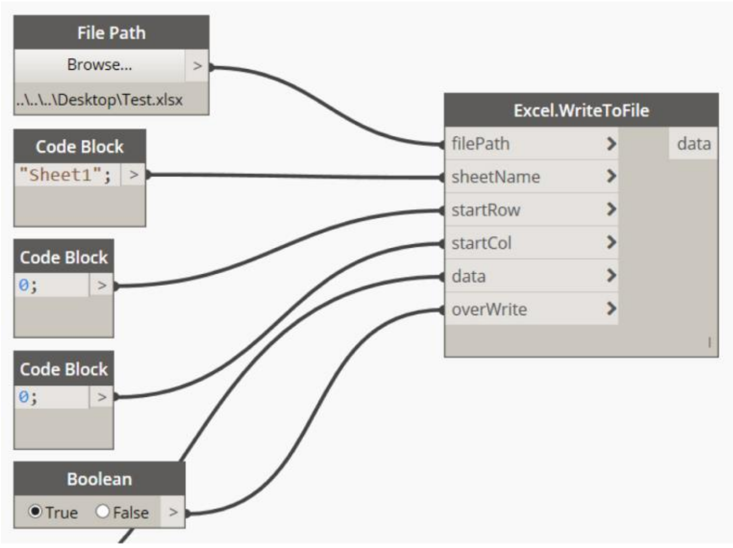

Figure 3.16 Node that exports the quantity results to an Excel file.

Table 3.2 Comparison of the material quantities between the accurate detailed BIM models and the inaccurate BIM models enhanced by the BCEQTI system.

Elements	Layers	Case 1			Case 2			Case 3		
		Accurate Detailed BIM Model	Inaccurate BIM Model Enhanced by the BCEQTI System		Accurate Detailed BIM Model	Inaccurate BIM Model Enhanced by the BCEQTI System		Accurate Detailed BIM Model	Inaccurate BIM Model Enhanced by the BCEQTI System	
		Area (m^2)	Area (m^2)	Deviation (%)	Area (m^2)	Area (m^2)	Deviation (%)	Area (m^2)	Area (m^2)	Deviation (%)
Walls	Core Structure	188.64	186.93	−0.91	258.76	256.37	−0.92	307.91	305.50	−0.78
	Exterior Finish	186.44	186.87	0.23	262.96	263.12	0.06	293.45	294.14	0.24
	Interior Finish	222.75	221.70	−0.47	315.18	313.42	−0.56	416.39	414.51	−0.45
	Restroom Tile	16.56	16.66	0.60	48.50	48.80	0.62	81.72	82.30	0.71
Floors	Exterior Floor	17.20	17.20	0.00	45.20	45.20	0.00	81.79	81.79	0.00
	Interior Floor	74.92	74.91	−0.01	107.43	107.80	0.34	130.79	130.79	0.00
	Restroom Floor	2.89	2.96	2.42	9.90	10.13	2.32	20.49	21.05	2.73

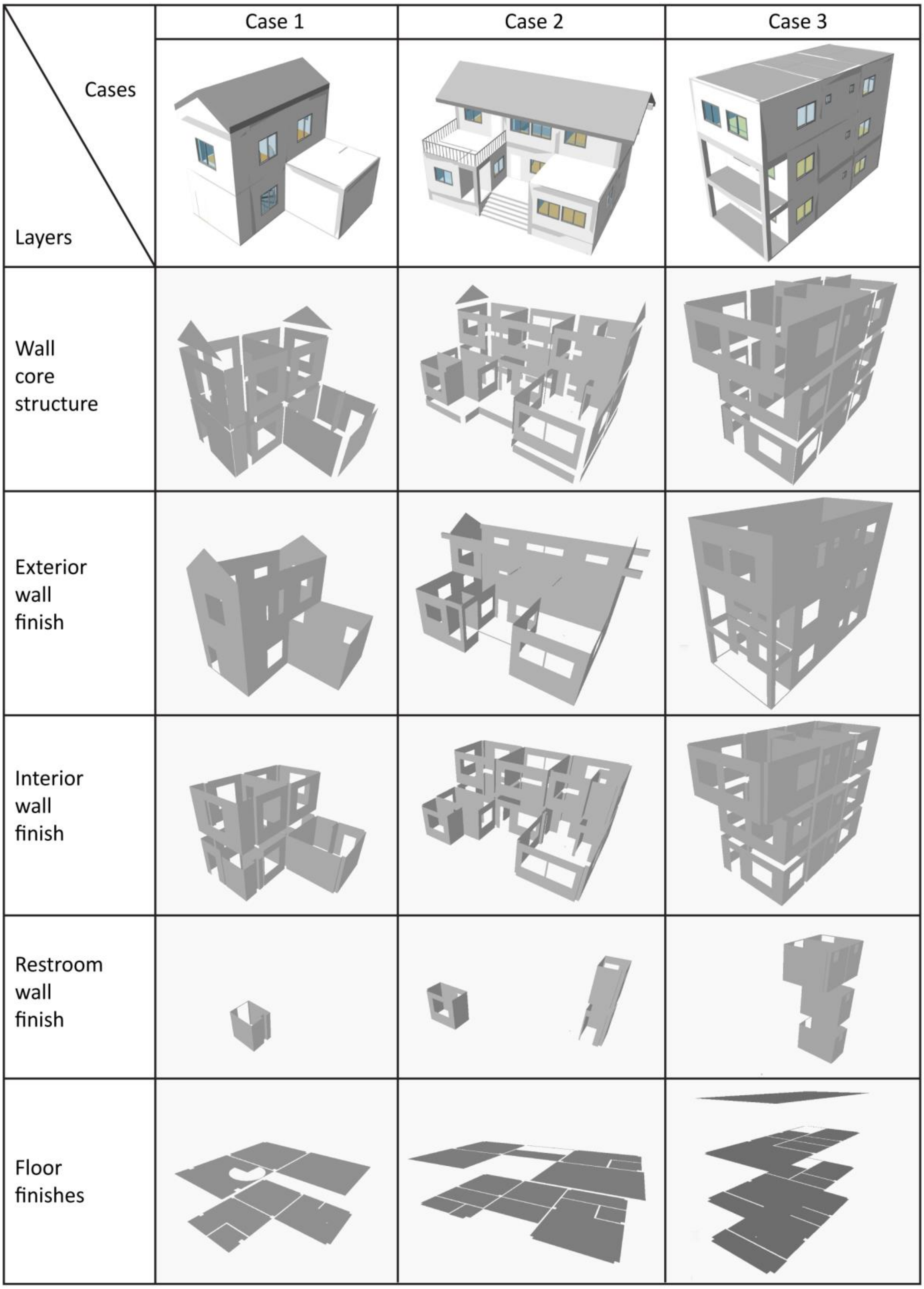

Figure 3.17 Visualization results for the three case studies from the BCEQTI system.

The comparison demonstrates that the BCEQTI system can reduce the deviation in every case and every element layer examined. In most of the cases, the inaccurate BIM models enhanced by the BCEQTI system have a deviation of element layers of less than ±1% compared to the baseline, which is the accurate detailed BIM model group. Only the deviation of the restroom floor layer ranges from 2.32% to 2.73%. Table 3.3 summarizes the deviation results of the BIM model before and after enhancement with the BCEQTI system.

Table 3.3 Deviation results of the BIM model before and after enhancement with the BCEQTI system.

Elements	**Layers**	**Case 1**		**Case 2**		**Case 3**	
		Inaccurate BIM Model	**Inaccurate BIM Model Enhanced by the BCEQTI System**	**Inaccurate BIM Model**	**Inaccurate BIM Model Enhanced by the BCEQTI System**	**Inaccurate BIM Model**	**Inaccurate BIM Model Enhanced by the BCEQTI System**
		Deviation (%)	**Deviation (%)**	**Deviation (%)**	**Deviation (%)**	**Deviation (%)**	**Deviation (%)**
Walls	Core Structure	23.45	−0.91	31.28	−0.92	23.13	−0.78
	Exterior Finish	−3.34	0.23	−4.32	0.06	−10.78	0.24
	Interior Finish	28.18	−0.47	35.74	−0.56	19.23	−0.45
	Restroom Tile	43.18	0.60	31.75	0.62	31.72	0.71
Floors	Exterior Floor	0.00	0.00	0.20	0.00	0.44	0.00
	Interior Floor	10.25	−0.01	10.68	0.34	10.79	0.00
	Restroom Floor	16.96	2.42	19.09	2.32	8.00	2.73

However, these three case studies are simple buildings that were designed for validating the BCEQTI method. The next step of the research is to study the accuracy and the performance of the BCEQTI system when applied to an actual residential building project. Consequently, the results of all case studies are discussed, and the conclusions of this research are then summarized.

3.4.2 Validation with an actual residential building project

The actual residential building project used in this validation is a two-story residential building that was designed by one of the authors. The building is located in Bangkok, Thailand. It is a two-story building with an approximate total floor area of 1,000 m^2. This building has a concrete frame structure. The typical column size is 300 × 300 mm. The depths of the beams vary according to the column spans. The first story is 4.50 m high, and the second story is 3.50 m high. The ceiling height differs in each room. The ceiling heights of the first story range from 2.35 m to 3.60 m, and the ceiling heights of the second story range from 2.75 m to 3.00 m. The building contains 8 wall finish materials and 17 floor finish materials. The wall core structure is masonry. Every wall has wall plaster on both sides. The side of the wall that is exposed to the exterior is covered by exterior plaster material. The side of the wall exposed to the interior is covered by interior plaster material. The walls in the restroom have a tile layer on top of the wall plaster layer. There are seven restrooms in this building. Five restrooms have different wall and floor materials, and two restrooms share the same wall and floor material. Figure 3.18 shows the 3D view of the residential building.

Figure 3.18 (a) Three-dimensional view of the residential building. (b) The actual construction.

The objectives of this validation are to test the BCEQTI system when it is applied to an actual building project and to study the performance, in accuracy and time, of the BIM model enhanced by the BCEQTI system. The accurate detailed BIM model, the inaccurate BIM model, and the inaccurate BIM model enhanced by the BCEQTI system are then used for a comparison of their material quantities. The accurate detailed BIM model is the baseline for calculating the deviation of the material quantities. Furthermore, the modeling time when creating the accurate detailed BIM model and the inaccurate BIM model were compared with the execution time of the BCEQTI system.

Similar to the previous comparison, the accurate detailed BIM model was precisely made in order to have the highest accuracy of the material quantities. The model was created according to the construction drawings. Every material layer was separated as an individual element. The wall core structure was created by avoiding its intersection with the structural elements. The wall finishes cover the wall core structures and the structural elements according to the construction drawings. The height of the interior finish reaches the ceiling height. The architectural floors were created on the structural floors, and the boundaries of the floors were created inside the wall finishes in each room. In addition, the modeling time was recorded for the comparison.

The inaccurate BIM model was created according to the modeling method issues. The walls are single model elements with defined material layers. The walls were divided into various wall types owing to the variety of the wall finish materials in this building. Each wall type is the combination of the core structural layer and the finish layers on both sides. The height of each wall layer was not edited, and the walls were created to overlap with the structural elements. The floors are single model elements with material layers that represent the architectural floor and structural floor. The floors were divided into different floor types according to the floor finish material in the construction drawings. Floors were created under the structural columns and the walls. Furthermore, in order to compare the modeling time, the model was created by the same person, and the modeling time was recorded. Figure 3.19 shows the 3D section views of the inaccurate BIM model and the accurate detailed BIM model.

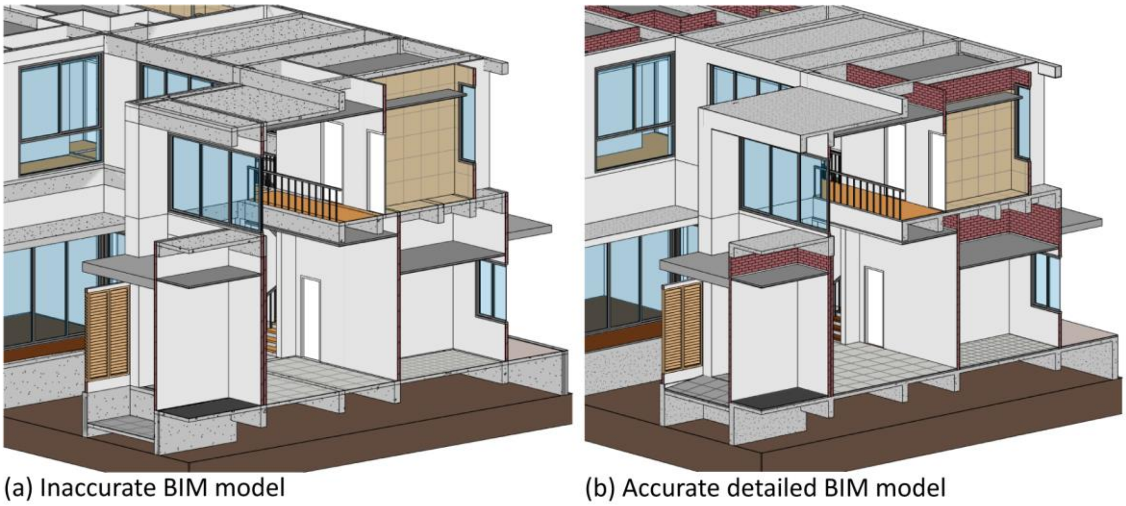

Figure 3.19 Three-dimensional section views of (a) the inaccurate BIM model and (b) the accurate detailed BIM model of the residential building.

The BCEQTI system was applied to the inaccurate BIM model. The quantity results from the system were exported to Excel files. The BCEQTI system is divided into three scripts: the script for eliminating the overlapping parts of the walls, the script for eliminating the overlapping parts of the floors, and the script for calculating the finish layers of the walls. The scripts execution times were recorded for the comparison. It should be noted that a computer with an Intel Core i7-8770 3.2 GHz CPU, 32 GB RAM, and Nvidia GeForce GTX 1060 6 GB graphics card was used. Figure 3.20 shows the visualization of the BCEQTI system. Table 3.4 shows the comparison of the material quantities between the accurate detailed BIM model, the inaccurate BIM model, and the inaccurate BIM model enhanced by the BCEQTI system. Table 3.5 shows the modeling time of the accurate detailed BIM model and the inaccurate BIM model. Table 3.6 shows the scripts execution times for the inaccurate BIM model enhanced by the BCEQTI system.

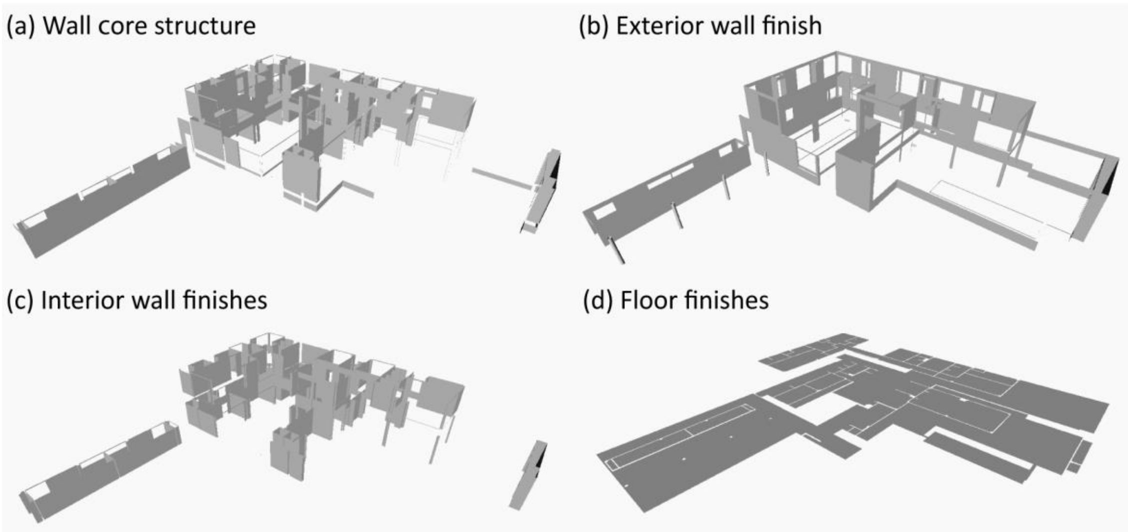

Figure 3.20 Visualization results for (a) the wall core structure, (b) the exterior wall finish, (c) the interior wall finishes, and (d) the floor finishes from the BCEQTI system.

Table 3.4 Comparison of the material quantities among the accurate detailed BIM model, the inaccurate BIM model, and the inaccurate BIM model enhanced by the BCEQTI system.

Elements	Layers	Accurate Detailed BIM Model	Inaccurate BIM Model		Inaccurate BIM Model Enhanced by the BCEQTI System	
		Area (m^2)	Area (m^2)	Deviation (%)	Area (m^2)	Deviation (%)
Walls	Core Structure (Masonry Units)	1,370.46	1,674.53	22.19	1,358.34	−0.88
	Exterior Plaster Finish	901.39	949.22	5.31	906.16	0.53
	Interior Plaster Finish	1,342.19	2,399.73	78.79	1,334.37	−0.58
	Restroom Tile 01	34.14	55.10	61.39	34.25	0.32
	Restroom Tile 02	40.04	64.88	62.04	40.15	0.27
	Restroom Tile 03	17.64	35.43	100.85	17.74	0.57
	Restroom Tile 04	36.77	46.20	25.65	36.82	0.14
	Restroom Tile 05	37.41	47.68	27.45	37.45	0.11
	Restroom Tile 06	60.54	76.07	25.65	60.66	0.20
Floors	Floor 01 Ceramic Tile Exterior	172.91	182.62	5.62	172.91	0.00
	Floor 02 Wood Interior	148.88	163.83	10.04	149.13	0.17
	Floor 03 Wood Exterior	74.31	74.32	0.01	74.31	0.00
	Floor 04 Rubber Tile	19.98	22.62	13.21	19.98	0.00
	Floor 05 Ceramic Tile 600 × 600 mm	22.13	22.30	0.77	22.06	−0.32
	Floor 06 Ceramic Tile 600 × 600 mm	33.35	37.55	12.59	33.50	0.45
	Floor 07 Concrete	70.69	72.84	3.04	70.75	0.08
	Floor 08 Laminated Wood Interior	64.44	69.55	7.93	64.37	−0.10
	Floor 09 Tile 300 × 600 mm	6.76	6.76	0.00	6.76	0.00
	Floor 10 Concrete Stamp Exterior	219.10	219.38	0.13	219.07	−0.01
	Floor 11 White Tile 300 × 300 mm	34.03	40.32	18.48	34.03	0.00
	Floor 12 Restroom Tile 01	6.61	6.84	3.48	6.74	1.97
	Floor 13 Restroom Tile 02	8.72	10.00	14.68	8.87	1.72
	Floor 14 Restroom Tile 03	3.40	3.48	2.35	3.48	2.35
	Floor 15 Restroom Tile 04	8.30	9.20	10.84	8.44	1.69
	Floor 16 Restroom Tile 05	8.50	9.03	6.24	8.66	1.82
	Floor 17 Restroom Tile 06	11.74	13.29	13.20	11.97	1.96

Table 3.5 The modeling time of the accurate detailed BIM model and the inaccurate BIM model.

BIM Models	Modeling Time
Accurate detailed BIM model	30 h 30 min
Inaccurate BIM model	14 h 35 min

Table 3.6 The scripts execution times for the inaccurate BIM model enhanced by the BCEQTI system.

Inaccurate BIM Model Enhanced by the BCEQTI System	Scripts Execution Times
Script for eliminating the overlapping parts of the walls	34.81 s
Script for eliminating the overlapping parts of the floors	10.08 s
Script for calculating the finish layers of the walls	1 min 48.08 s
Total	2 min 32.97 s

Similar to the previous comparison, the material quantities of the inaccurate BIM model for most of the material layers have significant deviations when compared to the accurate detailed BIM model. The deviations vary among material layers. For the wall layers, the deviations range from 5.31% to 100.85%. For the floor layers, the deviations range from 0.00% to 18.48%. The material layer that has the most deviation is the wall restroom tile 03 layer, which has a deviation of 100.85%. This is because the designed ceiling height is a lot lower than the floor-to-floor height. The material layer that has the least deviation is the floor tile 09 layer, which has no deviation. This is because this floor has no intersection with the walls or columns.

After applying the BCEQTI system to the inaccurate BIM model, the deviations of the wall layers decrease to within the range of −0.88% to 0.57%. The deviations of the floor layer decrease to within the range of −0.32% to 2.35%. In most of the material layers, the deviation is less than ±1%. The accuracy is similar to that in the previous three case studies. Accordingly, the system is applicable to this complex BIM model without any problems, although the execution time was a bit longer than that for the simple BIM models.

The modeling time of the accurate detailed BIM model is 30 h 30 min, while the modeling time of the inaccurate BIM model is 14 h 35 min. The inaccurate BIM model is built more than 50% faster than the accurate detailed BIM model. The total script execution time is 2 min 32.97 s. When combined with the inaccurate BIM modeling time, the total time used to create the inaccurate BIM model enhanced by the BCEQTI system is about 14 h 38 min, which is still much faster than the modeling time of the accurate detailed BIM model.

3.5 Discussion

3.5.1 The BCEQTI method and prototype system

The BCEQTI method was validated using the three case studies. Each case study is a simple building with less than 250 m^2 total floor area. To clarify, the total floor areas of the first, second, and third cases were 95 m^2, 162.5 m^2, and 233 m^2, respectively. After validation using the simple buildings, the BCEQTI method was validated with an actual residential building project. This building can be considered the fourth case study. The building is bigger than the three case studies. The total area of this building is approximately 1,000 m^2. Moreover, its walls and floors are also more complex. There are 8 wall finish materials and 17 floor finish material in the building. Based on the validation, the BCEQTI system is applicable to actual residential building projects using the complex BIM model, although the execution time is longer than that for the simple BIM models.

The performance of the BCEQTI system is stable across all cases. It can improve the accuracy of the material quantities effectively even though all cases have different building shapes and designs. Before applying the BCEQTI system, the comparison of the material quantities in all cases and all element layers vary in their deviations, ranging from −10.78% to 100.85% (see Table 3.1 and Table 3.4). After applying the BCEQTI system, the deviations in most material layers were reduced to ±1% (see Table 3.2 and Table 3.4). Only the deviation of the restroom floor layer was reduced to the range of 1.69% to 2.73% (see Table 3.2 and Table 3.4). The existing deviation could be caused by the material thickness in the accurate detailed BIM model and the calculation algorithms. For example, In the case of the restroom floor layer, the quantities from the accurate detailed BIM models are less than the results from the BCEQTI system because the restroom walls in the accurate detailed BIM models have a tile layer that makes the wall thicker, thus decreasing the floor area. The boundary of the floor area in the accurate detailed BIM model is a bit smaller than the result from the calculation algorithm.

The BCEQTI method not only improves the accuracy of the compound element quantity takeoff but also saves the time dedicated to making an accurate detailed BIM model or editing a BIM model that is incorrect or incomplete for quantity takeoff. The validation with the actual residential building project reveals that the accurate detailed BIM model requires more than twice the time to create when compared to the inaccurate BIM model (see Table 3.5). This is because the modeler has to create each layer of each element layer separately, and all elements in every intersection have to be checked to avoid their overlapping. The inaccurate BIM model enhanced by the BCEQTI system takes only a few minutes to execute the scripts (see Table 3.6), but resulting material quantities are equivalent to the results from the accurate detailed BIM model (see Table 3.4). Therefore, the BCEQTI method can save the time and the cost that is spent to create an accurate detailed BIM model for quantity takeoff.

3.5.2 Limitations

The BCEQTI method still has some limitations. Firstly, the calculation method for eliminating the overlapping parts of the walls and the floors can separate and group the surfaces according to the wall or floor types. However, if the wall or floor types are not well-defined, the surfaces will be classified into the same group. Secondly, the calculation method for the exterior finish layer can be used in the case in which only one material covers the entire exterior surfaces of a building. Thirdly, the calculation method for the interior finish layer can separate and group the surfaces according to their room names. However, if there are multiple wall materials in a room, this calculation method cannot separate the material types. The second and third limitations can be achieved in future studies by developing methods that can identify and separate multiple materials of the exterior and interior wall finish layers based on material locations. Lastly, the BIM models after applying the BCEQTI method have not yet been corrected. Thus, the BIM models that are transferred among parties in the design and construction phases still provide inaccurate quantity takeoff results. To handle this limitation, there are two possible solutions. First, the BIM models should be automatically modified. This method is developed and described in Chapter 4. Second, the quantity takeoff results could be embedded back into the parameters in the BIM models. This method is developed and described in Chapter 5.

3.6 Summary

The inaccuracy of the quantities extracted from BIM models is caused by their incompleteness and incorrectness. Some details have not yet been created in the BIM model, while some details were created using an inappropriate modeling method. Generally, compound elements, including walls and floors, in a BIM model are single model elements with multiple material layers. In order to obtain accurate material quantities, each material layer must be defined, and its size should reflect the actual construction. Besides, the compound elements should not overlap with other building model elements because it can cause excess material quantities. However, manual modifying compound elements in the BIM model is time-consuming, cost-intensive, and error-prone.

This chapter proposes the BCEQTI method, which improves the accuracy of the quantities of compound elements from the BIM models that are incomplete or incorrect by integrating the concept of BIM-based clash detection into the process of BIM-based quantity takeoff. The intersection information in the BIM model is used to automatically subtract the overlapping quantities and add the missing quantities. The validation was conducted using three simple buildings and one actual residential building project. The BCEQTI prototype system effectively decreased the deviation of the material quantities from the BIM model, and the accuracy was stable across all cases.

The BCEQTI method is applicable to the development of quantity takeoff algorithms in any BIM software product. Using this method, accurate material quantities can be obtained from BIM models that are incomplete or incorrect when compared to the actual building. The automatic algorithms can improve the accuracy of the quantity takeoff without manipulation of the BIM model. Therefore, the file size and the geometries in a BIM model do not increase, which stabilizes performance, and yet, the model is still easily edited if the design is changed. Furthermore, this method can reduce the working time, cost, and human error associated with editing a BIM model to match the quantity takeoff requirement. Nevertheless, the BIM models that are not edited after applying the BCEQTI method can cause inaccurate quantity takeoff results when extracting quantities directly from the BIM models. To solve this issue, the automatic method for modifying BIM models is proposed in Chapter 4, and the method for calculating and embedding quantity results into BIM models is proposed in Chapter 5.

Chapter 4
Automatic modification of BIM models

Quantity takeoff is inaccurate for compound elements such as walls and floors modeled as single model elements with defined material layers because the size and composition of each layer cannot be freely adjusted. Furthermore, overlapping regions of compound elements with other elements result in excess material quantities. The previous chapter proposed a BCEQTI method that automatically detects overlapping regions and calculates the correct material quantities from compound elements in a BIM model. The BCEQTI method does not modify the original BIM model, which causes inaccuracy when extracting material quantities directly from the BIM model. Therefore, the BIM model needs to be modified to preserve the correct material quantities. The modified BIM model, with its greater detail, is also essential in the construction phase where higher LOD is required. However, modifying each compound element layer manually is a time-consuming and cost-intensive process. Also, the complexity of 3D models increases the risk of human error.

In this chapter, a BIM-based method is proposed that automatically modifies compound elements in BIM models by separating each layer into an individual model element and eliminating the overlapping regions of the compound elements. The objectives of this chapter are as follows: (1) to improve the accuracy of the quantities of compound elements extracted from BIM models, (2) to develop a method that automatically modifies BIM compound elements for accurate quantity takeoff, and (3) to reduce the working time and cost of editing or recreating BIM models. In the following sections, the overview of the proposed method and the development of the prototype system are explained. Two case studies, a residential building and an office building, are used to verify the prototype system and to validate the proposed method. The results are discussed and the limitations of the proposed method are identified. Finally, the conclusions are summarized.

4.1 Overview of the automatic compound element modification (ACEM) method

An automatic compound element modification (ACEM) method is proposed to automatically correct BIM models and improve the accuracy of the quantities of compound elements. The ACEM method fetches model elements as inputs to a system via an API. The calculation algorithms in the system automatically recreate wall and floor elements by separating each layer into an individual model element and eliminating the wall and floor regions that overlap with other elements, such as columns and beams. The calculation methods for detecting the overlapping regions of the model elements are based on the BCEQTI method in Chapter 3. The ACEM method results in a modified BIM model that contains correct material quantities for the architectural walls and floor finishes.

The ACEM method comprises five main processes, as shown in Figure 4.1. To recreate wall and floor elements, the first process is to extract information about materials from an original BIM model. Material names and thicknesses of finish layers of walls and floors as well as room names and floor levels for the wall and floor materials must be exported to an external database. The database can be manually modified by users if the information is incomplete or incorrect.

In the second process, original walls and floors are converted into walls and floors with only a core structural layer. The material and the thickness of the core structural layer have to be preserved in this process. For example, a wall in which the core structural layer is brick and the finish layers are plaster will be converted to a wall with only a brick layer.

In the third process, exterior and interior wall finishes are recreated from the extracted information. The algorithms create new wall types that represent wall finishes of the original walls based on the material names and thicknesses of the wall finishes from the first process. One new wall type is equal to one wall finish layer of the original wall. The new wall types are assigned to either the rooms or the exterior of the building according to the information extracted from the first process. The height of the new walls that are exterior wall finishes will reach the floor level above. The height of the new walls that are interior wall finishes will reach the ceiling height of each room.

In the fourth process, exterior and interior floor finishes are recreated from the extracted information. Similar to the third process, the algorithms create new floor types that represent floor finishes of the original floors. The material names and thicknesses of the floor finishes from the first process are used to create the new floor types. The new floor types are then placed on the floors that have been converted into the floor with only a core structural layer from the second process. The new floor types in each room or each exterior floor are placed according to the information extracted from the first process. The boundaries of walls and columns are subtracted from the boundaries of the new floor types to avoid regions of overlap under walls and columns.

In the fifth process, walls are joined and overlapping regions of walls are eliminated. The walls that are wall finishes from the third process do not contain doors and windows. They cover the doors and windows on the walls that form the core structural layer from the second process without any subtraction. Therefore, the walls that are wall finishes have to be joined with the walls of the core structural layer to obtain a merged set of walls. Furthermore, the regions of the walls that overlap with other elements, such as floors, columns, and beams, must be eliminated in this process. The final product is the modified BIM model.

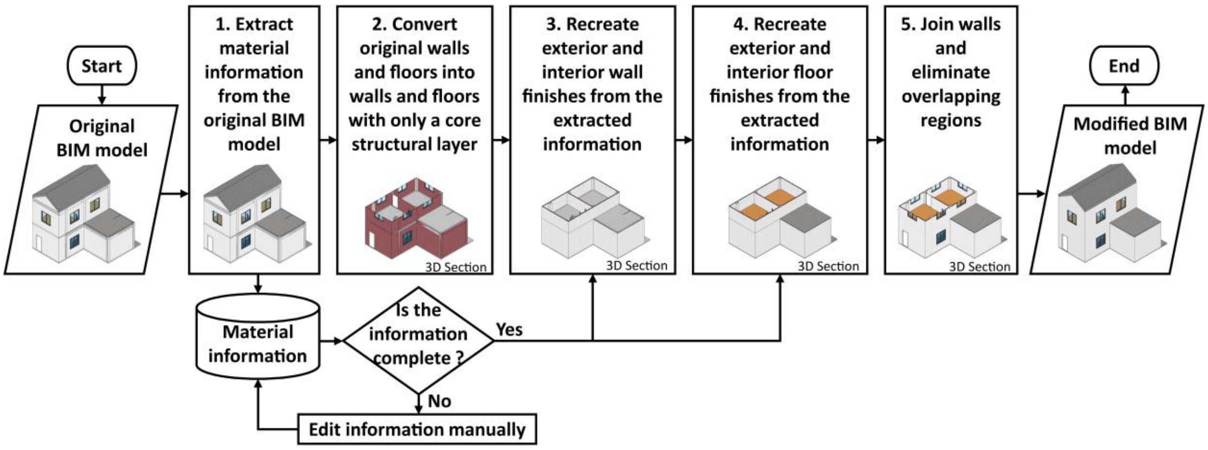

Figure 4.1 Overview of the ACEM method.

4.2 Development of the ACEM prototype system

Autodesk Revit 2018.2 and Dynamo 1.3.3.4111 were used to develop the ACEM prototype system. The explanation of the development of the prototype system is general for any BIM software product except the parts that relate to the Revit API, including the input model elements from Revit, the output model elements and properties of model elements to Revit, and some specific methods in the Revit API such as “JoinGeometry” in process 5.

Finish layers of wall and floors can vary from one layer to multiple layers, making the development of the ACEM system complex. Therefore, in this prototype system, finish layers of the interior wall are limited to a maximum of two, covering the scenarios in which some rooms have a single finish layer, such as a plaster layer, and some rooms have two finish layers, such as a mortar layer and a tile layer. The finish layer of the exterior wall is limited to one material and one layer, such as an exterior plaster layer. Finish layers of the interior and exterior floors are limited to a supporting layer, such as a concrete screed layer, and a top surface layer, such as a tile layer.

The ACEM prototype system was divided into five major processes according to the proposed method in Section 4.1.

4.2.1 Process 1: Extract material information from an original BIM model

Figure 4.2 provides the flowchart for process 1: extract material information from an original BIM model. Initially, material information is extracted from wall finishes. In this process, walls are imported from a Revit model. The wall elements are converted into part elements so that each wall layer can be detected by the system. The part elements of walls that are core structural layers are discarded. The leftovers are the wall finish layers that will be used in the following processes.

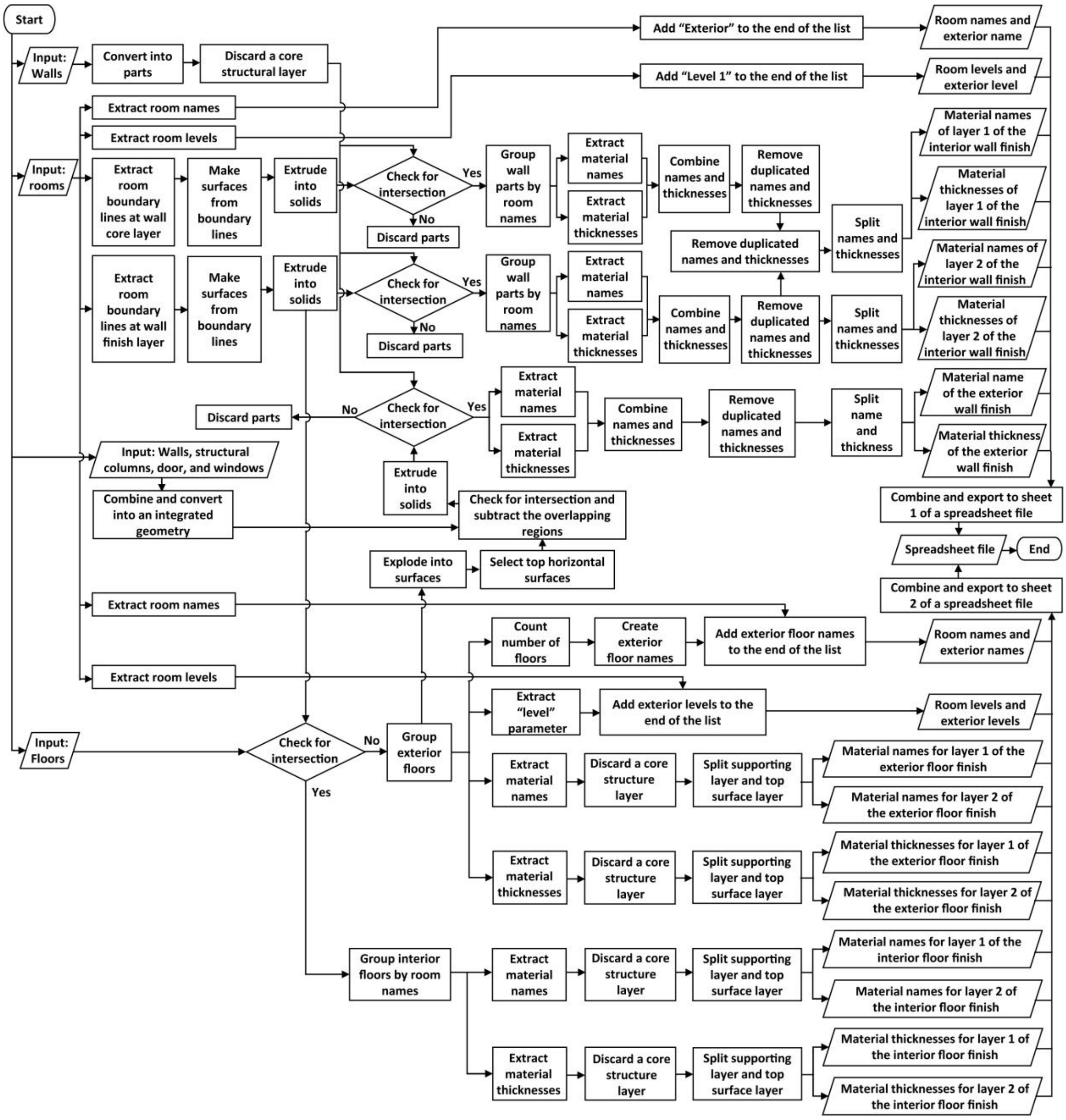

Figure 4.2 Flowchart for process 1: extract material information from an original BIM model.

Room elements are imported from a Revit model and used to detect two interior finish layers of the walls, which are the inner layer or layer 1 and the outer layer or layer 2. To generate a list of the inner layer or layer 1, the room boundary lines at the wall core layer are extracted. The boundary lines are then used to make surfaces and are extruded to solids. These solids are checked for their intersection with the wall finish layers. At this stage, the wall finish layers that intersect with the solids are both the inner layer and the outer layer because the boundary lines of the rooms correspond to the core layer of the wall. The wall finish layers are then grouped by room names. The material names and thicknesses of the wall finish layers are extracted, combined, and duplicates are removed. This yields a list that contains the material names and thicknesses of the inner layer and the outer layer of the interior wall finishes. To obtain a list that contains only the material names and thickness of the inner layer, the list of the outer layer must be used for subtraction. To obtain the list of the outer layer or layer 2, room boundary lines at the wall finish layer are extracted. Similar to the process for layer 1, the boundary lines are then used to make surfaces and are extruded to solids. These solids are checked for their intersection with the wall finish layers. This time, the wall finish layers that intersect with the solids are the outer layer. They are grouped by room names. Subsequently, the material names and thicknesses of the wall finish layers are extracted. They are then combined and duplicates are removed. The resulting list contains the material names and thicknesses of the outer layer of the interior wall finishes. This list is used to subtract the duplicated material names and thicknesses from the lists of the inner layer and the outer layer. The resulting list contains the material names and thicknesses of the inner layer of the interior wall finishes. The inner layer list and the outer layer list are then split into a list of material names of layer 1 (inner layer), a list of material thicknesses of layer 1, a list of material names of layer 2 (outer layer), and a list of material thicknesses of layer 2.

As for the exterior finish layer of the walls, building elements, which are floors, walls, structural columns, doors, and windows, are imported from the Revit model. The floors are checked for their intersection with the room solids. The floors that do not intersect with the room are the exterior floors. They are grouped into a list. After that, the exterior floors are exploded into surfaces and the top horizontal surfaces of the exterior floors are selected. The wall, structural columns, doors, and windows are combined and converted into an integrated geometry. This geometry is used to check for intersection and to subtract the overlapping regions of the exterior floor surfaces. The exterior floor surfaces after subtraction are extruded to solids. These solids are used to check for their intersection with the wall finish layers. The wall finish layers that intersect with the solids are the exterior finish layers and material names and thicknesses are extracted. These material names and thicknesses are combined and duplicates are removed. The result is a single material name and thickness. It is then split into a separate material name and thickness. The material name is added to the end of the list of material names of layer 1. The material thickness is added to the end of the list of material thicknesses of layer 1.

The room names and room levels are also needed for export to the spreadsheet file. The room names and room levels are extracted from the rooms. The string “Exterior” is added to the end of the room names list. The string “Level 1” is added to the room levels list. Finally, all lists are exported to sheet 1 of a spreadsheet file. As illustrated in Figure 4.3a, sheet 1 of the spreadsheet file contains room names, levels, wall material names of layer 1, wall material thicknesses of layer 1, wall material names of layer 2, and wall material thicknesses of layer 2.

Next, material information is extracted from floor finishes. To detect the interior finish layers, floors that are imported from a Revit model are checked for their intersection with the room solids. The floors that intersect with the room are the interior floors. They are grouped by room names. After that, the material names and thicknesses of the floors are extracted and the material names and thicknesses of the core structural layer are discarded. The leftovers are then split into a list of material names of layer 1 (supporting layer), a list of material thicknesses of layer 1, a list of material names of layer 2 (top surface layer), and a list of material thicknesses of layer 2.

As for the exterior finish layer of the floors, material names, material thicknesses, number of floors, and levels of floors are extracted from the exterior floors from the above processes. The material names and thicknesses of the core structural layer are discarded. The leftovers are then split into a list of material names of layer 1 (supporting layer), a list of material thicknesses of layer 1, a list of material names of layer 2 (top surface layer), and a list of material thicknesses of layer 2. These lists are added to the end of the same lists from the detection of the interior finish layers of the floors.

The room names and room levels are extracted from the rooms and exported to the spreadsheet file. The number of the exterior floors is used to create a list of exterior floor names. This is added to the end of the list of room names. The levels of exterior floors are added to the list of room levels. Finally, all lists are exported to sheet 2 of a spreadsheet file. As illustrated in Figure 4.3b, sheet 2 of the spreadsheet file contains room names, levels, floor material names of layer 1, floor material thicknesses of layer 1, floor material names of layer 2, and floor material thicknesses of layer 2.

	A	B	C	D	E	F
1	Room Names	Levels	Wall Material names (Layer 1)	Wall Material Thicknesses (Layer 1)	Wall Material names (Layer 2)	Wall Material Thicknesses (Layer 2)
2	Entrance Hall	Level 1	Interior Plaster	15		
3	Living Room	Level 1	Interior Plaster	15		
4	Working Room	Level 1	Interior Plaster	15		
5	WC	Level 1	Tile Mortar	15	Ceramic Tile	10
6	Dining Room	Level 1	Interior Plaster	15		
7	WC	Level 1	Tile Mortar	15	Ceramic Tile	10
8	Kitchen	Level 1	Interior Plaster	15		
9	Bedroom	Level 2	Interior Plaster	15		
10	Stair Hall	Level 2	Interior Plaster	15		
11	Bedroom	Level 2	Interior Plaster	15		
12	WC	Level 2	Tile Mortar	15	Ceramic Tile	10
13	Storage	Level 1	Interior Plaster	15		
14	Exterior	Level 1	Exterior Plaster	15		

(a)

	A	B	C	D	E	F
1	Room Names	Levels	Floor Material names (Layer 1)	Floor Material Thicknesses (Layer 1)	Floor Material names (Layer 2)	Floor Material Thicknesses (Layer 2)
2	Entrance Hall	Level 1	Concrete screed	40	Oak Flooring	10
3	Living Room	Level 1	Concrete screed	40	Oak Flooring	10
4	Working Room	Level 1	Concrete screed	40	Oak Flooring	10
5	WC	Level 1	Concrete screed	40	Ceramic Tile	10
6	Dining Room	Level 1	Concrete screed	40	Oak Flooring	10
7	WC	Level 1	Concrete screed	40	Ceramic Tile	10
8	Kitchen	Level 1	Concrete screed	40	Ceramic Tile Interior 600 x 600	10
9	Bedroom	Level 2	Concrete screed	40	Oak Flooring	10
10	Stair Hall	Level 2	Concrete screed	40	Oak Flooring	10
11	Bedroom	Level 2	Concrete screed	40	Oak Flooring	10
12	WC	Level 2	Concrete screed	40	Ceramic Tile	10
13	Storage	Level 1	Concrete screed	40	Ceramic Tile Interior 600 x 600	10
14	Exterior1	Level 1	Concrete screed	40	Ceramic Tile Exterior 600 x 600	10
15	Exterior2	Level 2	Concrete screed	40	Ceramic Tile Exterior 600 x 600	10
16	Exterior3	Level 2	Concrete screed	40	Ceramic Tile Exterior 600 x 600	10

(b)

Figure 4.3 Example of (a) the extracted finish material information from walls and (b) the extracted finish material information from floors.

4.2.2 Process 2: Convert original walls and floors into walls and floors with only a core structural layer

In this process, the original walls or floors that share the same material name and thickness as the core structural layer are converted into the same new family type (see Figure 4.4a). The original walls or floors in which the core structural layer has the same material name but a different thickness is converted into different new family types (see Figure 4.4b).

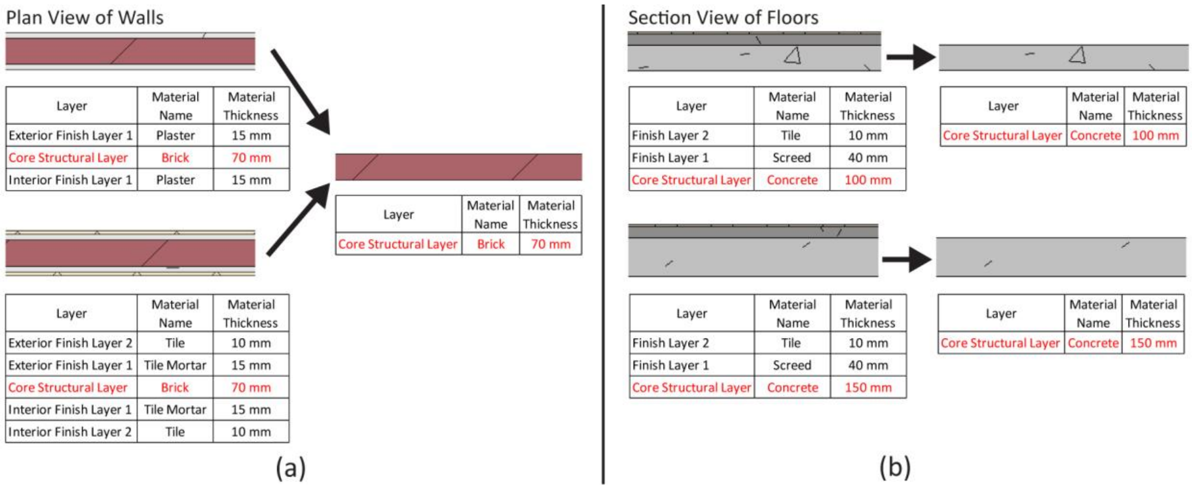

Figure 4.4 (a) Walls in which the core structural layer has the same material name and thickness are converted to the same new family type. (b) Floors in which the core structural layer has the same material name but a different thickness are converted to different new family types.

Figure 4.5 shows the flowchart for process 2: convert original walls and floors into walls and floors with only a core structural layer. First, original walls are converted to walls with only a core structural layer. To do this, new wall types must be created. The process begins with importing all walls from a Revit model. The material names and thicknesses are extracted from each wall. Only the material names and thicknesses of a core structural layer are selected and combined into a list. The duplicated names and thicknesses in the list are then removed. After that, the material names and thicknesses are split into a list of material names and a list of material thicknesses. These two lists are used to create new wall types in Revit by defining the material of a core structural layer and a thickness. Next, the original walls are converted into new walls. A list of new wall types is created by matching the material names and thicknesses of the new wall types with the list of material names and thicknesses of a core structural layer from the original walls. This list is then used to convert the original walls in the Revit model into the new walls.

Next, original floors are changed into floors with only a core structural layer. Similar to the processes in the first part, the new floor types are created using the material names and thicknesses of a core structural layer from the original floors. After that, the original floors in the Revit model are changed to the new floors. Moreover, the new floors have to be moved to below the original positions because the original floors have finish layers, but the new floors have only a core structural layer. If the new floors are not moved, the position of the core structural layer of the new floors will be higher than that of the original floors (see Figure 4.6). To do this, the finish layer thicknesses of the original floors are summed. Subsequently, the “height offset from level” parameters of the original floors minus the sum of the finish layer thicknesses of the original floors are used to set the new "height offset from level" parameters of the new floors.

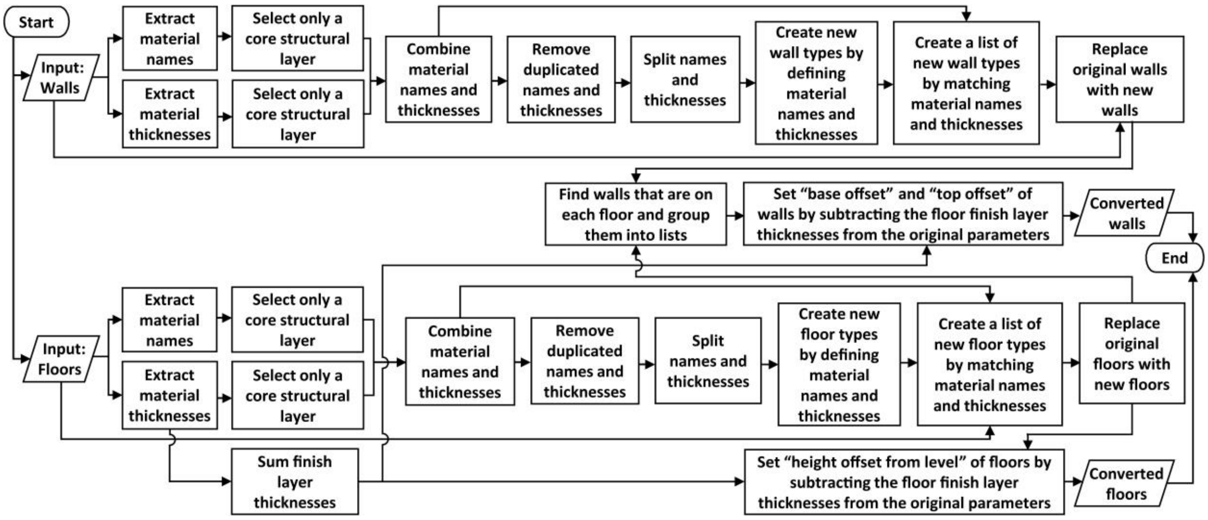

Figure 4.5 Flowchart for process 2: convert original walls and floors into walls and floors with only a core structural layer.

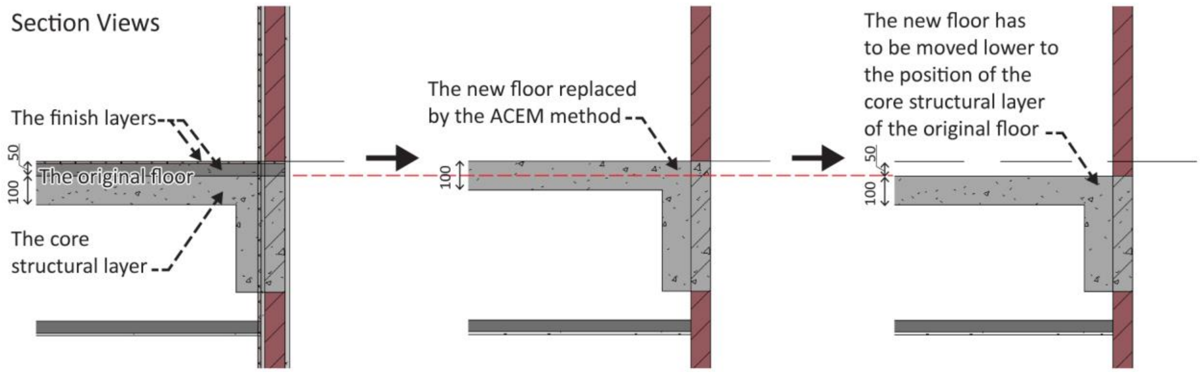

Figure 4.6 The position of the core structural layer of the new floor is higher than that of the core structural layer of the original floor; therefore, the new floor must be lowered.

In addition, the base of the new walls must be attached to the newly positioned floors and the top of the new walls must be lowered with the bases. To set the base and the top of the new walls, the walls on each floor are detected and grouped into lists. After that, the "base offset" parameters of the walls in the lists minus the finish layer thicknesses of the original floors are used to set the new "base offset" parameters of the walls in the lists. The "top offset" parameters of the walls in the lists minus the finish layer thicknesses of the original floors are used to set the new "top offset" parameters of the walls in the lists. In Figure 4.7b, the walls and floors with only a core structural layer in the example BIM model are shown.

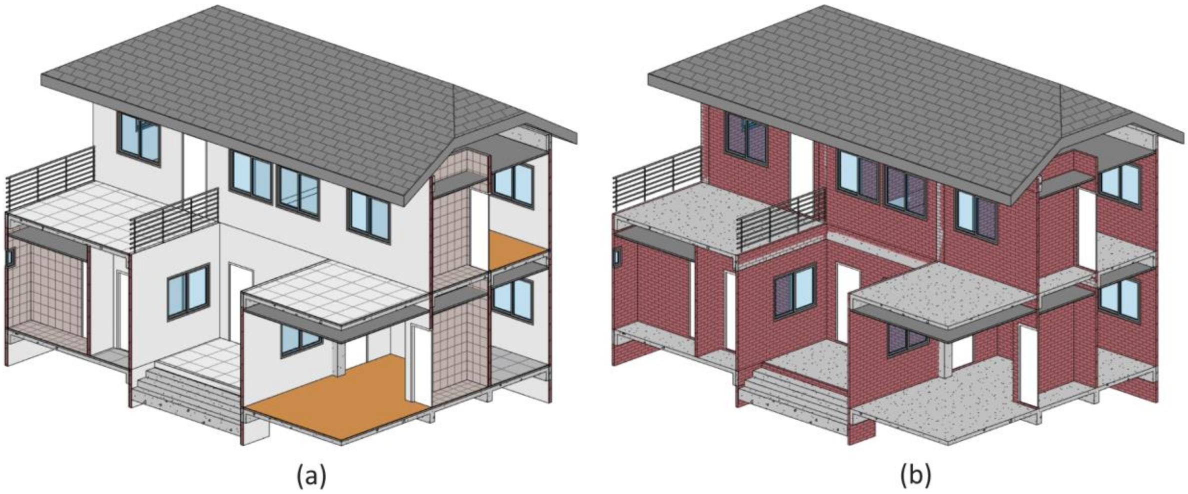

Figure 4.7 Example of (a) the original BIM model and (b) the BIM model after changing the original walls and floors into the walls and floors with only a core structural layer (process 2).

4.2.3 Process 3: Recreate walls that are exterior and interior wall finishes from the extracted information

Figure 4.8 shows the flowchart for process 3: recreate walls that are exterior and interior wall finishes from the extracted information. The information in sheet 1 of the spreadsheet file from the first process (Section 4.2.1) is imported into the system. The information in each column is then separated into lists. All lists consist of the material name of the exterior wall finish, the material thickness of the exterior wall finish, the material names of layer 1 of the interior wall finish, the material names of layer 2 of the interior wall finish, the material thicknesses of layer 1 of the interior wall finish, and the material thicknesses of layer 2 of the interior wall finish. It should be noted that according to the spreadsheet file, all lists are sorted by room names and exterior name (see Figure 4.3a).

To recreate the walls that are exterior finish, the first step is to create a new wall type using the material name and material thickness of the exterior wall finish. Next, location lines and heights of the new walls are prepared. Rooms, walls, structural columns, and level are imported from the Revit model. The rooms, walls, and structural columns are combined into an integrated geometry. From the levels, elevations are extracted and sorted in ascending order. A plane is then created at each elevation. The planes are intersected with an integrated geometry to obtain intersected surfaces. The perimeter curves are extracted from the surfaces. These curves are the boundary lines of the building for every elevation. After that, the curves are offset by half of the material thickness of the exterior wall finish. The result is the location lines of the walls. The height of the walls is extracted from the elevations. The elevations are split into two lists. The last item is removed from the first list. This list will be the starting levels of the walls. The first item is removed from the second list. This list will be the final levels of the walls. Finally, the wall type, location lines, start levels, and end levels are used to create walls that are exterior wall finishes in the Revit model.

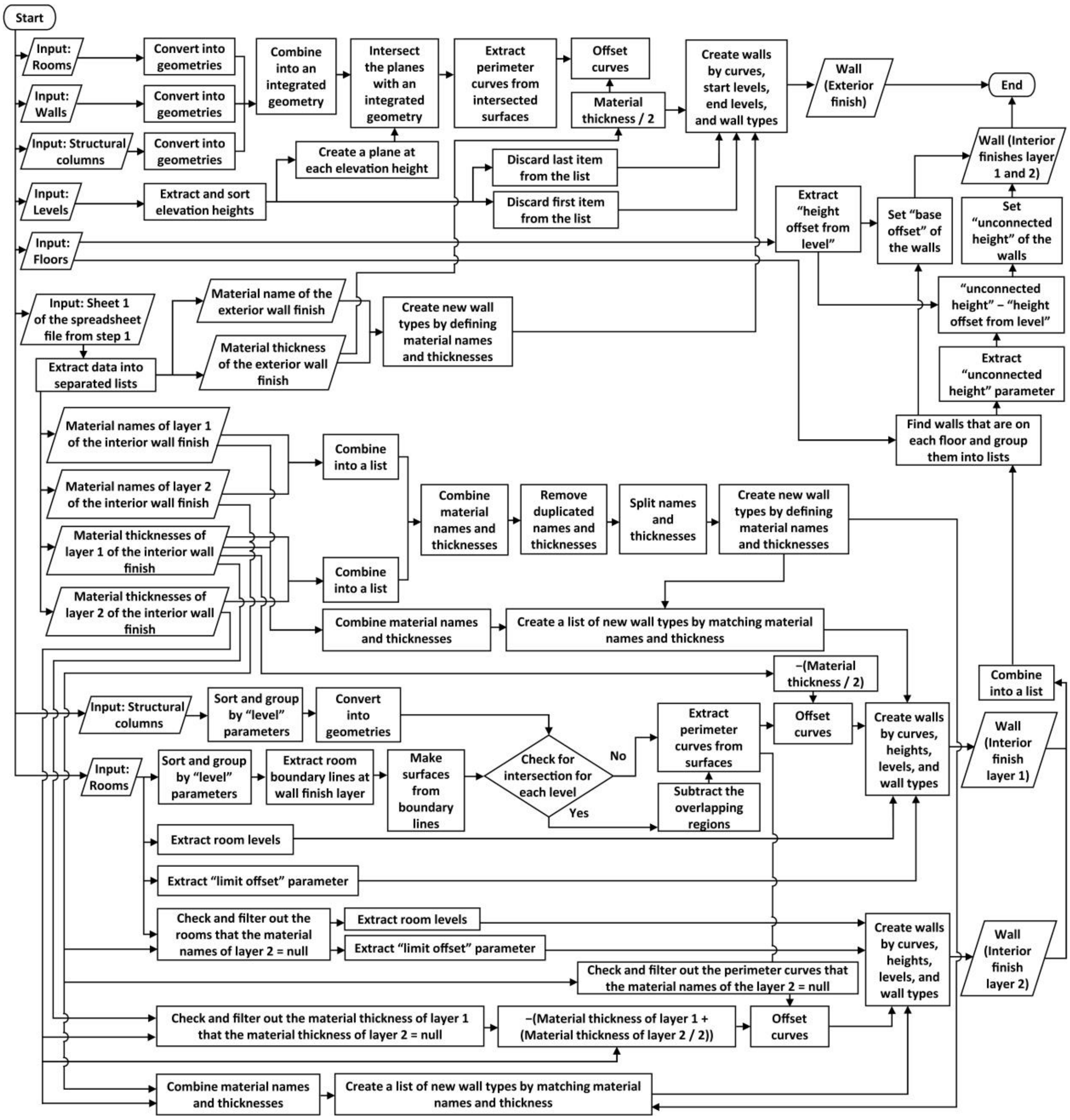

Figure 4.8 Flowchart for process 3: recreate walls that are exterior and interior wall finishes from the extracted information.

To create walls that are interior finish, the first step is to create new wall types. The material names of layer 1 of the interior wall finish, the material names of layer 2 of the interior wall finish, the material thicknesses of layer 1 of the interior wall finish, and the material thicknesses of layer 2 of the interior wall finish are used to create new wall types. The duplicated material names and thicknesses are removed before creating the new wall types. A list of new wall types that are layer 1 of the interior wall finish is created by matching material names and thicknesses of the new wall types with the list of material names and thicknesses of layer 1 of the interior wall finish from the spreadsheet file. This list of wall types is used to create walls that are layer 1 of the interior wall finish. Another list of new wall types that are layer 2 of the interior wall finish is also created by matching material names and thicknesses of the new wall types to the list of material names and thicknesses of layer 2 of the interior wall finish from the spreadsheet file. This list of wall types is used to create walls that are layer 2 of the interior wall finish.

To create the walls for layer 1 of the interior wall finish, location lines, heights, and levels have to be prepared. To find the location lines, rooms and structural columns are imported from the Revit model. They are then sorted and grouped by the level parameters. Room boundary lines at the wall finish layer are extracted and used to make surfaces. The structural columns are converted into geometries. Subsequently, the room surfaces are checked for their intersection with the geometries for each level. Overlapping regions are subtracted. The surfaces after subtraction are used to extract perimeter curves. The curves are offset inside by one half the material thickness of layer 1 of the interior wall finish. It should be noted that this requires conversion to negative numbers to offset inside. The result is the location lines of the walls that will be layer 1 of the interior wall finish. The heights of the walls are extracted from the "limit offset" parameter of the rooms. The levels at which the walls will be placed are extracted from the room levels. Finally, the list of wall types that are layer 1 of the interior wall finish, the location lines, the heights, and the level are used to create walls that are layer 1 of the interior wall finish in the Revit model.

To create the walls for layer 2 of the interior wall finish, location lines, heights, and levels have to be prepared. To find the location lines, the perimeter curves of the room surfaces from the previous process are used. The list of perimeter curves is checked against the list of material names of layer 2. The perimeter curves for which the material names of layer 2 return null are removed from the list. In parallel, the list of material thicknesses of layer 1 is checked against the list of material thicknesses of layer 2. The material thicknesses of layer 1 for which the material thicknesses of layer 2 equal null are removed from the list. After that, the perimeter curves are offset inside by the sum of the material thickness of layer 1 and half of the material thickness of layer 2. This yields the location lines of the walls that will be layer 2 of the interior wall finish. To find the heights of the walls and the levels, the list of rooms is checked against the list of material names of layer 2. The room for which the material names of layer 2 return null are removed from the list. After that, the heights of the walls are extracted from the "limit offset" parameter of the rooms and the levels are extracted from the room levels. Finally, the list of wall types for layer 2 of the interior wall finish, the location lines, the heights, and the level are used to create walls for layer 2 of the interior wall finish in the Revit model.

Furthermore, the bases of all walls that are the interior wall finishes have to attach to the floors that have been moved down. In order to set the base of the walls, the walls on each floor are detected and grouped into lists. The "height offset for level" parameters from the floors are used to set the "base offset" parameters of the walls. Nevertheless, when the base offset is set lower, the whole walls are moved to a lower position. This is because the walls created by the algorithms have an "unconnected height" parameter, which does not attach the top of the walls to the floor level above. To maintain the top of the wall to the previous level, the "unconnected height" parameter minus the "height offset for level" parameters from the floors are used to set the new "unconnected height" parameter of the wall. For example, the "height offset for level" parameter of a floor is −50 mm and the "unconnected height" of a wall is 2400 mm. The result of the new "unconnected height" would be 2400 − (−50) = 2450 mm. Figure 4.9 shows the recreated walls that are exterior and interior wall finishes in the example BIM model.

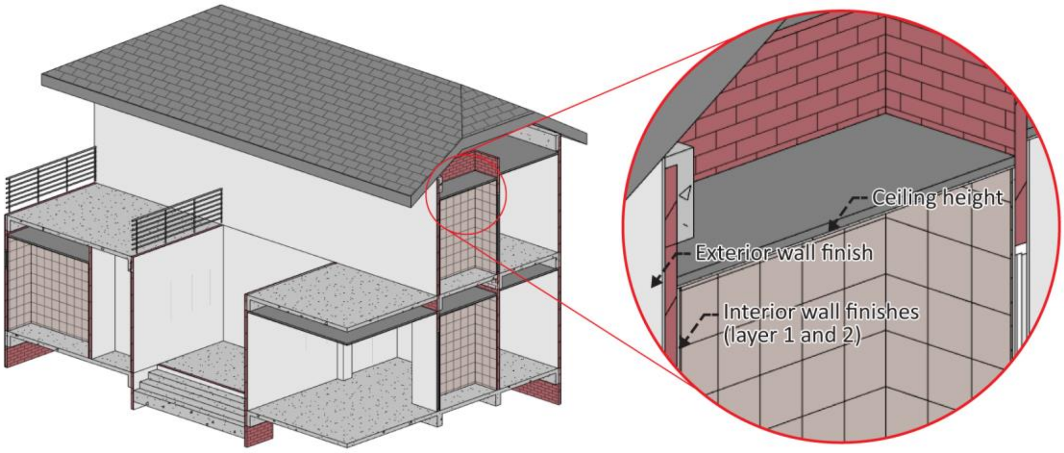

Figure 4.9 Example of the BIM model after the walls that are exterior and interior wall finishes have been recreated (process 3).

4.2.4 Process 4: Recreate floors that are exterior and interior floor finishes from the extracted information

Figure 4.10 shows the flowchart for process 4: recreate floors that are exterior and interior floor finishes from the extracted information. The information in sheet 2 of the spreadsheet file from the first process (Section 4.2.1) is imported into the system. The information in each column is then separated into lists. All lists consist of the material names of layer 1 of the floor finish, the material thicknesses of layer 1 of the floor finish, the material names of layer 2 of the floor finish, the material thicknesses of layer 2 of the floor finish, and the room and exterior levels of the floor finish. It should be noted that based on the spreadsheet file, all lists are sorted by room names and exterior name (see Figure 4.3b).

To recreate floors that are exterior and interior floor finishes, the first step is to create new floor types. In this process, the new floor types consist of two material layers, the supporting layer and the top surface layer. For the material names of layer 1 of the floor finish and the material thicknesses of layer 1 of the floor finish, duplicates are removed. Then, they are used to define the material names and thicknesses of the supporting layer of the new floor types. The material names of layer 2 of the floor finish and the material thicknesses of layer 2 of the floor finish are also used to remove duplicates. Then, they are used to define the material names and thicknesses of the top surface layer of the new floor types. After that, a list of new floor types is created by matching material names and thicknesses of the new floor types with the lists of material names and thicknesses of layer 1 and layer 2 of the floor finish from the spreadsheet file. This list of floor types will be used to create floors that are exterior and interior floor finishes.

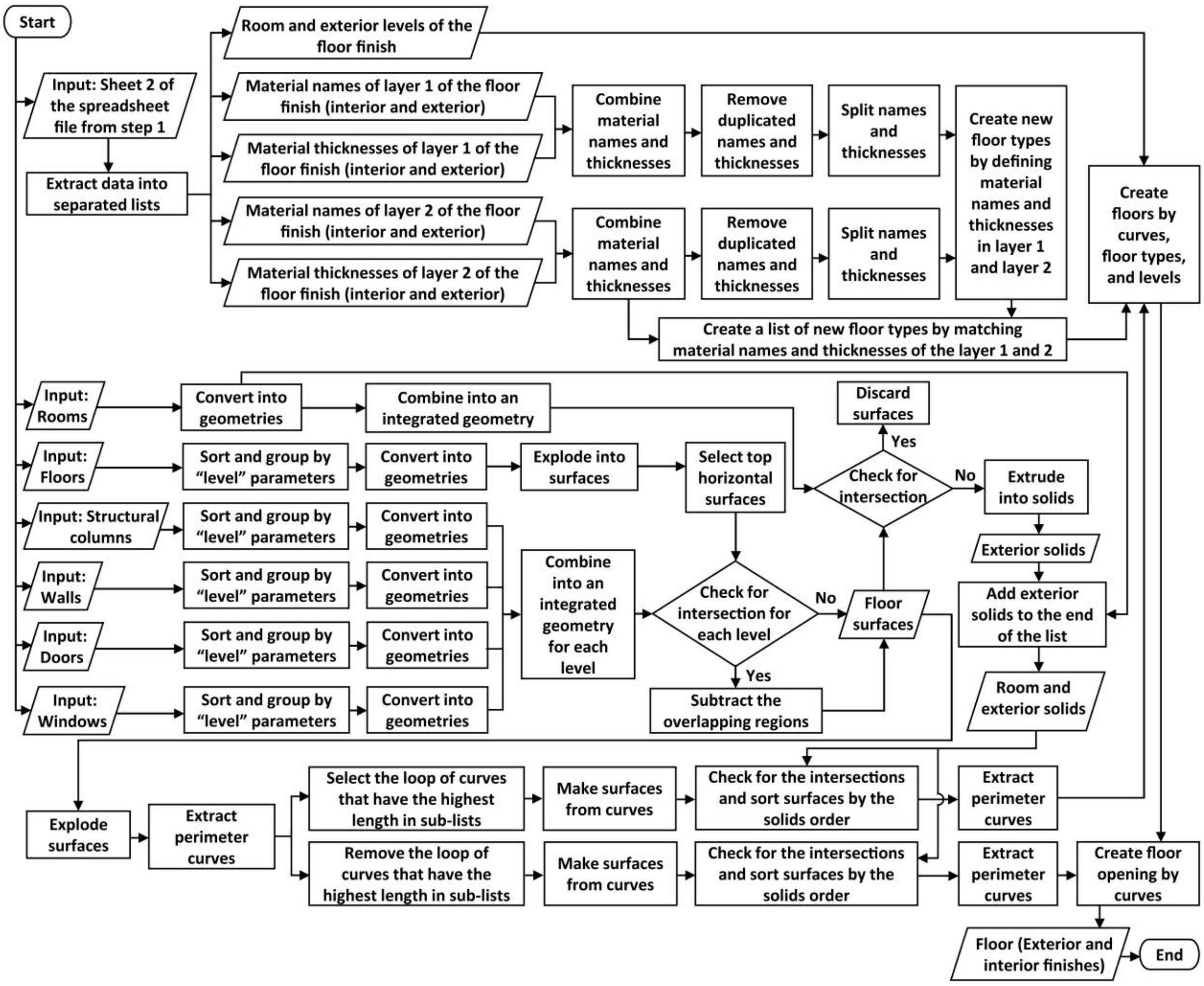

Figure 4.10 Flowchart for process 4: recreate floors that are exterior and interior floor finishes from the extracted information.

The next step is to prepare boundary lines for the floors and levels on which the floors would be placed. The levels on which the floors would be placed are obtained from the room and exterior levels of the floor finish. To find the boundary lines of the floors, building elements, which are floors, structural columns, walls, doors, and windows, are imported from the Revit model. They are sorted and grouped by the level parameters. After that, they are converted into geometries. The structural columns, walls, doors, and windows are combined into an integrated geometry for each level. The floors are exploded into surfaces and the top horizontal surfaces are selected. The surfaces are then checked for their intersection with the integrated geometries for each level and the overlapping regions are subtracted. Subsequently, the floor surfaces after subtraction are exploded into separated pieces of surfaces. The perimeter curves are then extracted from the exploded surfaces. If the floor surfaces have openings, such as stairways, the extracted curves will contain more than one loop of curves in sub-lists. Therefore, the curves in the sub-lists must be separated into the curves of floors and the curves of floor openings. The longest loop of curves in each sub-list is selected as the curves of floors. The leftovers are selected as the curves of floor openings. Then, floor surfaces are created from the curves of floors and floor opening surfaces are created from the curves of floor openings. After that, the floor surfaces and the floor opening surfaces need to be sorted according to the list of floor types. To do that, rooms are imported from the Revit model. They are converted into geometries (solids) and combined into an integrated geometry. The floor surfaces are checked for their intersection with the integrated geometry for the room. The floor surfaces that do not intersect with the integrated geometry are selected as exterior floor surfaces. The exterior floor surfaces are then extruded to solids and these solids are added to the end of the list of the room geometries (solids). The floor surfaces and the floor opening surfaces are checked for their intersections with the room and exterior solids. They are then sorted by the room and exterior solids order. After that, the floor surfaces are extracted their perimeter curves. These perimeter curves are the boundary lines of the floors. The perimeter curves and the room and exterior levels of the floor finish from the spreadsheet are then used to create floors that are exterior and interior floor finishes in the Revit model. Finally, the floor opening surfaces are used to extract perimeter curves. These curves are used to create floor openings on the created floors. Figure 4.11 shows the recreated floors that are exterior and interior floor finishes in the example BIM model.

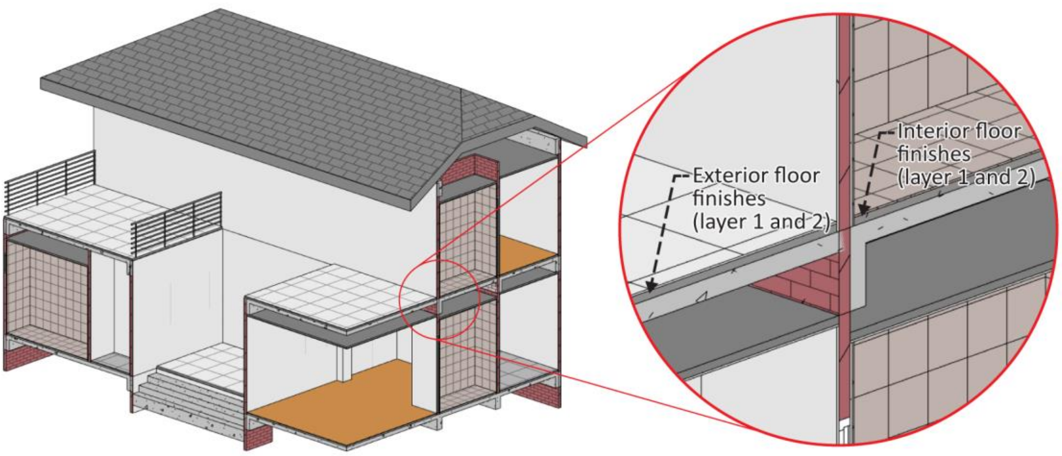

Figure 4.11 Example of the BIM model after the floors that are exterior and interior wall finishes have been recreated (process 4).

4.2.5 Process 5: Join walls and eliminate overlapping regions of walls

In this process, the walls that cover the doors and windows have to join with the walls that are the host of doors and windows by using the "JoinGeometry" method in the Revit API. For the walls that intersect with floors, columns, and beams, the overlapping regions must be eliminated using the "JoinGeometry" method in the Revit API.

Figure 4.12 shows the flowchart for process 5: join walls and eliminate the overlapping regions of walls. To join walls, only the walls that intersect with doors and windows need to be joined; therefore, they have to be selected from all walls in the Revit model. Wall, doors, and windows are imported from the Revit model. The doors and windows are converted into geometries and exploded into surfaces. The vertical surfaces of the geometries are selected. The surfaces are then thickened into solids by a distance of 200 mm, which would be enough to intersect all wall finishes. The walls are checked for their intersection with the solids. The walls that intersect the solids are selected. Afterward, all selected walls are joined with each other.

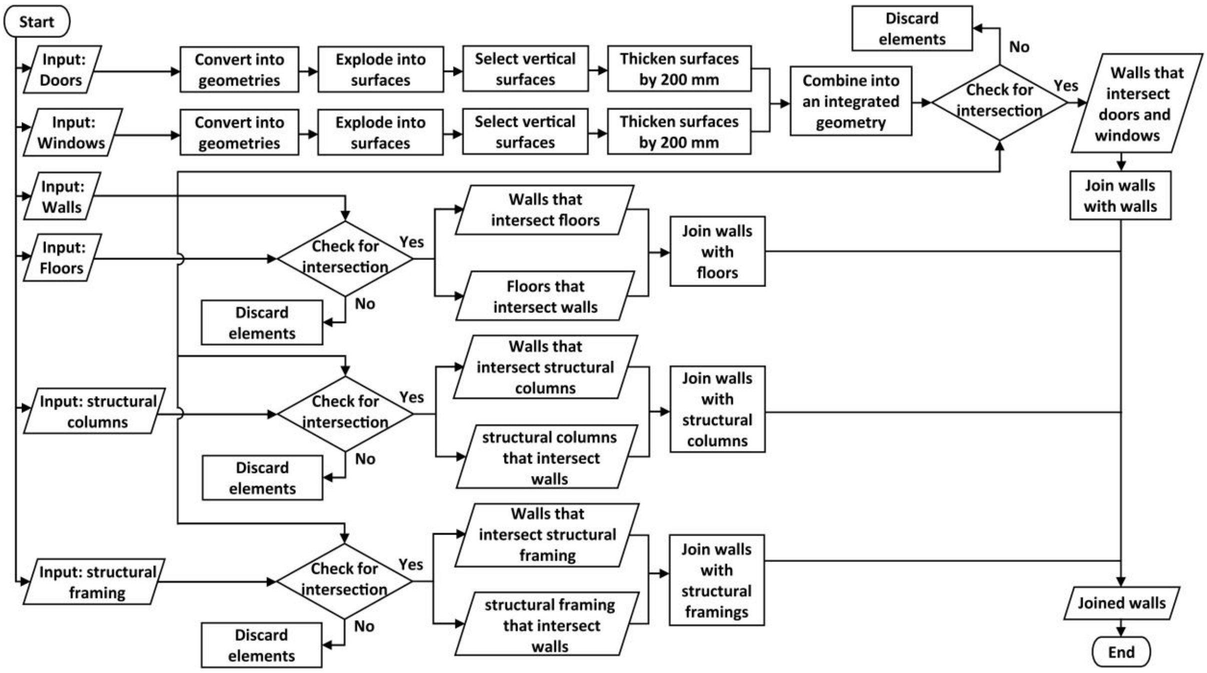

Figure 4.12 Flowchart for process 5: join walls and eliminate the overlapping regions of walls.

To eliminate the overlapping regions of walls, floors, structural columns, and structural framing (beams) are imported from the Revit model. All elements in each category are checked for their intersection with the walls and the walls are checked for their intersection with the elements in each category. Then, the elements in each category that intersect the walls are selected and the walls that intersect the elements in each category are selected to obtain three pairs of elements. The first pair is the walls that intersect the floors and the floors that intersect the walls. The second pair is the walls that intersect the structural columns and the structural columns that intersect the walls. The third pair is the walls that intersect the structural framing and the structural framing that intersect the walls. Finally, the elements in each pair are joined. Figure 4.13 shows the result of the example BIM model after the walls are joined and the overlapping regions are eliminated.

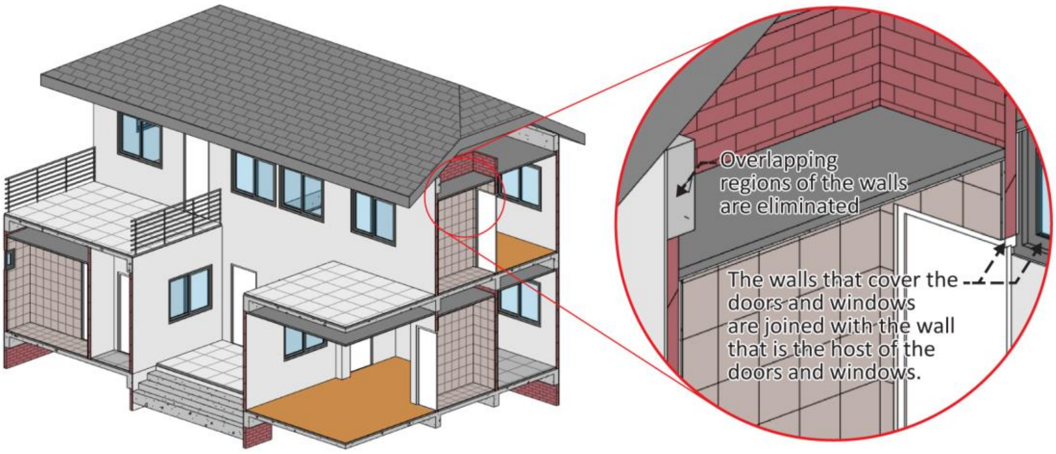

Figure 4.13 Example of the BIM model after the walls are joined and the overlapping regions are eliminated (process 5).

4.3 Validation

To verify the ACEM prototype system and validate the ACEM method, material quantities of architectural walls and floor finishes from BIM models modified by the ACEM method were compared with the material quantities of architectural walls and floor finishes from original BIM models and manual modified BIM models (baseline). Furthermore, the execution times of the ACEM prototype system were also compared with the modification times of the manual modified BIM models. It should be noted that in this validation, Autodesk Revit 2018.2 and a computer with an Intel Core i7-8770 3.2 GHz CPU, 32 GB RAM, and NVIDIA GeForce GTX 1060 6 GB graphics card was used.

Two case studies were used for validation. The first case study was a residential building, for which BIM models were created by the authors to validate the ACEM method. The second case study was an office building, for which the original BIM model was obtained from a construction firm in Bangkok, Thailand and used to validate the ACEM method in real working conditions.

4.3.1 Case study 1

4.3.1.1 Overview of the case study 1

A two-story residential building is selected as the first case study. The building is a concrete frame structure with the total construction floor area of 318 m^2. It consists of 15 rooms, 6 wall materials, and 8 floor finish materials. It has brick masonry walls with wall finishes on both sides. The floors are reinforced concrete structures with floor finishes on top. The first story is 1.00 m above the ground level. The floor height of the first story is 3.00 m, and the floor height of the second story is 3.20 m. The ceiling heights of the first story are 2.30 m, 2.40 m, and 2.45 m, depending on the room. The ceiling heights of the second story are 2.40 m and 2.60 m, depending on the room.

Material quantities for walls and floors are compared among three BIM models. The first model is the original BIM model (see Figure 4.14a). This BIM model yields inaccurate material quantities for walls and floors. The second model is the manually modified BIM model (see Figure 4.14b). This BIM model is the original BIM model with modified walls and floors for accurate material quantities. The manually modified BIM model is used as a baseline for the comparison. The last model is the original BIM model automatically modified by the ACEM method (see Figure 4.14c).

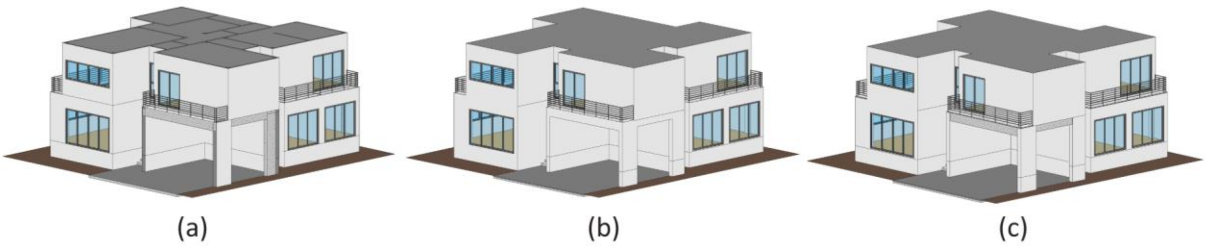

Figure 4.14 (a) The original BIM model, (b) manually modified BIM model (baseline), and (c) BIM model modified by the ACEM method for case study 1.

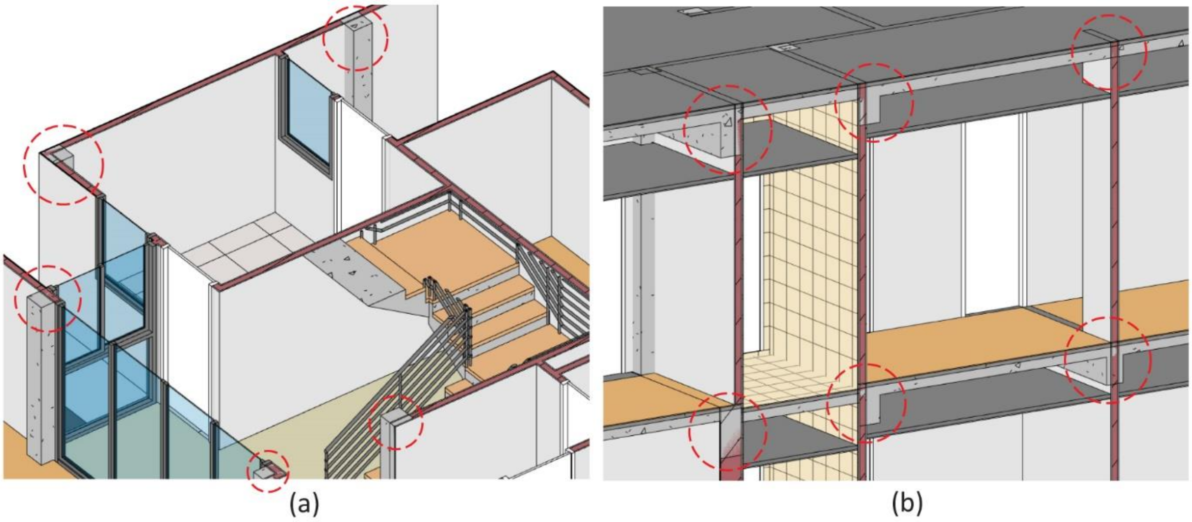

Figure 4.15 (a) Walls were created to overlap with columns. (b) Walls were created to overlap with beams and floors

The original BIM model was created using modeling methods commonly used in the design phase. The walls and floors are single model elements with defined material layers. They are equivalent to LOD 300 according to the LOD specification by the BIMForum (BIMForum, 2019). Each wall type consists of a core structural layer and finish layers on both sides. The heights of all layers were equal. The walls were created to overlap with the structural elements, which were columns, beams, and floors (see Figure 4.15). Each floor type consists of a core structural layer, which is reinforced concrete, and two finish layers, which are a supporting layer and a top surface layer. The floors were created under columns and walls (see Figure 4.16a and b). The floors at each level were divided into pieces according to the floor finish materials. The nearby rooms that share the same floor finishes used the same piece of floor (see Figure 4.16). Figure 4.17a shows a 3D section view of the original BIM model.

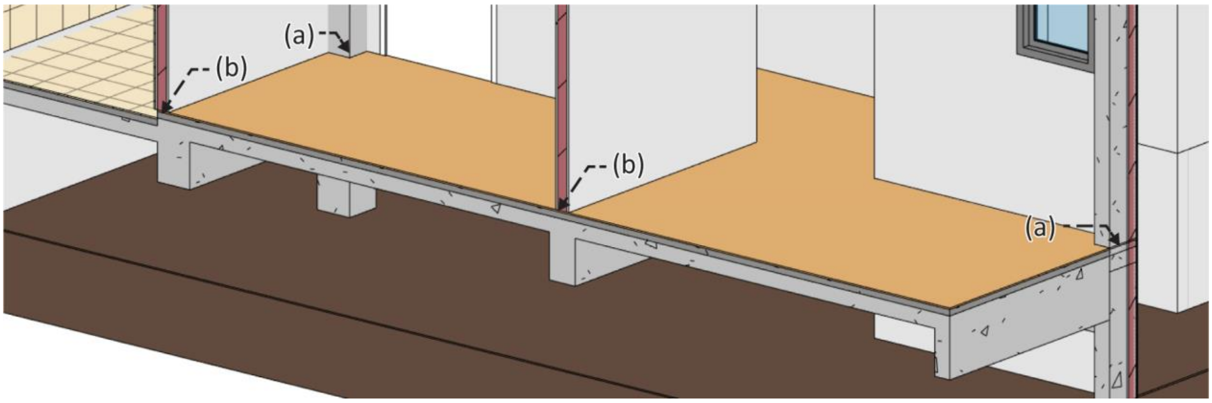

Figure 4.16 Floors created under (a) columns and (b) walls.

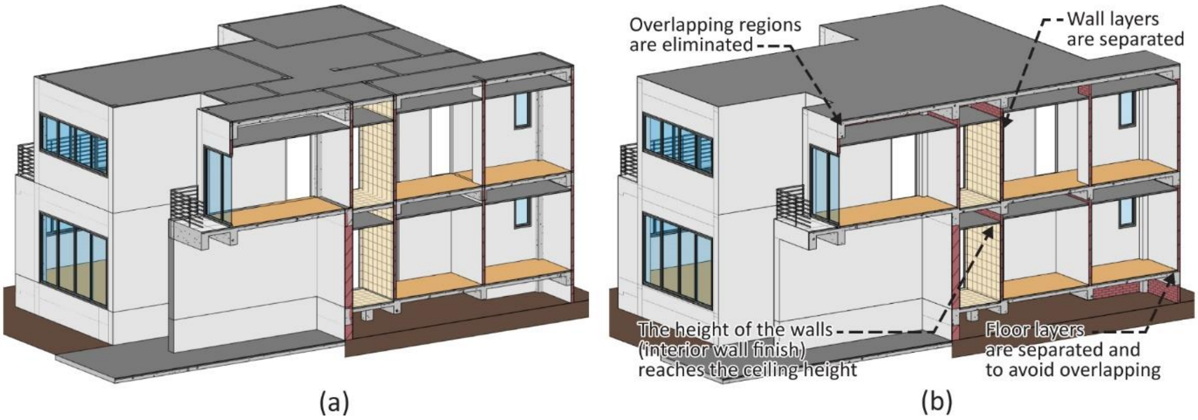

Figure 4.17 Three-dimensional section views of (a) the original BIM model and (b) the manually modified BIM model for case study 1.

To construct the manually modified BIM model, the original BIM model was manually modified according to the actual construction. The modification time was recorded for comparison. All wall and floor layers were separated as individual model elements corresponding to LOD 350 according to the LOD specification by the BIMForum (BIMForum, 2019). The original walls were changed to walls with only a core structural layer. Moreover, they were edited by eliminating intersections with columns, beams, and floors. The wall finishes were recreated as new wall types. The exterior wall finish covered the core structural layer and the structural elements that are exposed to the exterior. The interior wall finish covered the core structural layer and the columns inside of rooms. The height of the walls classified as the interior wall finish reached the ceiling height. The original floors were changed to floors that have only a core structural layer, which is a reinforced concrete slab. The floor finishes were recreated as new floor types. They were created on the floors that form the core structural layer. The boundaries of the floors that are floor finishes were adjusted to avoid overlap with walls and columns in both the interior and exterior of the building. Figure 4.17 shows 3D section views of the original BIM model and the manually modified BIM model.

Additionally, the ACEM prototype system was applied to the original BIM model. The ACEM prototype system is divided into five processes, as explained in Section 4. The execution time for each process was recorded and the total time was used for comparison with the modification time of the manually modified BIM model. Figure 4.18 shows 3D section views of the BIM model during processes 2–5 of the ACEM prototype system.

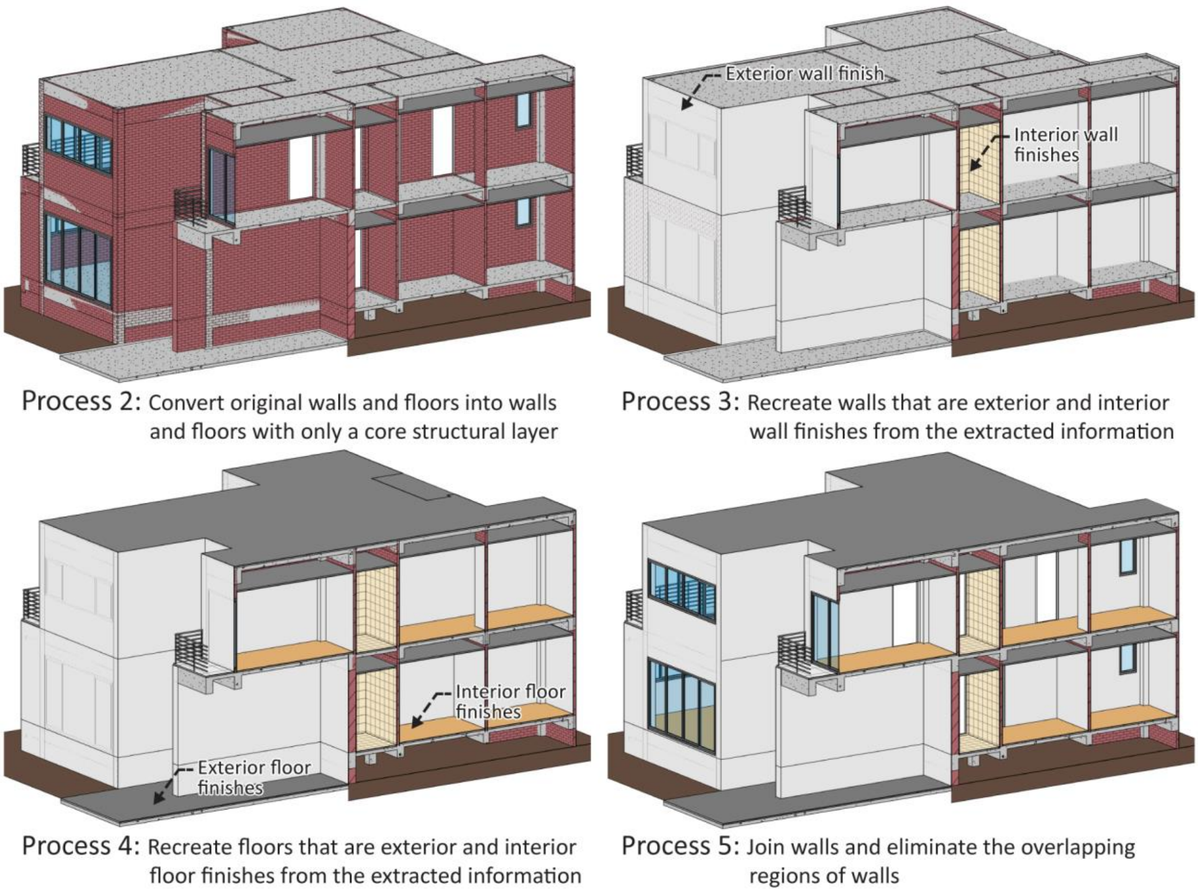

Figure 4.18 Three-dimensional section views of the BIM model during processes 2–5 of the ACEM prototype system for case study 1.

4.3.1.2 Comparative analysis

Material quantities were extracted from the original BIM model, the manually modified BIM model, and the BIM model modified by the ACEM method by creating material takeoff schedules using Autodesk Revit. The results of the manually modified BIM model are the baseline for calculating deviations. Table 4.1 provides a comparison of material quantities among the original BIM model, the manually modified BIM model, and the BIM model modified by the ACEM method. Furthermore, Table 4.2 summarizes the comparison between the manual modification time of the BIM model and the execution time of the ACEM prototype system.

Table 4.1 Comparison of the material quantities among the original BIM model, the manually modified BIM model, and the BIM model modified by the ACEM method.

Elements	Material Layers	Manually Modified BIM Model (Baseline)	Original BIM Model			BIM Model Modified by the ACEM Method		
		Area (m²)	Area (m²)	Difference (m²)	Deviation (%)	Area (m²)	Difference (m²)	Deviation (%)
Walls	Brick 70 mm	393.46	522.33	128.87	32.75	393.46	0.00	0.00
	Brick 250 mm	35.68	49.76	14.08	39.46	35.68	0.00	0.00
	Interior Plaster	436.22	642.05	205.83	47.18	432.10	−4.12	−0.94
	Interior Ceramic Tile	56.64	75.83	19.19	33.88	56.64	0.00	0.00
	Interior Tile Mortar	57.38	75.84	18.46	32.17	57.38	0.00	0.00
	Exterior Plaster	442.81	426.28	−16.53	−3.73	439.94	−2.87	−0.65
Floors	Interior Wood Flooring	157.46	170.46	13.00	8.26	157.46	0.00	0.00
	Interior Ceramic Tile - Stair Hall	35.01	37.31	2.30	6.57	35.01	0.00	0.00
	Interior Ceramic Tile - WC	11.93	12.95	1.02	8.55	11.93	0.00	0.00
	Interior Ceramic Tile - Kitchen	8.91	9.91	1.00	11.22	8.91	0.00	0.00
	Exterior Ceramic Tile	33.49	34.23	0.74	2.21	33.49	0.00	0.00
	Exterior Granite	52.42	52.91	0.49	0.93	52.42	0.00	0.00
	Exterior Roofing	129.96	129.96	0.00	0.00	129.96	0.00	0.00
	Concrete Screed	429.18	447.73	18.55	4.32	429.18	0.00	0.00

As shown in Table 4.1, the material quantities of the original BIM model for most of the material layers deviate substantially from those of the manually modified BIM model. For the wall layers, the deviations ranged from −3.73% to 47.18%. For the floor layers, the deviations ranged from 0.00% to 11.22%. A negative deviation indicates that the value is less than the baseline.

After applying the ACEM prototype system to the original BIM model, the material quantities for most of the material layers are equal to the material quantities obtained from the manually modified BIM model, except for two material layers of the walls. The exterior plaster layer of the wall had a deviation of −0.65% and the interior plaster layer of the wall had a deviation of −0.94%. The small deviations occurred because the ACEM prototype system did not create walls that are exterior and interior wall finishes in some places. For the exterior plaster layer, the system did not create walls that are exterior wall finish on the surfaces of beams that do not attach to walls (see Figure 4.19a). For the interior plaster layer, the height of the walls that are interior wall finish at the stairway must reach the floor level above. However, the height of the walls created by the system was equal to the ceiling height of the stair hall (see Figure 4.19b). This is because the stair hall and the stairway that connects to the stair hall are in the same room. The system uses the "limit offset" parameter of the room, which equals the ceiling height, as the height for recreating walls.

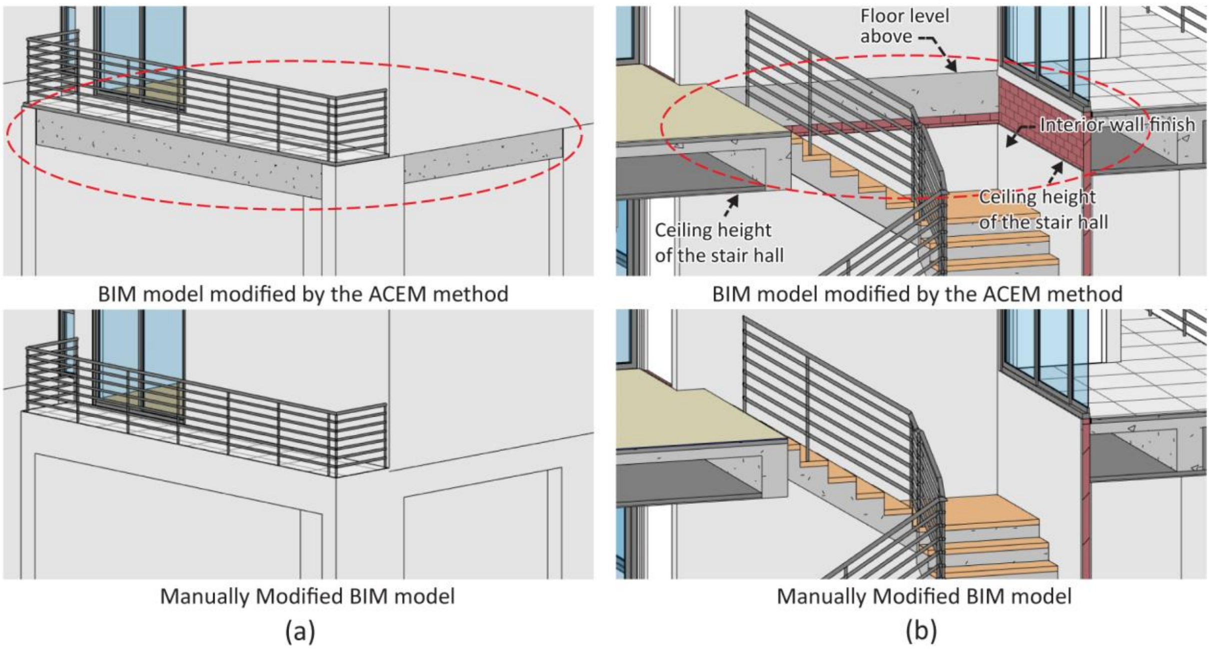

Figure 4.19 (a) The ACEM prototype system did not create walls that are exterior wall finish on the surfaces of beams that do not attach to walls. (b) The height of the walls that are interior wall finish at the stairway was equal to the ceiling height of the stair hall, while in actual construction, the height of the walls must reach the floor level above.

Table 4.2 Comparison between the manual modification time of the BIM model and the execution time of the ACEM prototype system.

Manual Modification Time of the BIM model		**Execution Time of the ACEM Prototype System**		
Time	**Time (seconds)**	**Processes**	**Time**	**Time (seconds)**
		1	35.64 s	35.64
		2	36.45 s	36.45
		3	35.21 s	35.21
		4	27.80 s	27.80
		5	2 min 29.64 s	149.64
4 h 18 min	**15,480**	**Total**	**4 min 44.74 s**	**284.74**

As shown in Table 4.2, the ACEM prototype system took 4 min 35 s (or 275 s) to complete while the manual modification took 4 h 18 min (or 15,480 s) to complete. The execution time of the ACEM prototype system was about 54 times faster than the manual modification time. Although the speed of manual modification may vary among BIM modelers, this method is much slower than the ACEM prototype system.

4.3.2 Case study 2

4.3.2.1 Overview of the case study 2

The second case study is a six-story office building. The building is an actual construction project in Bangkok, Thailand. It is a concrete frame structure with a total construction floor area of 1,336 m^2. The BIM model of this building was obtained from a construction firm in Bangkok, Thailand. Based on the specification, the building consists of 32 rooms, 9 wall materials, and 13 floor finish materials. The walls are lightweight concrete masonry walls with wall finishes on both sides. The floors are reinforced concrete structures with floor finishes on top. The first story is 1.00 m above ground level. The floor height of the first story is 3.50 m. The floor height of the second story to the fifth story is 3.05 m. The floor height of the sixth story is 2.60 m. The ceiling heights of the first story are 2.80 m and 2.60 m, depending on the room. The ceiling heights of the second story to the fifth story are 2.55 m and 2.50 m, depending on the room. The ceiling height of the sixth story is 2.45 m.

Similar to the validation process for case study 1, material quantity of walls and floors were compared among three BIM models. The first model is an original BIM model (see Figure 4.20a). The modeling issues resulting in inaccurate material quantities for walls and floors are reported in Section 5.2.2. The second model is a manually modified BIM model, which is the baseline (see Figure 4.20b). The last model is the BIM model modified by the ACEM method (see Figure 4.20c).

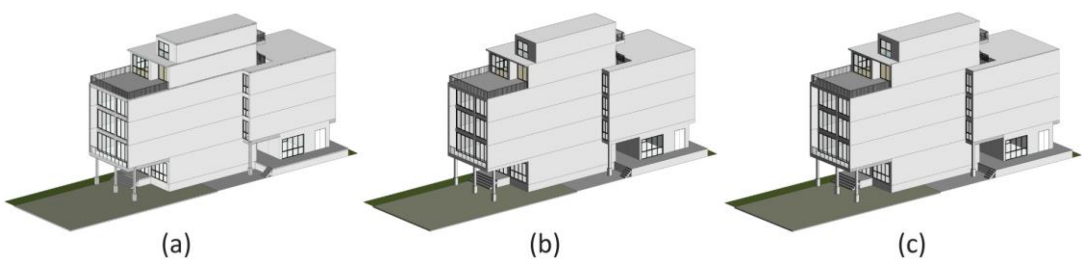

Figure 4.20 (a) Original BIM model, (b) manually modified BIM model (baseline), and (c) BIM model modified by the ACEM method for case study 2.

For the manually modified BIM model, the original BIM model was manually modified according to the actual construction after model inspection. The modification time was recorded. Similar to case study 1, all wall and floor layers were separated as individual model elements and overlapping regions were eliminated. Figure 4.21 shows 3D section views of the original BIM model and the manually modified BIM model.

Figure 4.21 Three-dimensional section views of (a) the original BIM model and (b) the manually modified BIM model for case study 2.

For the BIM model modified by the ACEM method, the ACEM prototype system was applied to the original BIM model. The execution time for each process and the total time were recorded and compared with the manual modification time. Figure 4.22 shows 3D section views of the BIM model during processes 2–5 of the ACEM prototype system.

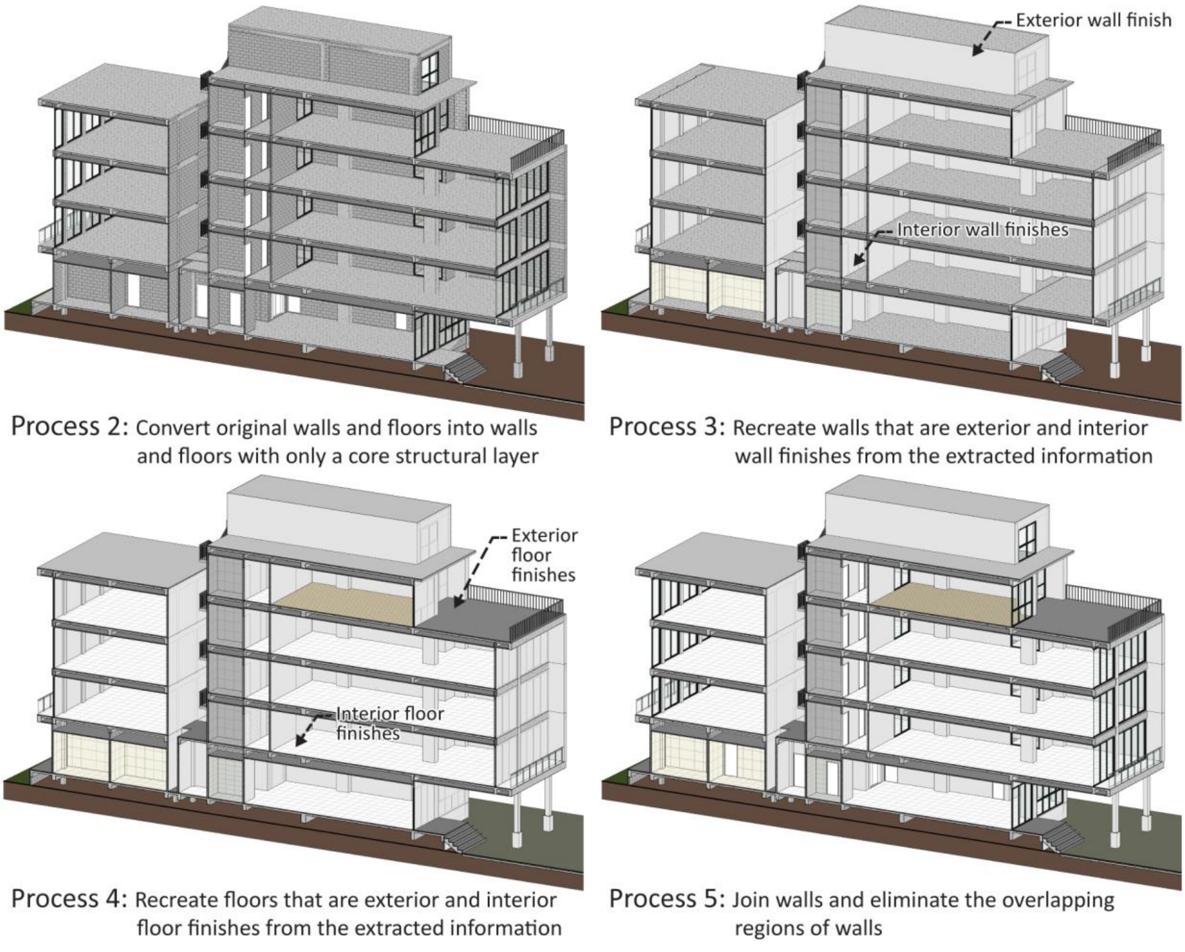

Figure 4.22 Three-dimensional section views of the BIM model during processes 2–5 of the ACEM prototype system for case study 2.

4.3.2.2 Modeling issues

The original BIM model obtained from the construction firm was created in the design development phase in parallel with 2D construction drawings. The building is now under construction using 2D construction drawings and the BIM model is used as a supplementary source.

According to the model inspection, modelers created walls and floors at LOD 300 according to the LOD specification by the BIMForum (BIMForum, 2019). The walls and floors are single model elements with defined material layers. The inaccurate material quantities for walls and floors can be attributed to five major issues.

First, the walls are single model elements; therefore, all wall layers have the same height, which is not consistent with the actual construction. In this BIM model, some walls attach to the soffit of the floor, but some walls attach to the top of the floor. Therefore, some walls overlap with beams above while some walls overlap with both beams and floors above (see Figure 4.23a). In the actual construction, the height of the core structural layer of the wall, which is a lightweight concrete masonry layer, reaches the soffit of the beam or the floor above. The interior wall finishes reach the ceiling height or the height of the soffit of the floor above if there is no ceiling in that room. The height of the exterior wall finishes reaches the floor above or the roof. Figure 4.23b shows the walls in the manually modified BIM model after editing and the separation of each wall layer. Figure 4.23c shows the lightweight concrete masonry layer and the interior plaster layer of a wall in the actual construction.

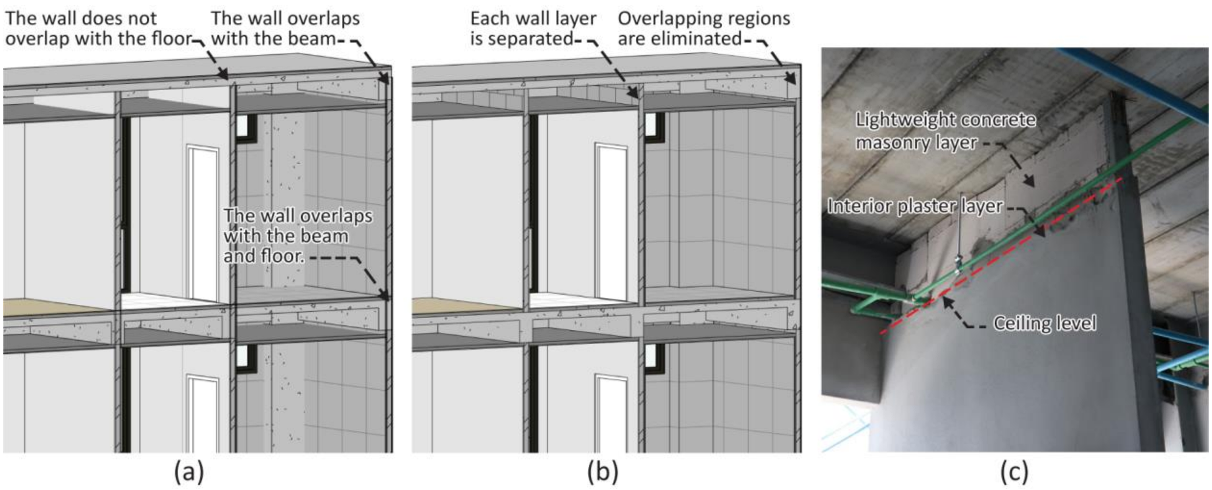

Figure 4.23 (a) All wall layers in the original BIM model have the same height and overlap with the beams and floors. (b) Walls in the manually modified BIM model after editing and the separation of each wall layer. (c) Lightweight concrete masonry layer and interior plaster layer of a wall in the actual construction.

Second, when the walls meet structural columns, some walls overlap with structural columns and some walls are joined with structural columns (see Figure 4.24a). This results in inaccurate quantities for the core structural layer of the wall and the interior finish layer. Figure 4.24b shows the walls in the manually modified BIM model after editing and the separation of each wall layer.

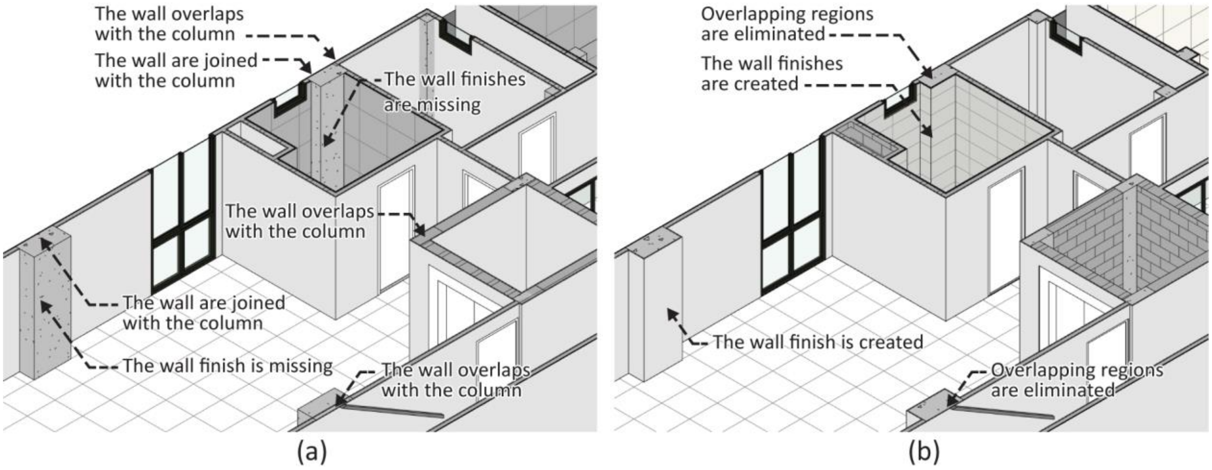

Figure 4.24 (a) Some walls in the original BIM model overlap with structural columns and some walls are joined with structural columns. (b) Walls in the manually modified BIM model after editing and the separation of each wall layer.

Third, the wall finish that should cover isolated columns in the rooms is missing (see Figure 4.25a). This makes the quantities of the interior finish layer of the wall inaccurate. Figure 4.25b shows the wall finish that covers the isolated column in the manual modified BIM model. Figure 4.25c shows the wall finish that covers the isolated column in the actual construction.

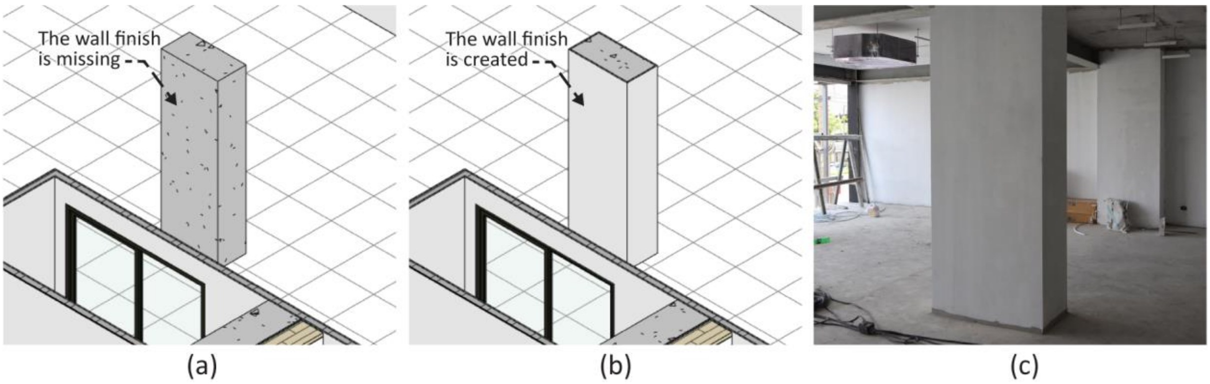

Figure 4.25 (a) The wall finish around the isolated column in the original BIM model is missing. (b) The wall finish that covers the isolated column in the manually modified BIM model. (c) The wall finish that covers the isolated column in the actual construction.

Fourth, the floors are single model elements with a core structural layer and finish layers. They are created under structural columns and walls (see Figure 4.26a). This results in overestimates of the quantities for the floor finishes. In the actual construction, the columns and walls are constructed on the reinforced concrete layer of the floors, which are the structural floors. The floor finishes are then constructed after the columns and walls. Figure 4.26b shows the floor finishes in the manually modified

BIM model that have been edited according to the actual construction. Figure 4.26c shows the walls in the actual construction that are constructed on the structural floors, before the floor finishes are installed.

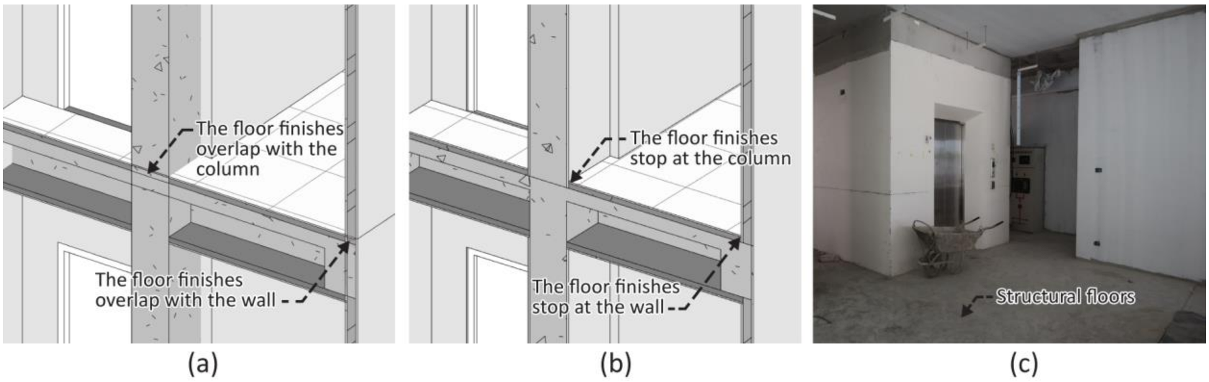

Figure 4.26 (a) Floor finishes in the original BIM model are under structural columns and walls. (b) Accurate floor finishes in the manually modified BIM model. (c) In the actual construction, the walls are constructed on the structural floors and the floor finishes are not yet installed.

Fifth, the wall finish and floor finish of all 11 toilet rooms in the original BIM model use the same material (see Figure 4.27a). However, according to the specification and the actual construction, three materials are used for the toilet rooms. Therefore, the quantities of two materials are missing from the original BIM model. The material information extracted from the original BIM model also lacks these two materials. Consequently, the information extracted from process 1 of the ACEM prototype system has to be edited manually before proceeding to the next process. Figure 4.27b shows the correct wall finish and floor finish of the toilet rooms in the manually modified BIM model.

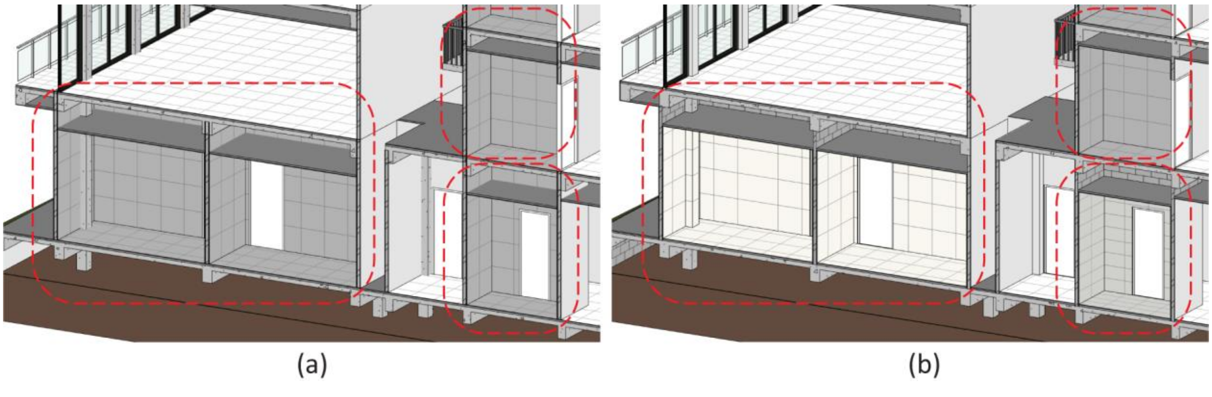

Figure 4.27 (a) The wall finish and floor finish of the toilet rooms in the original BIM model have the same material. (b) The correct wall finish and floor finish of the toilet rooms in the manually modified BIM model.

4.3.2.3 Comparative analysis

Similar to case study 1, material quantities were extracted from the three BIM models. The results of the manually modified BIM model are the baseline for the comparison. Table 4.3 shows the comparison of the material quantities among the original BIM model, the manually modified BIM model, and the

BIM model modified by the ACEM method. Table 4.4 shows the comparison between the manual modification time of the BIM model and the execution time of the ACEM prototype system.

Table 4.3 Comparison of the material quantities among the original BIM model, the manually modified BIM model, and the BIM model modified by the ACEM method.

Elements	Material Layers	Manually Modified BIM Model (Baseline)	Original BIM Model			BIM Model Modified by the ACEM Method		
		Area (m^2)	Area (m^2)	Difference (m^2)	Deviation (%)	Area (m^2)	Difference (m^2)	Deviation (%)
Walls	Lightweight Concrete Masonry Unit 75 mm	1,193.55	1,554.60	361.05	30.25	1,193.55	0.00	0.00
	Lightweight Concrete Masonry Unit 200 mm	92.44	141.95	49.51	53.56	92.44	0.00	0.00
	Lightweight Concrete Masonry Unit 250 mm	31.32	38.16	6.84	21.84	31.32	0.00	0.00
	Interior Plaster	1,472.01	1,920.18	448.17	30.45	1,453.14	−18.87	−1.28
	Interior Tile - WC Matt Grey 600×600	160.03	281.15	121.12	75.69	160.03	0.00	0.00
	Interior Tile - WC Matt Grey 300×600	22.65	0.00	−22.65	−100.00	22.65	0.00	0.00
	Interior Tile - WC Matt Yellow 600×600	64.51	0.00	−64.51	−100.00	64.51	0.00	0.00
	Interior Tile Mortar	250.02	306.80	56.78	22.71	250.02	0.00	0.00
	Exterior Plaster	1,317.02	1,237.31	−79.71	−6.05	1,277.07	−39.95	−3.03
Floors	Interior Tile - White 600×600	752.14	801.17	49.03	6.52	752.14	0.00	0.00
	Interior Tile - WC Matt Grey 600×600	33.88	70.02	36.14	106.67	33.88	0.00	0.00
	Interior Tile - WC Matt Grey 300×600	4.83	0.00	−4.83	−100.00	4.83	0.00	0.00
	Interior Tile - WC Matt Yellow 600×600	21.36	0.00	−21.36	−100.00	21.36	0.00	0.00
	Interior Wood Flooring	56.52	60.49	3.97	7.02	56.52	0.00	0.00
	Interior Epoxy Flooring	38.20	43.46	5.26	13.77	38.20	0.00	0.00
	Exterior Stamped Concrete	217.29	217.80	0.51	0.23	217.29	0.00	0.00
	Exterior Granite	81.57	82.28	0.71	0.87	81.57	0.00	0.00
	Exterior Tile - White 300×300	32.33	35.65	3.32	10.27	32.33	0.00	0.00
	Exterior Tile - Matt Grey 600×600	56.60	56.76	0.16	0.28	56.60	0.00	0.00
	Exterior Concrete, Broom Finish	24.96	25.29	0.33	1.32	24.96	0.00	0.00
	Exterior Concrete Roofing	206.92	207.21	0.29	0.14	206.92	0.00	0.00
	Concrete Screed	1,526.60	1,600.13	73.53	4.82	1,526.60	0.00	0.00

As shown in Table 4.3, the material quantities obtained from the original BIM model for most of the material layers deviate substantially from those obtained from the manual modified BIM model. For the wall layers, the deviations range from −100% to 75.69%. For the floor layers, the deviations range from −100% to 106.67%. The materials with the greatest deviations are three interior tiles for the toilet rooms. This is because, as mentioned in Section 5.2.2, the wall finish and floor finish of all toilet rooms in the original model use the same material, which is “Interior Tile – WC Matt Grey 600×600.” Two materials, “Interior Tile – WC Matt Grey 300×600” and “Interior Tile – WC Matt Yellow 600×600,” are missing from the model. Therefore, the area of “Interior Tile – WC Matt Grey 600×600” substantially exceeds the baseline value (75.69% in the wall category and 106.67% in the floor category). Conversely, the area of “Interior Tile – WC Matt Grey 300×600” and “Interior Tile – WC Matt Yellow 600×600” are equal to 0 m^2 and the deviations from the baseline are −100%.

After applying the ACEM prototype system to the original BIM model, the material quantities for most of the material layers are equal to the material quantities of the manually modified BIM model, except for two material layers of the walls. The exterior plaster layer of the wall had a deviation of −3.03% and the interior plaster layer of the wall had a deviation of −1.28%. Similar to case study 1, the deviations occurred because the ACEM prototype system did not create walls that are exterior and interior wall finishes in some places. For the exterior plaster layer, the system did not create walls that are exterior wall finish on the surfaces of beams that do not attach to walls, the surfaces of beams that extend from the building, the surfaces of beams that do not align with the surface of exterior walls, and the surface of floor edges that extend from the building (see Figure 4.28). For the interior plaster layer, the height of the walls that are interior wall finish at the stairways created by the system was equal to the ceiling height of the stair halls, while in actual construction, the height of the walls must reach the floor level above (see Figure 4.29).

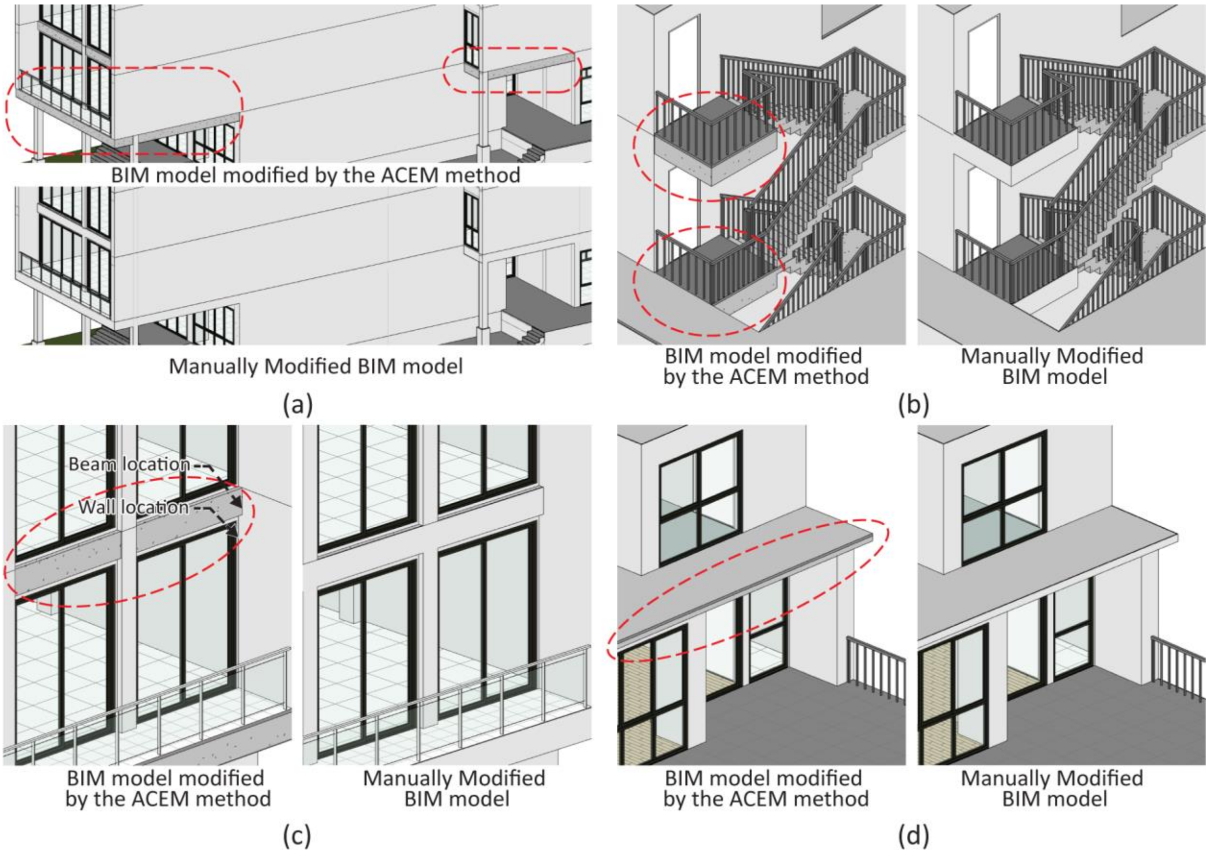

Figure 4.28 The ACEM prototype system did not create walls that are exterior wall finish on (a) the surfaces of beams that do not attach to walls, (b) the surfaces of beams that extend from the building, (c) the surfaces of beams that do not align with the surface of exterior walls, and (d) the surface of floor edges that extend from the building.

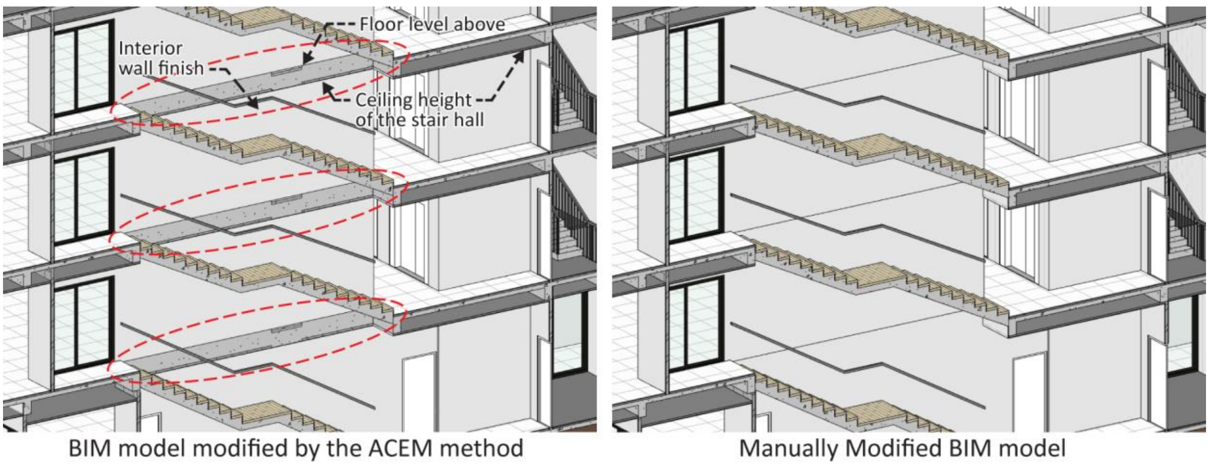

Figure 4.29 The height of the walls that are interior wall finish at the stairways was equal to the ceiling height of the stair halls, while in actual construction, the height of the walls must reach the floor level above.

Table 4.4 Comparison between the manual modification time of the BIM model and the execution time of the ACEM prototype system.

Manual Modification Time of the BIM Model		**Execution Time of the ACEM Prototype System**		
Time	**Time (seconds)**	**Processes**	**Time**	**Time (seconds)**
		1	1 min 34.05 s	94.05
		2	1 min 10.24 s	70.24
		3	2 min 05.75 s	125.75
		4	2 min 09.22 s	129.22
		5	29 min 57.53 s	1,797.53
30 h 32 min	**109,920**	**Total**	**36 min 56.79 s**	**2,216.79**

As shown in Table 4.4, the ACEM prototype system took 36 min 56.79 s (or 2,216.79 s) to complete. The manual modification by the same modeler as the case study 1 took 30 h 32 min (or 109,920 s) to complete. The ACEM prototype system was about 50 times faster than the manual modification time. The execution time of the ACEM prototype system in case study 2 is longer than that in case study 1 (see Table 4.2) because the building is bigger and the numbers of wall and floor elements are larger. However, the manual modification time in case study 2 is also longer than that of case study 1.

4.4 Discussion

4.4.1 The ACEM method and prototype system

Based on two validation case studies, the proposed ACEM method can automatically modify compound elements in BIM models, which are walls and floors, by separating each layer into an individual model element and eliminating regions of overlapping compound elements. The ACEM prototype system was successfully applied to both case studies. The material quantities for compound elements extracted from the BIM models modified by the ACEM prototype system are as accurate as those for compound elements extracted from the detailed BIM model, which was manually modified.

Before applying the ACEM prototype system, the deviations in the material quantities in all cases varied among material layers when compared to values for the manually modified BIM models, based on accurate construction details (see Table 4.1 and Table 4.3). The deviations can be explained by many factors, including the design of buildings, ceiling heights, size of structural elements, and overlapping regions of the compound elements. After applying the ACEM prototype system, the deviations in most material layers were reduced to 0% when compared to the values from manually modified BIM models (see Table 4.1 and Table 4.3). Only small deviations exist at the interior plaster layer and the exterior plaster layer. The deviation for the interior plaster layer was reduced to −0.94% in case study 1 and −1.28% in case study 2. The deviation of the exterior plaster layer was reduced to −0.65% in case study 1 and −3.03% in case study 2. The observed deviations reflect a limitation of the ACEM prototype system, which cannot create walls that are exterior and interior wall finishes in some places. At present, additional manual corrections in such places are necessary if 0% deviation is required.

Apart from improving the accuracy of the material quantities of compound elements, the ACEM method also reduces the working time and cost of editing or recreating BIM models that are inaccurate for quantity takeoff. The results indicate that the ACEM prototype system requires much less time for modifying BIM models than does the manual method. The ACEM prototype system was approximately 54 times faster in case study 1 and 50 times faster in case study 2. It should be noted that process 5 of the ACEM prototype system required the most execution time of all the processes. This is because the selected walls have to join with other building elements, which are walls, structural columns, beams, and floors, one at a time. Therefore, if the number of elements in a BIM model that have to be joined increases, the matching between these elements increases considerably.

4.4.2 Interoperability of BIM models in a collaborative work environment

The corrected compound elements in BIM models after applying the ACEM method can be used in the construction phase. They can be exchanged among parties in a collaborative work environment using IFC files, the open standard file format of BIM. Figure 4.30 shows the BIM model modified by the ACEM method for case study 2 after export to an IFC file. It was opened in Autodesk Navisworks Manage 2018, which is used to review, combine, manage, and analyze BIM models and 3D models from multiple file formats. Similar to the Revit file, each wall and floor material layer that has been modified can be selected separately. However, the correctness of the information from the IFC file and the other issues that might occur during an IFC implementation must be studied in future research.

Figure 4.30 BIM model modified by the ACEM method for case study 2 after export to an IFC file.

4.4.3 Limitations

The ACEM method has some limitations. First, it applies only to cases in which all of the walls in each room are of the same type and all of the floors in each room are of the same type. For more than one wall type or floor type in each room, algorithms for separating each wall type of floor type should be developed in future research. Second, the ACEM method applies only to cases in which one wall finish material covers the entire exterior of a building. Separating multiple exterior wall finish materials according to exterior surface segments will require additional algorithms. Third, the ACEM method was not designed for complex wall types such as slanted walls, stacked walls (walls with different finishes along their height), and curtain walls. These wall types cannot be modified by the proposed method. Fourth, the ACEM prototype system in this research was limited with respect to the number of wall and floor layers, as mentioned in Section 4.2. Further development of the system should account for cases with more complex material layers of walls and floors. Finally, as mentioned in Sections 4.3.1.2, 4.3.2.3, and 4.4.1, the ACEM prototype system cannot create walls that are exterior and interior wall finishes in some places. Algorithms for creating exterior wall finishes on the surfaces of beams that do not attach to walls and algorithms for creating interior wall finishes that have different heights in a room should be developed in future studies.

4.5 Summary

Incorrect and incomplete compound elements result in inaccurate quantity takeoff for each material layer. Compound elements treated as single model elements with defined material layers are not flexible; the size and composition of each layer cannot be controlled and adjusted. Therefore, inaccurate material quantities are obtained when the size and composition of layers vary according to the actual requirements. Moreover, overlapping compound elements result in excess material quantities. For accurate quantity takeoff, modifying compound elements in a BIM model by separating each layer into an individual model element and eliminating overlapping regions is necessary. However, manual modification is a time-consuming, cost-intensive, and error-prone process, especially for large-scale projects or complex models.

This chapter proposes an ACEM method to automatically separate each layer of compound elements into an individual model element and eliminate overlapping regions. The ACEM method includes five main processes: (1) extraction of material information from an original BIM model, (2) conversion of original walls and floors into walls and floors with only a core structural layer, (3) recreation of walls that are exterior and interior wall finishes from the extracted information, (4) recreation of floors that are exterior and interior floor finishes from the extracted information, and (5) joining walls and eliminating the overlapping regions of walls. Validation was conducted using two case studies. The ACEM method effectively modified compound elements in BIM models in much less time than that required for the manual method. The material quantities of compound elements from the BIM models modified by the ACEM method are equivalent to those from manually modified BIM models, indicating a high accuracy.

The ACEM method introduces an approach to automatically correct compound elements in BIM models. It is applicable to the development of automatic systems in any BIM software product. Using this method, the working time, cost, and error associated with editing BIM models to include accurate details of compound elements are reduced. The modified BIM models are useful in the construction phase, which require higher LOD of BIM elements, and are exchangeable in a collaborative work environment. Accurate material quantities can be obtained from the modified BIM model. They can be used for important tasks, such as detailed cost estimation in the pre-construction phase and material purchase in the construction phase. However, this approach increases geometries in a BIM model, which could affect the performance of the software. Therefore, an alternative approach to obtain the correct material quantities from compound elements in a BIM model is proposed in the next chapter.

Chapter 5
Automatic calculation and embedding of quantity results into BIM models

The previous chapter introduced an approach that automatically modified compound elements in a BIM model. However, the increased geometries in the BIM model after modification would consume more memory resources and slow down processing time of the software (Khosakitchalert et al., 2019a; Sacks et al., 2018). This chapter proposes an alternative approach by calculating material quantities and embedding them into the existing compound elements. In addition, this chapter focuses on the issue in which the sub-components of a compound element are absent from a BIM model. The focal compound element in this chapter is drywall, which consists of a wall framing system as a core structural layer and wall panels, such as plasterboard, gypsum board, or wood board, as finish layers. The wall framings must be measured by a general contractor or sub-contractor for material purchase in the construction phase. However, wall framing is a building model element that is usually absent from the BIM models given to contractors or sub-contractors (Olsen and Taylor, 2017), and hence they must develop their own BIM models. Developing BIM models manually under a tight schedule during the construction phase is challenging and time-consuming for construction practitioners. Model errors due to time constraints can occur and cause deviations in the material quantities. Therefore, a method for calculating quantities of wall framings from a BIM model that does not contain wall framing elements is required.

This chapter presents a method for calculating quantities of wall framings from drywalls in a BIM model and embedding them into the drywall properties in the BIM model. The objectives of this chapter are as follows: (1) to develop and improve the algorithms for calculating accurate quantities of wall framings, (2) to develop a method for embedding quantities of wall framings into the drywall elements in a BIM model, and (3) to reduce the working time and avoid human error in obtaining quantities of wall framings. The wall framing system used in this chapter is a light-gauge steel wall framing system for non-load bearing walls. In the following sections, an overview of the proposed method is described, and then the development of the prototype system is explained in detail. A case study, which is an actual construction project, is used to verify the prototype system and validate the proposed method. Then, the results and limitations are discussed, and the conclusions are summarized.

5.1 Overview of the BIM-based wall framing quantity takeoff (BWFQT) method

In our BIM-based wall framing quantity takeoff (BWFQT) method, building model elements are imported from a BIM model to the system via an API. The algorithms automatically generate drywall surfaces from the BIM model and subtracts the regions of the surfaces that overlap with doors, windows, columns, beams, and floors. The algorithms for subtracting the overlapping regions are from the BCEQTI method in Chapter 3. The surfaces after subtraction are used to calculate the location and the length of each member of the wall framing (C-studs and U-tracks) (see Figure 2.4 for the components in a light-gauge steel framing system). After that, the quantities of the wall framings are stored in the drywall properties in the BIM model to allow the model to be used for quantity takeoff.

The BWFQT method comprises six major processes (see Figure 5.1). Process 1 generates drywall surfaces from a BIM model. The drywall elements are selected from a BIM model. The drywall surfaces along the length of the walls are created, and then building elements, which are doors, windows, columns, beams, and floors, that overlap with the drywalls, are subtracted from the drywall surfaces. This yields the subtracted drywall surfaces that can be used to generate lines that represent wall framings.

Process 2 generates lines that represent U-tracks (horizontal members), which consist of top tracks, bottom tracks, nogging tracks, header tracks, and sill trimmer tracks. The lines that represent top tracks are obtained from the lines at the top edge of the drywall surfaces. The lines that represent bottom tracks are obtained from the lines at the bottom edge of the drywall surfaces. The lines that represent nogging tracks are generated from the input spacing value of U-tracks and the distance between the top and bottom tracks. The lines that represent header tracks are obtained from the lines at the top edge of the door and windows. The lines that represent sill trimmer tracks are obtained from the lines at the bottom edge of the windows.

Process 3 generates lines that represent C-studs (vertical members), which consist of common studs and jack studs. The lines that represent common studs are generated from the input spacing value of common studs and the length of each segment of drywall. The lines that represent jack studs are generated from the input spacing value of jack studs and the length of each header or sill trimmer.

Process 4 generates lines that represent extra C-studs at intersections and corners. These lines are generated according to different construction details. For construction detail A (see Figure 2.5), one extra C-stud is needed at a corner and a T-intersection, and two extra C-studs are needed at a cross intersection. For construction detail B (see Figure 2.5), one extra C-stud is needed at a cross intersection. Users choose construction detail A or B as an input. Then an algorithm generates the lines that represent extra C-studs at each intersection and corner.

Process 5 generates lines that represent extra C-studs at both sides of openings. Users can enable this process when two C-studs combined into boxed studs are used at both sides of openings (door and windows). If this process is enabled, the algorithm generates the lines that represent extra C-studs at both sides of openings.

Process 6 calculates quantities of wall framings and embeds them into the properties of the drywalls in the BIM model. New parameters, including the lengths and the number of U-tracks and C-studs, are added to the properties of the wall elements. All lines that represent wall framings from processes 2–5 are separated into each drywall. The lengths and the number of lines in each drywall are calculated and written to each new parameter. All the drywall elements contain the quantities of wall framings, which can be extracted directly from the BIM model.

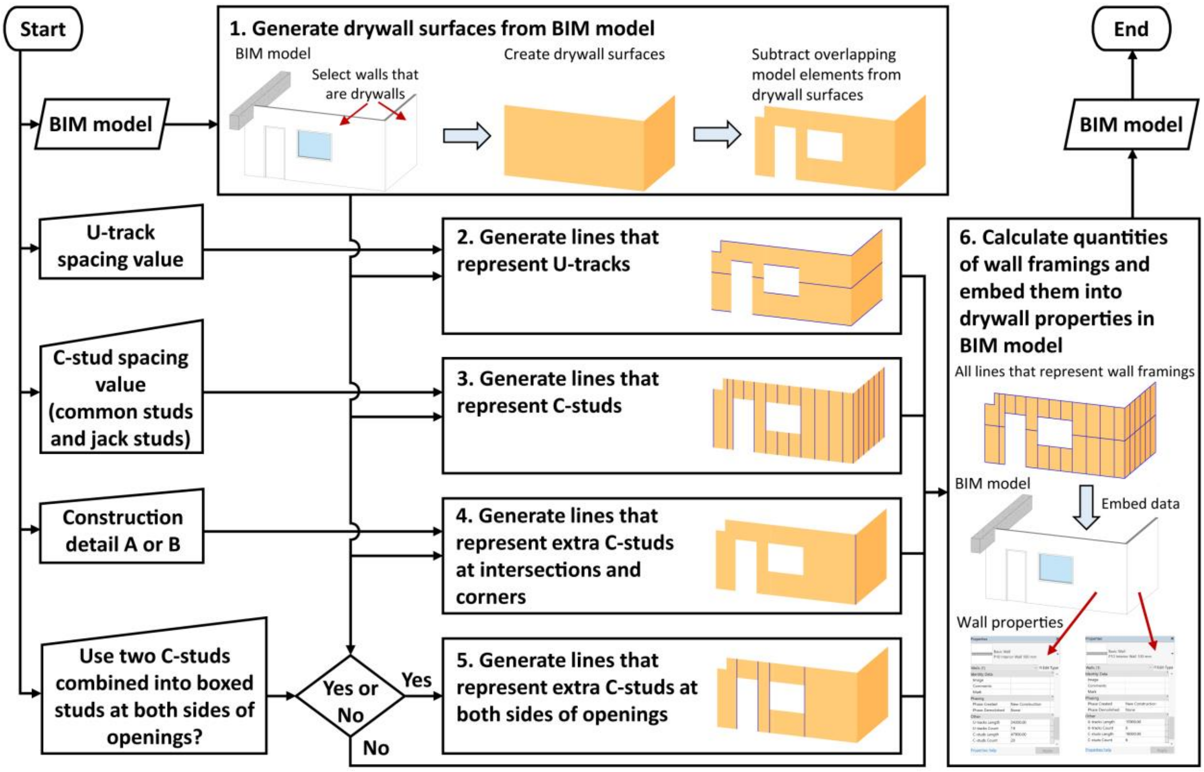

Figure 5.1 Overview of the BWFQT method.

5.2 Development of the BWFQT prototype system

Autodesk Revit 2018.2 and Dynamo 1.3.3.4111 were used to develop the BWFQT prototype system. The explanation of the development of the prototype system is divided into six major processes according to the proposed method in Section 5.1. All the processes are general for any BIM software product, except the parts that relate to Revit API, including the part that inputs model elements from a Revit model in process 1 and the parts that create new parameters for wall elements and write data to those parameters in process 6.

5.2.1 Process 1: Generate drywall surfaces from a BIM model

Figure 5.2 shows the flowchart for process 1: generate drywall surfaces from a BIM model. First, building model elements, including walls, structural columns, structural framings (beams), floors, doors, and windows, are imported from a BIM model to the system (see Figure 5.3a). The wall type name of a target drywall is input manually into the system by a user. The system extracts the wall type names from the input wall elements and compares them with the wall type names input by the user. The wall elements with the same wall type name as the input wall type name are selected and the rest are discarded (see Figure 5.3b). The wall location lines and wall heights are extracted from the selected wall elements (drywalls). The wall surfaces are created by extruding the wall location lines by the wall heights (see Figure 5.3c). In the second step, the input structural columns, structural framings (beams), floors, doors, and windows are converted into geometries and combined into an integrated geometry. The wall surfaces are checked for their intersection with the integrated geometry and overlapping regions of the wall surfaces are subtracted (see Figure 5.3d). Process 1 provides the subtracted wall surfaces, the wall location lines, and the wall heights, which are used in processes 2–6.

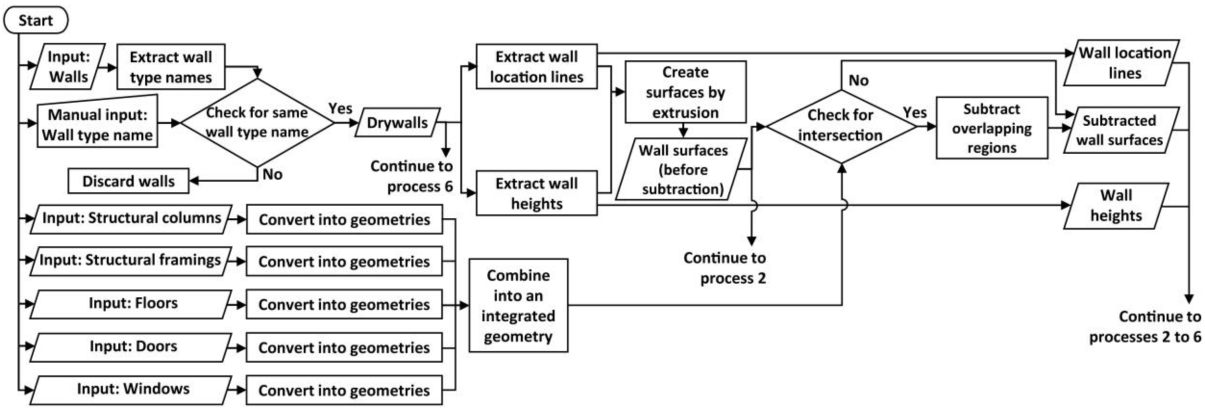

Figure 5.2 Flowchart for process 1: generate drywall surfaces from a BIM model.

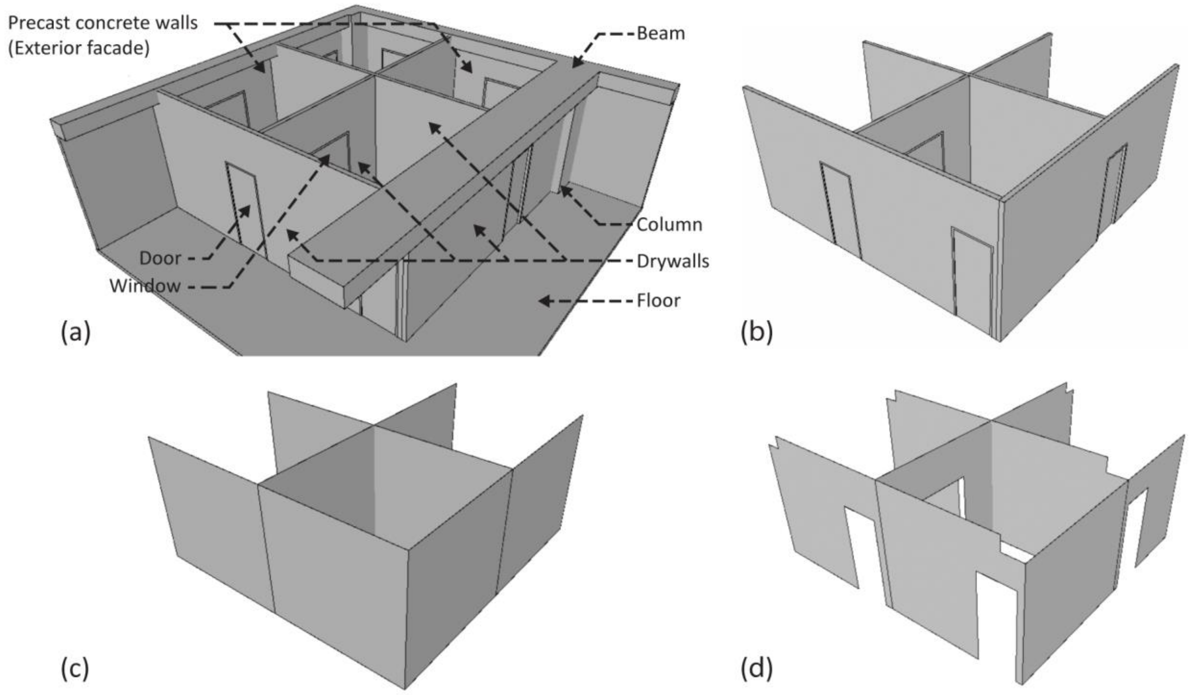

Figure 5.3 (a) Building model elements are imported from a BIM model to the system. (b) Wall elements that are not drywalls are discarded. (c) Wall surfaces created by the system. (d) Overlapping building elements are subtracted from the wall surfaces.

5.2.2 Process 2: Generate lines that represent U-tracks

Figure 5.4 shows the flowchart for process 2: generate lines that represent U-tracks. The process is broken down into processes for the top, bottom, nogging, header, and sill trimmer tracks. For the top tracks and the bottom tracks, the perimeter lines of the subtracted wall surfaces from process 1 are extracted. The algorithm selects the lines at the top edge of the wall surfaces to obtain the lines that represent the top tracks (see Figure 5.5a). Another algorithm selects the lines at the bottom edge of the wall surfaces to obtain the lines that represent the bottom tracks (see Figure 5.5b).

For the nogging tracks, first, the number of nogging tracks on a wall is calculated by dividing the wall heights from process 1 by the input spacing value of U-tracks and rounding up the results to a whole number. The number of nogging tracks and the spacing value of U-tracks are used to create a sequence of points on the Z-axis of the subtracted wall surfaces. Second, the wall location lines are duplicated to the points except for the first point, which is the location of the bottom track. The lines are intersected with the subtracted wall surfaces. The parts of the lines that are outside the subtracted wall surfaces, such as the regions of doors and windows, are eliminated to obtain the lines that represent nogging tracks (see Figure 5.5c).

For the header tracks and the sill trimmer tracks, first, the door and window surfaces are created. The input doors and windows are converted into geometries and bounding boxes are created on the geometries. The wall surfaces before subtraction in process 1 are intersected with the bounding boxes.

The results are the surfaces inside the bounding boxes, which are door surfaces and window surfaces. Second, the perimeter lines are extracted from these surfaces. The algorithm selects the lines at the top edge of the door surfaces to obtain the lines that represent header tracks at the doors (see Figure 5.5d). Another algorithm selects the lines at the top edge and bottom edge of the window surfaces to obtain the lines that represent header tracks and sill trimmer tracks at the windows (see Figure 5.5e).

Process 2 gives the lines that represent top tracks, bottom tracks, nogging tracks, header tracks, and sill trimmer tracks, which are used in process 6.

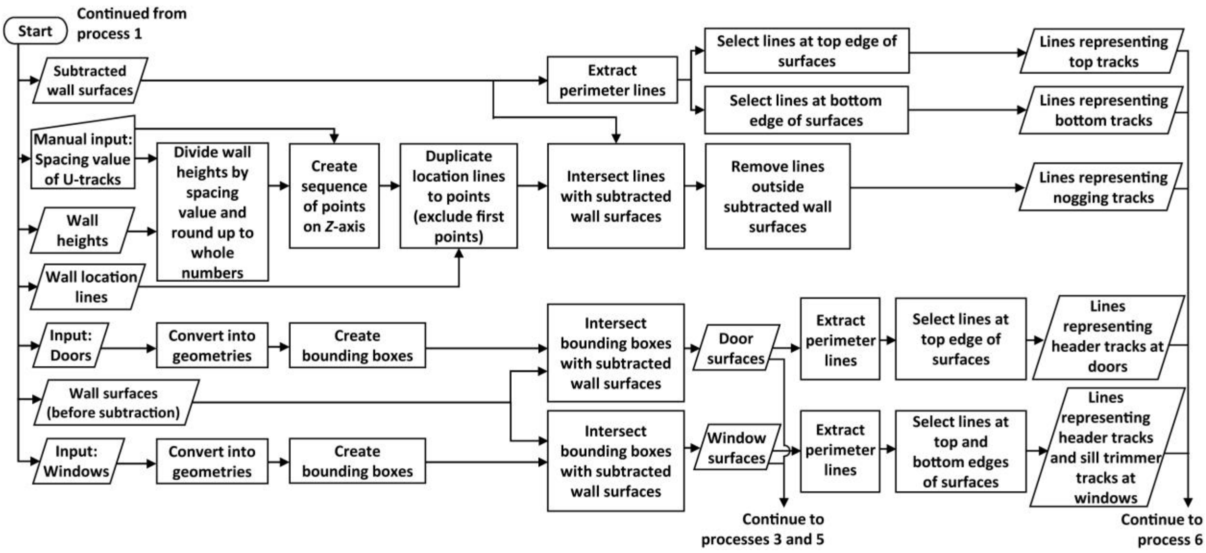

Figure 5.4 Flowchart for process 2: generate lines that represent U-tracks.

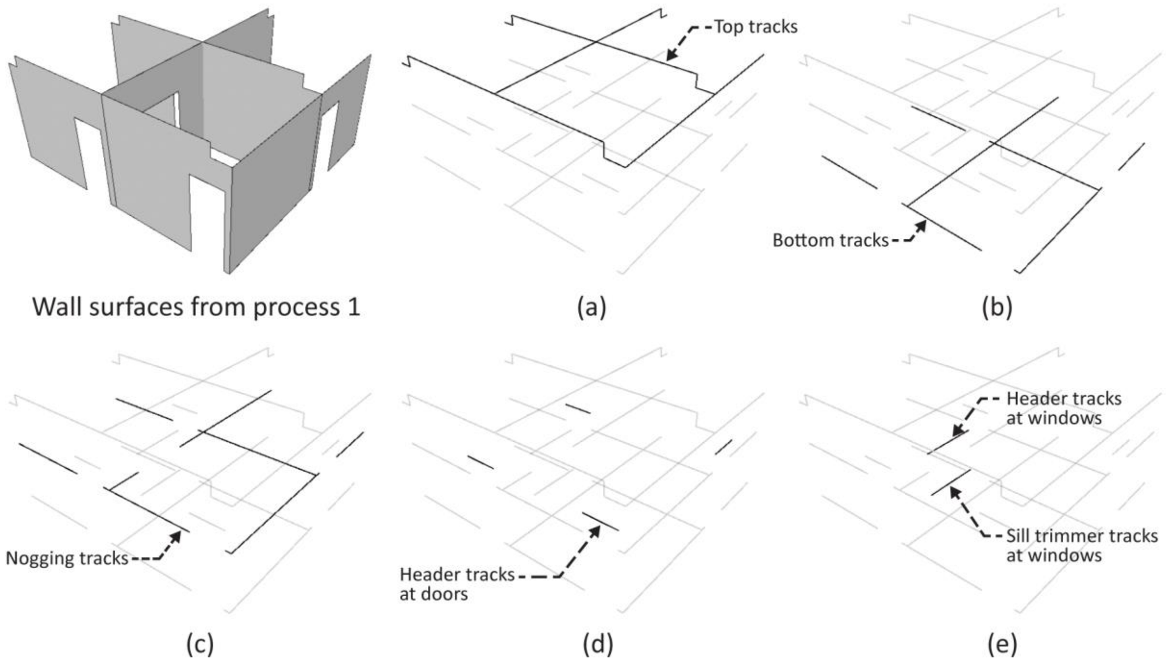

Figure 5.5 Lines that represent (a) top tracks, (b) bottom tracks, (c) nogging tracks, (d) header tracks at doors, and (e) header tracks and sill trimmer tracks at windows.

5.2.3 Process 3: Generate lines that represent C-studs

Figure 5.6 shows the flowchart for process 3: generate lines that represent C-studs. The process is broken down into processes for common studs and jack studs. For the common studs, first, the wall location lines are divided into segments by the locations of doors and windows. The corner points of the door surfaces and the window surfaces from process 2 are extracted and projected on the wall location lines from process 1. The points are used to divide the wall location lines into segments. Second, the divided wall location lines are used to calculate the location of the common studs. The divided wall location lines are calculated for the segment lengths, which are then divided by the input spacing value of the common studs. The results, which are the number of common studs on each wall segment, are rounded up to whole numbers. The number and spacing value of common studs are used to create a sequence of points on the divided wall location lines. The end points of the divided wall location lines are extracted and added to the lists of the sequence of points. The results are the points where the vertical lines that represent common studs are created. The wall heights from process 1 are used to define the height of the vertical lines. Finally, the vertical lines are intersected with the subtracted wall surfaces from process 1 and the parts of the lines that are outside the subtracted wall surfaces are eliminated to obtain the lines that represent the common studs (see Figure 5.7a).

For the jack studs, first, the locations of the jack studs are calculated. The perimeter lines of the door surfaces and the window surfaces from process 2 are extracted. The algorithm selects the lines at the top edge of the door surfaces. Another algorithm selects the lines at the top edge and bottom edge of the window surfaces. The lengths are calculated from the selected lines and divided by the input spacing value of the jack studs, and the results are rounded up to a whole number to give the number of jack studs on each door and window. The number and spacing value of the jack studs are used to create a sequence of points on the lines. Second, the vertical lines that represent the jack studs are created. For the jack studs between the top tracks and the header tracks, the vertical lines are created from the points at the top edge of the doors and the windows to the top of the walls. For the jack studs between the sill trimmer tracks and the bottom tracks, the vertical lines are created from the points on the bottom edge of the windows to the base of the walls. Finally, the vertical lines are intersected with the subtracted wall surfaces from process 1 and the parts of lines that are outside the subtracted wall surfaces are eliminated to obtain the lines that represent jack studs (see Figure 5.7b).

The final products of process 3 are the lines that represent common studs and jack studs, which are used in process 6.

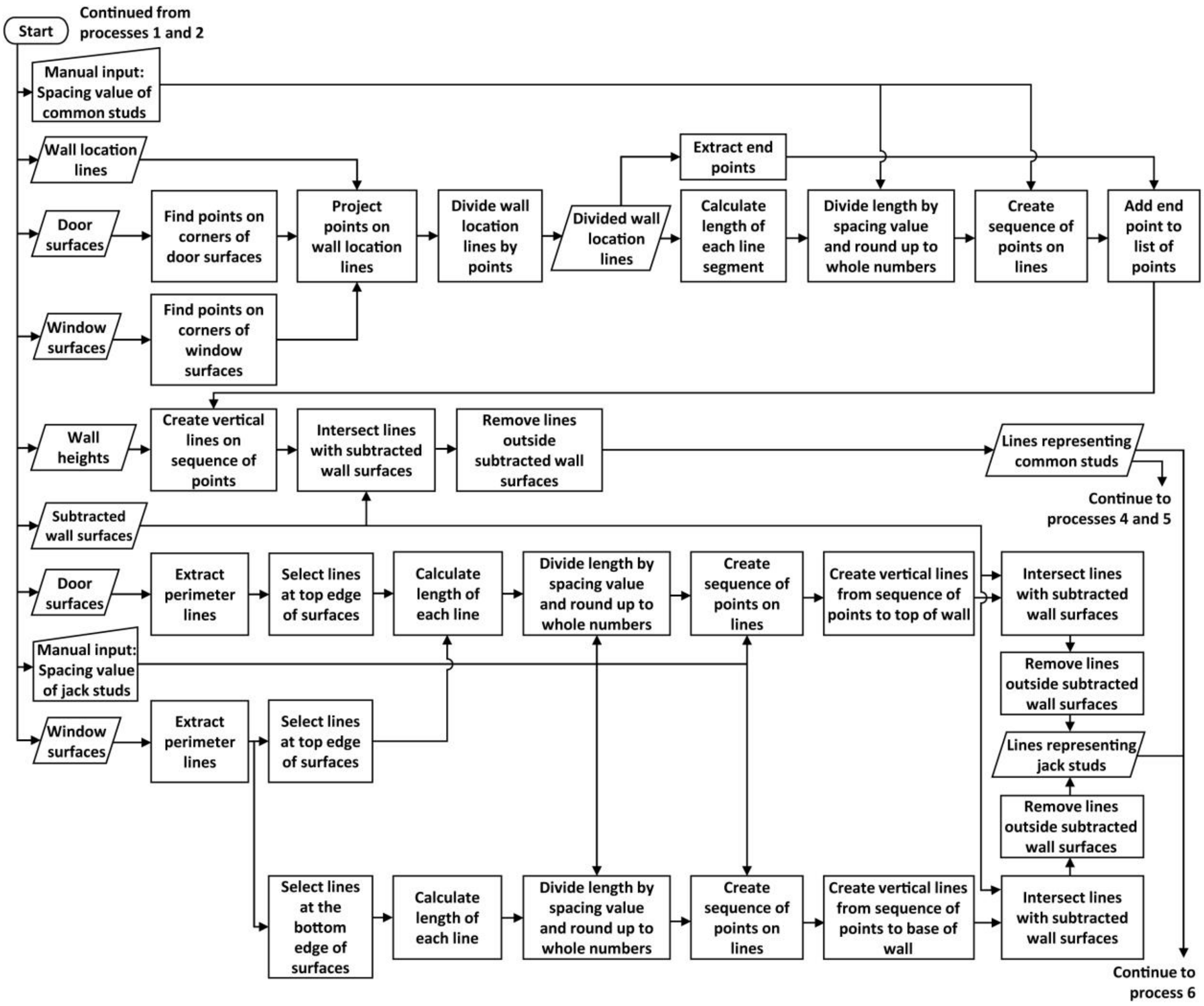

Figure 5.6 Flowchart for process 3: generate lines that represent C-studs.

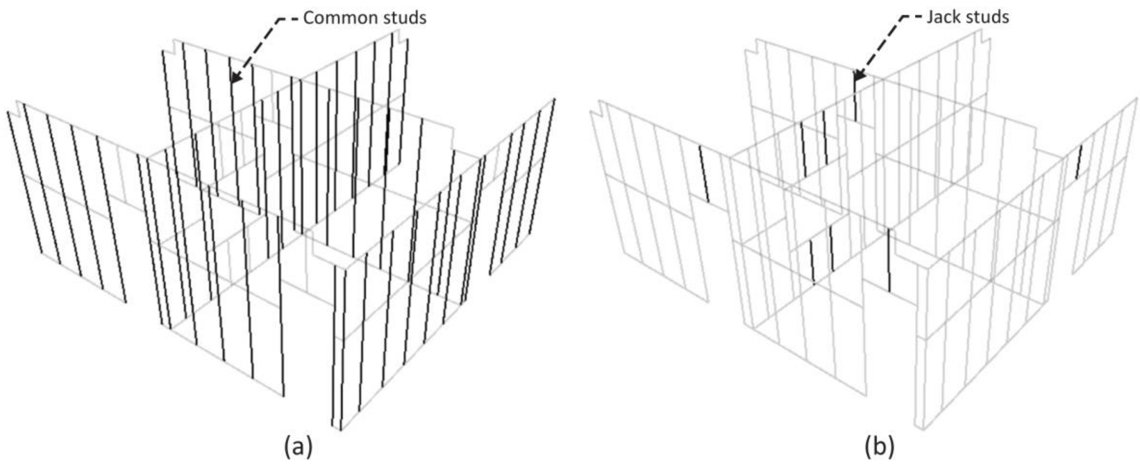

Figure 5.7 Lines that represent (a) common studs and (b) jack studs.

5.2.4 Process 4: Generate lines that represent extra C-studs at intersections and corners

Figure 5.8 shows the flowchart for process 4: generate lines that represent extra C-studs at intersections and corners. Initially, construction detail A or B is chosen by a user. If construction detail A is chosen, the system generates one line that represents extra C-studs at corners and T-intersections and two lines that represent extra C-studs at cross intersections. To do this, an algorithm finds intersection points on the wall location lines from process 1. The duplicate points that are in the same locations are removed. Each point is then checked for an intersection with the lines that represent common studs from process 3. The lines that intersect the points are collected into a list as lines that represent extra studs at corners, T-intersections, and cross intersections (see Figure 5.9a). Next, the algorithm finds the second extra studs at cross intersections. The cross intersection points are identified by finding the intersection points on the wall location lines that have four duplicates at the same position. The cross intersection points are then checked for intersections with the lines that represent common studs. The lines that intersect the points are collected into another list as the lines that represent the second extra stud at cross intersections (see Figure 5.9b).

If construction detail B is chosen, the system generates one line that represents extra C-studs at cross intersections. To do this, the algorithm finds intersection points on the wall location lines from process 1. The points of cross intersections are identified by finding the intersection points on the wall location lines that have four duplicates at the same position. The cross intersection points are then checked for intersections with the lines that represent common studs. The lines that intersect the points are collected into a list as the lines that represent extra studs at cross intersections (see Figure 5.9c).

The final products of process 4 are the lines that represent extra C-studs at intersections and corners, which are used in process 6.

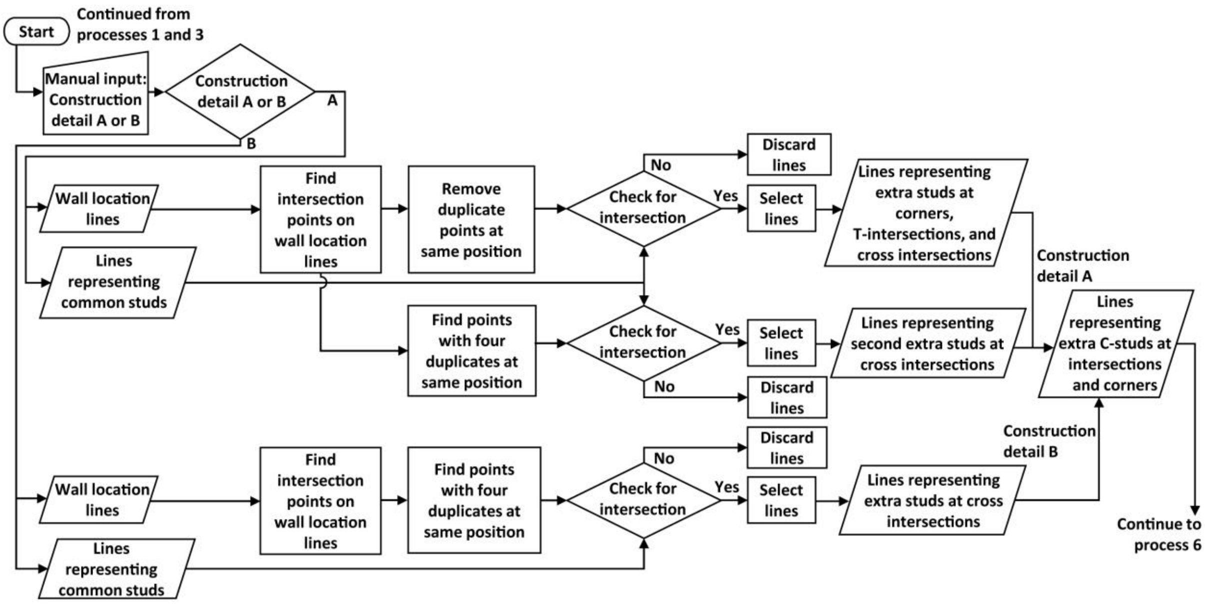

Figure 5.8 Flowchart for process 4: generate lines that represent extra C-studs at intersections and corners.

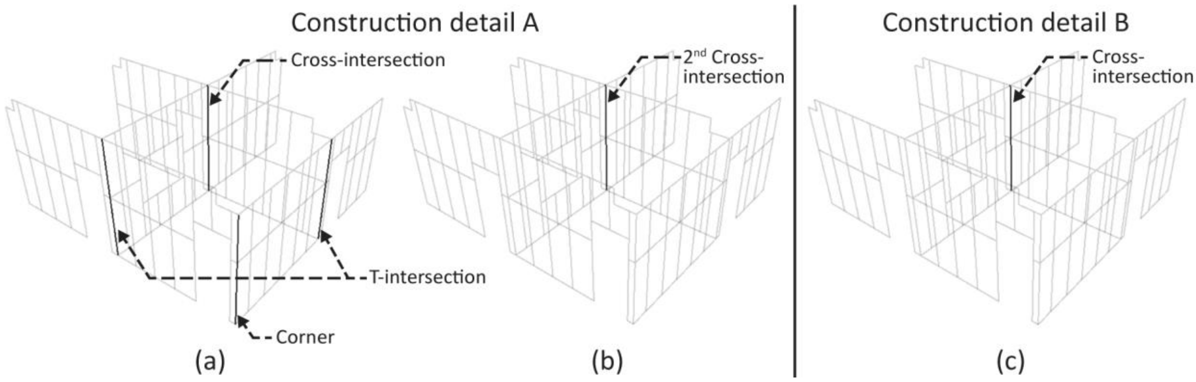

Figure 5.9 Lines that represent (a) extra studs at corners, T-intersections, and cross intersections for construction detail A, (b) second extra studs at cross intersections for construction detail A, and (c) extra studs at cross intersections for construction detail B.

5.2.5 Process 5: Generate lines that represent extra C-studs at both sides of openings

Figure 5.10 shows the flowchart for process 5: generate lines that represent extra C-studs at both sides of openings. Initially, users choose whether two C-studs combined into boxed studs are used at both sides of openings via a Boolean data type. If the Boolean value is false, this process is skipped. If the Boolean value is true, the system generates lines that represent extra C-studs at both sides of openings. First, the perimeter lines of the door surfaces and the window surfaces from process 2 are extracted. Then the vertical lines are selected. Second, the vertical lines are checked for intersections with the lines that represent common studs from process 3. Finally, the lines representing common studs that intersect the vertical lines are collected into a list as the lines that represent extra studs at both sides of openings (see Figure 5.11), which are used in process 6.

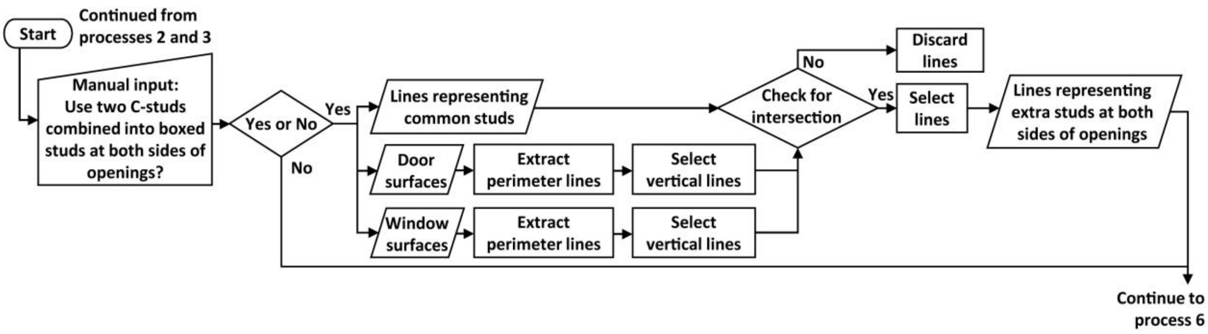

Figure 5.10 Flowchart for process 5: generate lines that represent extra C-studs at both sides of openings.

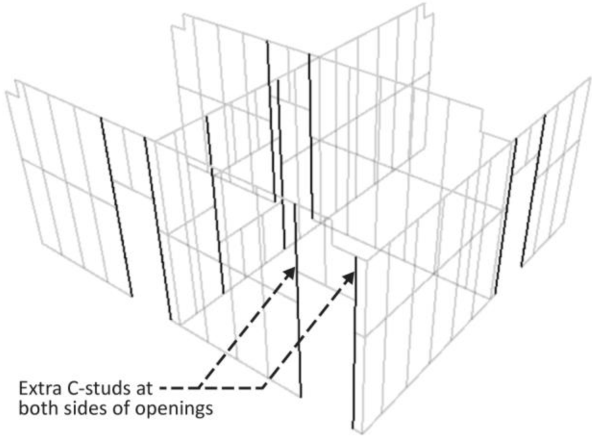

Figure 5.11 Lines that represent extra studs at both sides of openings.

5.2.6 Process 6: Calculate quantities of wall framings and embed them into the drywall properties in the BIM model

Figure 5.12 shows the flowchart for process 6: calculate quantities of wall framings and embed them into the properties of drywalls in the BIM model. First, the system automatically creates new parameters for wall elements in a Revit project using shared parameters. The new parameters are "U-tracks Length", "U-tracks Count", "C-studs Length", and "C-studs Count." Second, the lines that represent top tracks, bottom tracks, header tracks, sill trimmer tracks, and nogging tracks from process 2 are combined into a list of U-tracks. A list of C-studs is generated from the lines that represent common studs and jack studs from process 3, the extra C-studs at intersection and corners from process 4, and the extra C-studs at both sides of openings from process 5. Third, the lines in the lists of U-tracks and C-studs are checked for intersections with each subtracted wall surface from process 1. The lines that intersect the same surface are grouped into the same sub-lists. Fourth, the system calculates the lengths of lines and counts the number of lines in every list. Finally, the results are embedded into the properties of each drywall. The lengths of the U-tracks and C-studs are written to the "U-tracks Length" and "C-studs Length" parameters, respectively. The numbers of U-tracks and C-studs are written to the "U-tracks Count" and "C-studs Count" parameters, respectively. Figure 5.13 shows the properties of a wall in Autodesk Revit that contains quantities of U-tracks and C-studs after applying the BWFQT prototype system.

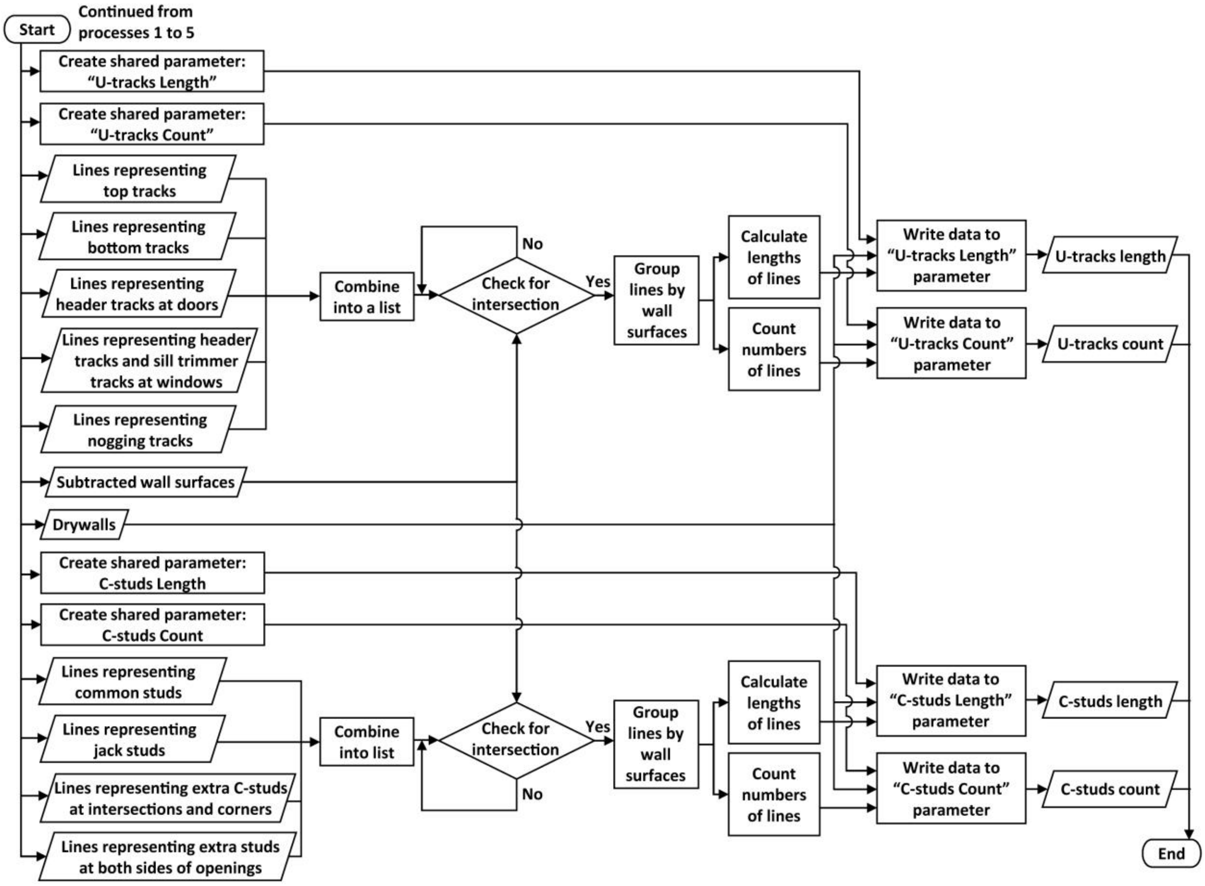

Figure 5.12 Flowchart for process 6: calculate quantities of wall framings and embed them into the properties of drywalls in the BIM model.

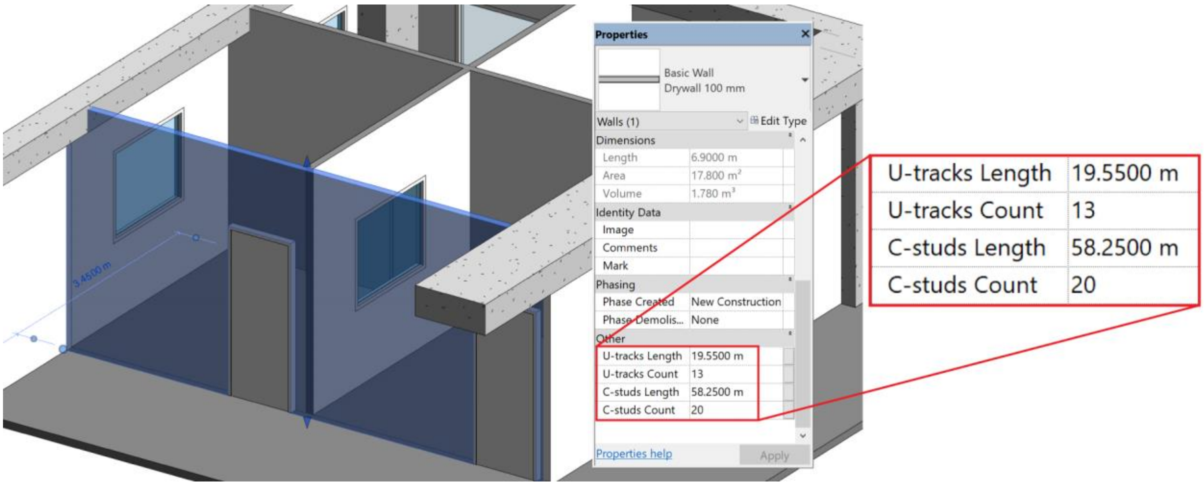

Figure 5.13 Properties of a wall in which the quantities of C-studs and U-tracks are embedded.

5.3 Validation

The BWFQT method was validated in an actual construction project. Quantities of wall framings from the BWFQT prototype system were compared with the quantities of wall framings from the complete detailed BIM model (baseline) and two traditional quantity takeoff methods that are described in Chapter 2, Section 2.2.1.1(2). Traditional quantity takeoff methods are used in the comparison because these methods have deviations when estimating the quantities of wall framings. Furthermore, the execution time of the BWFQT prototype system was compared with the modeling time of the BIM model and the manual calculation times of the traditional methods. Autodesk Revit 2018.2, Dynamo 1.3.3.4111, and a computer with an Intel Core i7-8770 3.2 GHz CPU, 32 GB RAM, and NVIDIA GeForce GTX 1060 6 GB graphics card were used to perform the prototype system.

5.3.1 Overview of the case study

The case study was an interior project on the fifth and sixth floors of Chulapat 14 building located at Chulalongkorn University, Bangkok, Thailand (see Figure 5.14a). The fifth and sixth floors were chosen because they contain drywalls meeting at corners, T-intersections, and cross intersections. Furthermore, these floors contain drywalls intersecting with doors, windows, structural columns, beams, and floors. The gross internal area of these floors is about 2,560 m^2. There are 28 rooms on the fifth floor and 25 rooms on the sixth floor separated by drywalls.

The typical height of the drywall is 3.65 m and the height of the drywall under the beams is 3.45 m. The spacing of C-studs, including common studs and jack studs, is a maximum of 600 mm center-to-center. The spacing of U-tracks is a maximum of 600 mm center-to-center. The construction detail of the intersections and corners is construction detail A (see Figure 2.5 in Chapter 2). One extra C-stud is needed at a corner and a T-intersection and two extra C-studs are needed at a cross intersection. The C-studs at both sides of openings are two C-studs combined into boxed studs. Figure 5.14b shows the wall framings in the construction site.

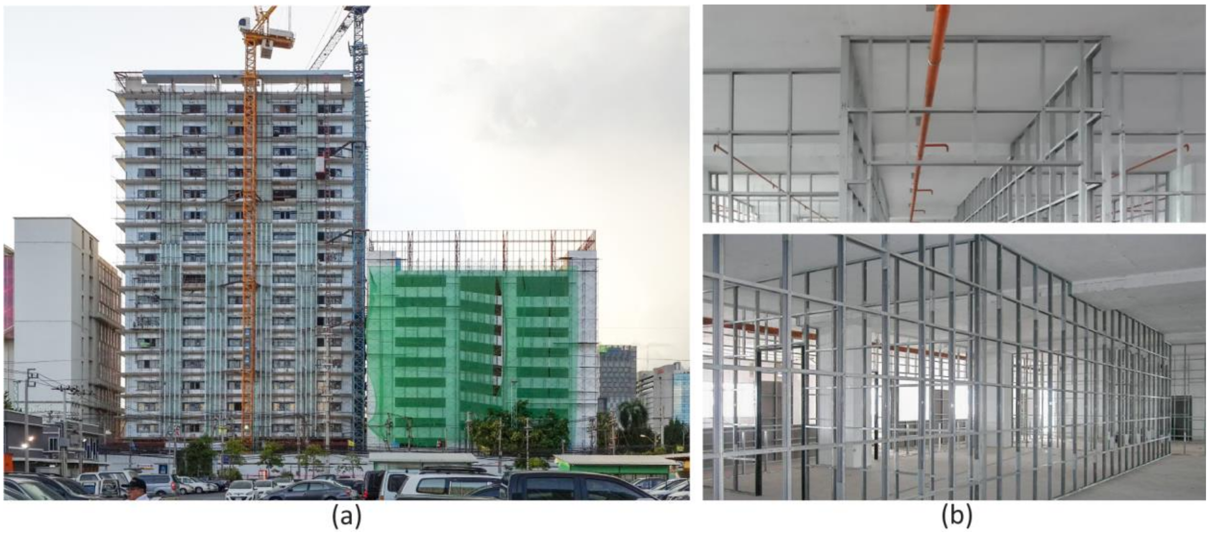

Figure 5.14 (a) Chulapat 14 building. (b) Interiors of the fifth and the sixth floors during construction.

The incomplete and complete detailed BIM models were both used in the validation. The incomplete detailed BIM model was created based on the 2D construction drawings and was used to test the prototype system (see Figure 5.15). The drywalls are single model elements with defined material layers, which were equivalent to walls at LOD 300. Wall framings were not created in this model. The drywalls were created to overlap with structural columns, beams, and floors. The BWFQT prototype system was applied to this BIM model. The execution time of the prototype system was recorded for comparison. Figure 5.16 shows the blue lines that are generated from the prototype system representing the wall framings in the incomplete detailed BIM model. The calculated quantities of C-studs and U-tracks were embedded into the properties of drywalls in the BIM model. The quantities schedule of drywall was created in Autodesk Revit to obtain the C-studs length and the U-tracks length (see Figure 5.17). The schedule was exported to a spreadsheet file for comparison.

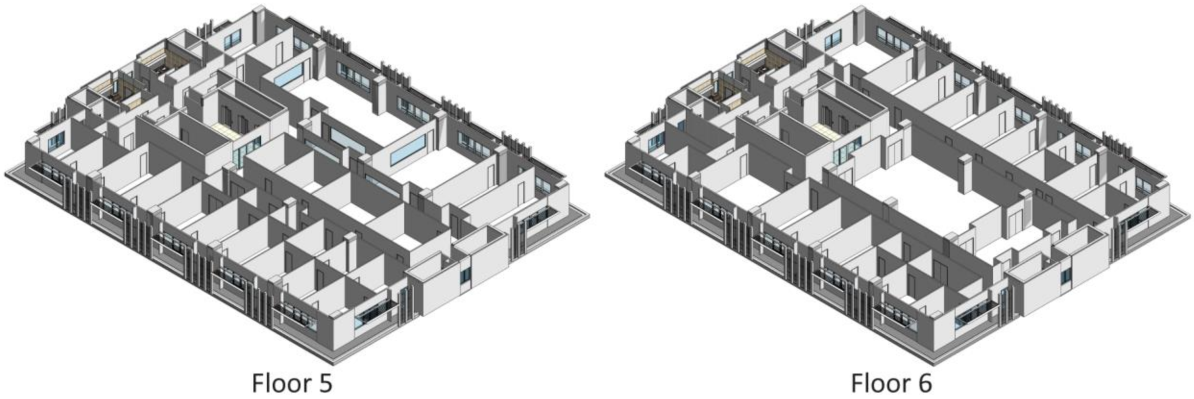

Figure 5.15 Incomplete detailed BIM model.

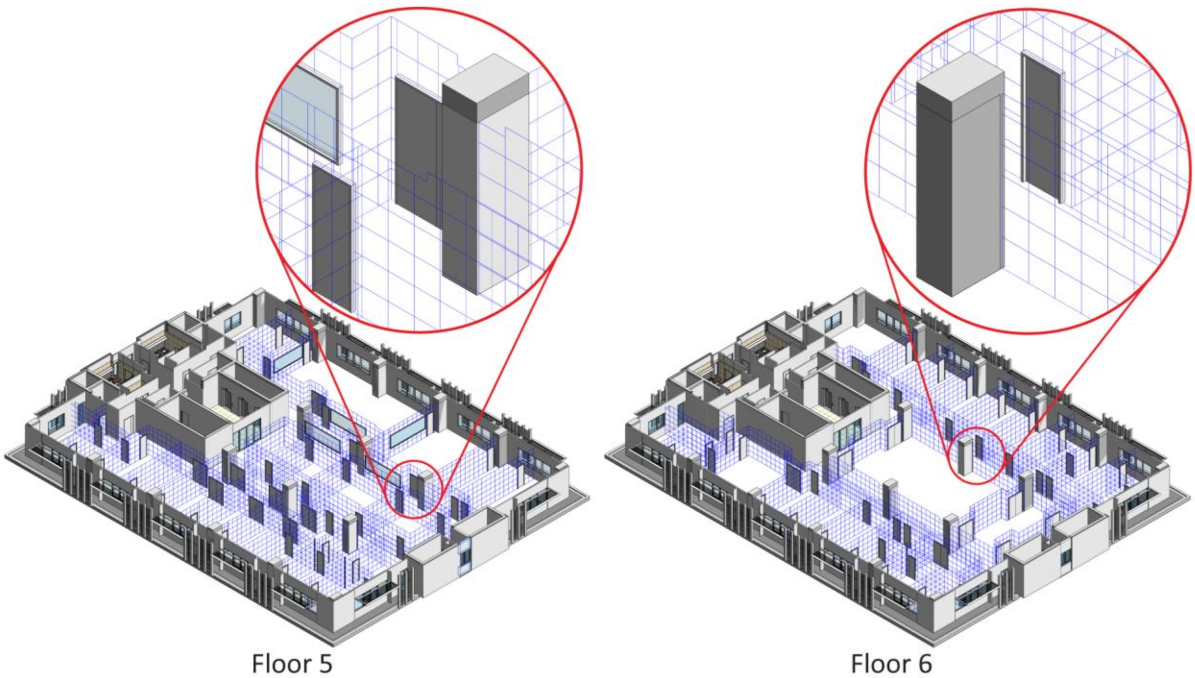

Figure 5.16 Blue lines that represent wall framings in the incomplete detailed BIM model (drywalls were hidden from the viewport).

<Drywalls Schedule>

A	B	C	D	E	F
Type	Base Constraint	C-studs Length	C-studs Count	U-tracks Length	U-tracks Count
P10 Interior Wall 100 mm	Floor 5	75.20	22	48.28	19
P10 Interior Wall 100 mm	Floor 5	37.00	11	22.85	15
P10 Interior Wall 100 mm	Floor 5	64.05	28	41.46	18
P10 Interior Wall 100 mm	Floor 5	43.20	12	40.80	9
P10 Interior Wall 100 mm	Floor 5	14.60	4	6.30	7
P10 Interior Wall 100 mm	Floor 5	28.05	10	9.40	15
P10 Interior Wall 100 mm	Floor 5	27.60	8	20.30	7
P10 Interior Wall 100 mm	Floor 5	39.65	21	32.29	14
P10 Interior Wall 100 mm	Floor 5	14.60	4	6.30	7
P10 Interior Wall 100 mm	Floor 5	24.40	9	7.51	15
P10 Interior Wall 100 mm	Floor 5	69.40	31	54.60	18
P10 Interior Wall 100 mm	Floor 5	64.70	29	51.85	22
P10 Interior Wall 100 mm	Floor 5	39.65	21	32.29	14
P10 Interior Wall 100 mm	Floor 5	14.60	4	6.30	7

Figure 5.17 Quantities schedule of drywalls from the incomplete detailed BIM model after applying the BWFQT prototype system.

The complete detailed BIM model was based on the incomplete detailed BIM model and was used as a baseline for the comparison. Wall framings were modeled manually at the core of the drywall according to the actual construction details (see Figure 5.18). The modeling time of the wall framings was recorded to compare with the execution time of the prototype system. The wall framing quantities were obtained directly from the model by creating the quantities schedule of wall framings in Autodesk Revit (see Figure 5.19). The lengths of the C-studs and U-tracks were exported to a spreadsheet file for comparison.

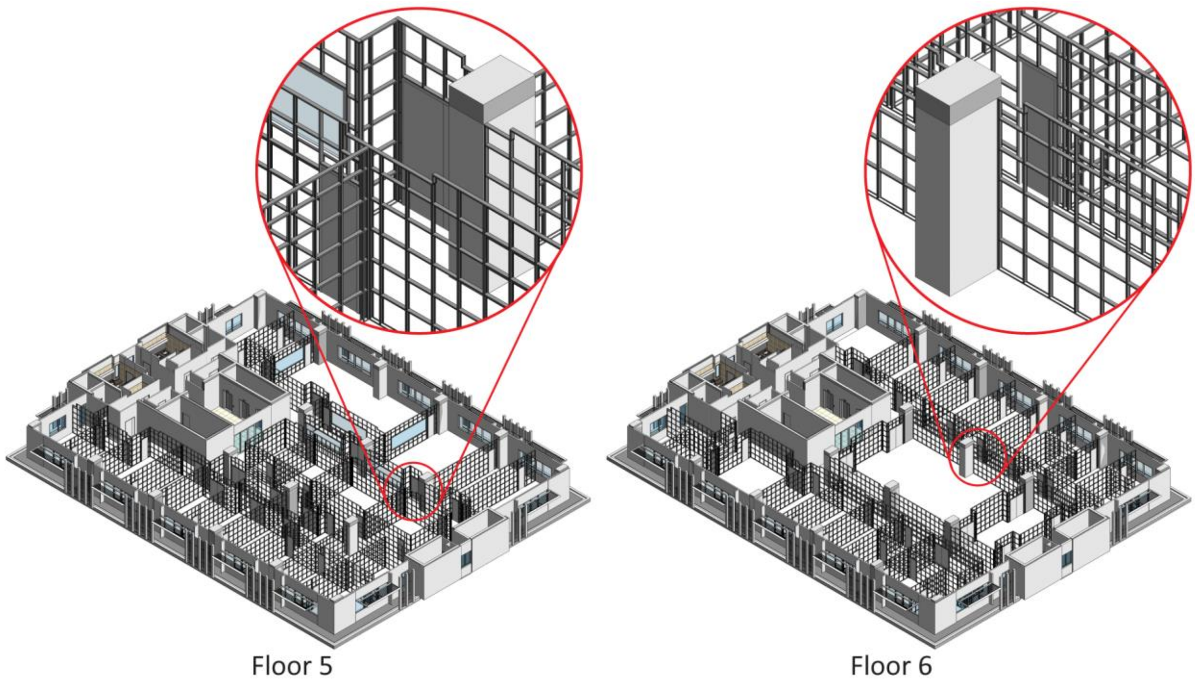

Figure 5.18 Complete detailed BIM model (drywalls were hidden from the viewport).

<Wall Framings Schedule>

A	B	C
Type	Length	Count
C-studs	0.58	1
C-studs	0.61	1
C-studs	0.61	1
C-studs	0.61	1
C-studs	0.61	1
C-studs	0.38	1
C-studs	0.58	1
C-studs	0.61	1
C-studs	0.61	1
C-studs	0.61	1
C-studs	0.58	1
C-studs	0.58	1

Figure 5.19 Quantities schedule of wall framings from the complete detailed BIM model.

Manual quantity takeoff was performed with the two traditional quantity takeoff methods in Chapter 2, Section 2.2.1.1(2) and the calculation times were also recorded for comparison.

Traditional method 1 is the manual method in which the length of wall framings is calculated from the wall dimensions and spacing values of the C-studs and U-tracks. The calculation used the following information: the total length of the wall measured from the 2D construction drawings of 621.20 m, wall height of 3.65 m, and the spacing of C-studs and U-tracks of 600 mm. Additionally, the extra studs at corners, T-intersections, and cross intersections, and the studs at both sides of openings were measured separately and added to the length of C-studs. There were 48 corners, 46 T-intersections, four cross intersections, 92 doors, and five windows, which were equal to 1,788.50 m of additional C-studs.

Traditional method 2 is the manual method in which the length of wall framings is calculated from wall areas and the lengths of C-studs and U-tracks per square meter. The calculation used the net wall area measured from the 2D construction drawings of 1,899.32 m^2, which excluded the areas of doors, windows, and of walls that overlapped with structural columns and beams. The lengths of C-studs and U-tracks per square meter were 2 m; there were two C-studs and two U-tracks per square meter because the spacing of C-studs and U-tracks was 600 mm. Similar to traditional method 1, the extra studs at corners, T-intersections, and cross intersections, and the studs at both sides of openings were measured separately and added to the length of C-studs.

5.3.2 Comparative analysis

Table 5.1 shows a comparison of the wall framing quantities obtained from the complete detailed BIM model (baseline), the BWFQT method, traditional method 1, and traditional method 2. Table 5.2 shows a comparison of the execution time of the BWFQT prototype system, the modeling time of the complete detailed BIM model, and the manual calculation times of traditional methods 1 and 2.

The BWFQT method provided similar quantities of wall framings compared with the complete detailed BIM model, which was the baseline (see Table 5.1). The quantities of C-studs from the BWFQT method had deviations of 0.12% on the fifth floor, 0.11% on the sixth floor, and 0.11% in total. The quantities of U-tracks from the BWFQT method had deviations of 0.16% on the fifth floor, 0.44% on the sixth floor, and 0.30% in total. The deviation of C-studs and U-tracks may arise from the thickness of the wall framings in the complete detailed BIM model making the lengths of wall framings shorter when they connect to each other.

Table 5.1 Comparison of the quantities of wall framings obtained from the complete detailed BIM model, the BWFQT method, traditional method 1, and traditional method 2.

Wall Framings	Complete Detailed BIM Model	The BWFQT Method			Traditional Method 1			Traditional Method 2		
	Length (m)	Length (m)	Difference (m)	Deviation (%)	Length (m)	Difference (m)	Deviation (%)	Length (m)	Difference (m)	Deviation (%)
Floor 5										
C-studs	2,726.18	2,729.35	3.17	0.12	2,857.95	131.77	4.83	2,837.52	111.34	4.08
U-tracks	1,971.49	1,974.63	3.14	0.16	2,199.40	227.91	11.56	1,895.82	−75.67	−3.84
Floor 6										
C-studs	2,666.85	2,669.80	2.95	0.11	2,715.60	48.75	1.83	2,749.62	82.77	3.10
U-tracks	1,917.97	1,926.44	8.47	0.44	2,149.00	231.03	12.05	1,902.82	−15.15	−0.79
Total										
C-studs	5,393.03	5,399.15	6.12	0.11	5,573.55	180.52	3.35	5,587.14	194.11	3.60
U-tracks	3,889.46	3,901.07	11.61	0.30	4,348.40	458.94	11.80	3,798.64	−90.82	−2.34

The quantities from traditional methods 1 and 2 were less accurate than those from the BWFQT method and had deviations ranging from −3.84% to 12.05%. A negative deviation indicates that the quantity is less than the baseline.

The quantities of C-studs from traditional method 1 had deviations of 4.83% on the fifth floor, 1.83% on the sixth floor, and 3.35% in total. The quantities of U-tracks from traditional method 1 had deviations of 11.56% on the fifth floor, 12.05% on the sixth floor, and 11.80% in total. The excess C-studs and U-tracks were calculated because traditional method 1 does not consider wall openings, such as doors and windows, and the parts of walls that overlap with structural elements.

The quantities of C-studs from traditional method 2 had deviations of 4.08% on the fifth floor, 3.10% on the sixth floor, and 3.60% in total. The quantities of U-tracks from traditional method 1 had deviations of −3.84% on the fifth floor, −0.79% on the sixth floor, and −2.34% in total. The excess C-studs and the insufficient U-tracks were calculated because the method calculates the lengths of wall framings based on the average wall framings per square meter, which may not perfectly fit walls that have doors and windows.

Table 5.2 Comparison of the execution time of the BWFQT prototype system, the modeling time of the complete detailed BIM model, and the manual calculation times of traditional methods 1 and 2.

The BWFQT Prototype System		Complete Detailed BIM Model		Traditional Manual 1		Traditional Manual 2	
Time	Time (seconds)	Time	Time (seconds)	Time	Time (seconds)	Time	Time (seconds)
4 min 42 s	282	25 hr 40 min	92,400	27 min	1,620	53 min	3,180

The BWFQT prototype system took the least time (4 min 42 s [282 s]) to find the quantities of wall framings (see Table 5.2). Modeling the complete detailed BIM model took the most time (25 h 40 min [92,400 s]). The calculation time of traditional method 1 was 27 min (1,620 s). In this method, most of the time was spent measuring the wall lengths and counting the numbers of corners, intersections, doors, and windows from the 2D construction drawings. The calculation time of traditional method 2 was 53 min (3,180 s). In this method, most of the time was spent measuring the wall areas from the 2D construction and subtracting the areas of doors, windows, columns, and beams that overlap with the walls.

The BWFQT prototype system was 328 times faster than the modeling time of the complete detailed BIM model, 6 times faster than traditional method 1, and 11 times faster than traditional method 2.

5.4 Discussion

5.4.1 The BWFQT method and prototype system

In the case study, the BWFQT prototype system calculated the quantities of wall framings and embedded them into the properties of drywalls in the BIM model. The quantities of wall framings obtained from the BWFQT method were as accurate as those extracted from the complete detailed BIM model. Small deviations can be found because the wall framings in the complete detailed BIM model have thickness. The improvement can be done by including the thickness of the wall framings in the calculations. The execution time of the BWFQT method was much faster than the manual modeling time of the complete detailed BIM model. The BWFQT method can reduce the working time and cost of creating wall framings in a BIM model for quantity takeoff. The quantities of wall framings are embedded into wall elements; therefore, this information can be extracted directly from the BIM model.

However, if wall framing models are needed for other tasks, such as visualizing a construction process or generating shop drawing documents, modeling for wall framings is still required. The BWFQT method could be developed by the converting lines that represent the wall framings generated from the system to the wall framing components in a BIM model. Nevertheless, the increased wall framings in a BIM model result in a larger file size that would consume more memory resources and slow down the software performance. According to the case study, the file size of the complete detailed BIM model that contains wall framings is 66% larger than the file size of the incomplete detailed BIM model that does not contains wall framings, while the file size of the incomplete detailed BIM model after applying the BWFQT prototype system is still similar to the original model (see Figure 5.20). The impact of difference in file sizes between the BIM model that contains wall framings and does not contain wall framings would be bigger in a large-scale building that has a huge number of drywalls. Therefore, the BWFQT method is a better approach for BIM-based quantity takeoff, and if the wall framing models are needed for producing shop drawing documents, they should only be created in a selection of representative areas.

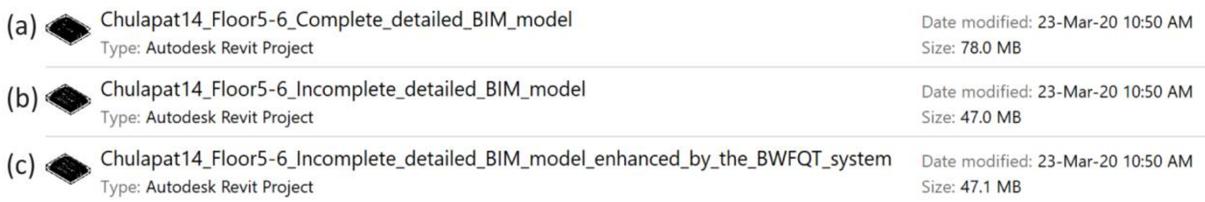

Figure 5.20 The file sizes of (a) the complete detailed BIM model, (b) the incomplete detailed BIM model, and (c) the incomplete detailed BIM model after applying the BWFQT prototype system.

The BWFQT method also delivers more accurate quantities of wall framings than the traditional methods because it calculates the lengths of wall framings based on the lines that represent the wall framings in the correct positions in the BIM model. Traditional method 1 calculates rough quantities of wall framings based on the lengths of walls and spacing values of wall framing without considering wall openings. Traditional method 2 calculates approximate quantities of wall framings based on the wall surface area and the wall framings per area. Both methods also need to add the extra studs at corners, T-intersections, and cross intersections, and the studs at both sides of openings to the length of C-studs. In this case study, the total additional C-stud was 1,788.50 m. If this quantity were not added to the length of C-studs, the deviation of the quantity of C-studs would be −29.82% instead of 3.35% in traditional method 1 and −29.56% instead of 3.60% in traditional method 2. Therefore, the deviations could vary if quantity surveyors with different levels of experience perform the quantity takeoff.

The BWFQT method is also faster than traditional methods 1 and 2. Most of the time is spent on measuring wall length and net wall area in traditional methods 1 and 2, respectively. The traditional methods could be sped up by using semi-automatic BIM-based methods to extract the length and the area of walls from a BIM model. However, the walls in the BIM model must be checked and the overlapping regions corrected manually, whereas the BWFQT method eliminates the overlapping regions automatically.

5.4.2 Limitations

The BWFQT method has some limitations. First, the prototype system can be used only for straight walls; it is unsuitable for slanted walls and curved walls. Algorithms for generating wall surfaces and lines that represent wall framings from slanted walls and curved walls should be developed. Second, the prototype system uses bounding boxes for doors and windows in the calculation. Therefore, doors and windows that are not rectangular or square may cause inaccuracies. Algorithms for generating the exact outline of the doors and windows should be developed to replace the bounding boxes. Finally, the prototype system cannot calculate wall framings for different drywall types simultaneously. A parallel calculation for different drywall types at the same time should be developed in future research.

5.5 Summary

General contractors or sub-contractors require the quantities of wall framings during the construction phase. Traditionally, the quantities of wall framings are estimated using manual calculations. However, BIM can improve the accuracy and speed of quantity takeoff by allowing quantities of building elements to be extracted directly from a BIM model. However, wall framings are detailed elements that are not usually present in BIM models. Creating wall framing models only for quantity takeoff is a time-consuming, costly, and error-prone task. Furthermore, the increased geometries in a BIM model also slow down the software performance. Therefore, this chapter provides an alternative method of calculating quantities of wall framings from a BIM model that does not contain wall framing models.

The BWFQT method calculates quantities of wall framings from drywalls in a BIM model. The algorithms automatically calculate the locations and the lengths of wall framings from the drywall surfaces and the input spacing values of wall framings. The results are embedded into the properties of drywalls in the BIM model, and the quantities of wall framings can then be obtained from the model directly without creating any wall framing models.

Validation was conducted using an actual construction project. The BWFQT method provided accurate quantities of wall framings compared with the complete detailed BIM model in which the wall framings were modeled manually. The BWFQT method was more accurate than the traditional quantity takeoff methods, and the execution time for the prototype system was faster than the modeling time of the complete detailed BIM model and the calculation times of the traditional methods.

The BWFQT method contributes to developing an approach for quantity takeoff of wall framings that are not present in a BIM model. Using this method, construction practitioners can obtain accurate quantities of wall framings from a BIM model that does not contain wall framing models. Deviations due to manual calculations can be reduced and the time and cost of creating wall framings in a BIM model for quantity takeoff can be saved. The accurate quantities of wall framings are beneficial for purchasing materials and reducing the costs associated with excess materials. The BWFQT method does not increase the geometries in the BIM model; therefore, the file size of the model does not increase, which stabilizes performance, and the model is easy to edit. Finally, the BWFQT method can be used to develop a wall framing calculation system in any BIM software product.

Chapter 6
Conclusions

This dissertation presented the development of quantity takeoff methods for compound elements based on BIM. The background information, problem statements, research objectives, research significance, and research scope were introduced in Chapter 1. Chapter 2 presented the literature reviews on the topic of traditional quantity takeoff, focal compound elements, BIM, tools for extending the capabilities of BIM, and BIM-based quantity takeoff. Subsequently, a comparative study to examine the inaccurate quantities was conducted, and a method to improve the accuracy of BIM-based quantity takeoff for compound elements was proposed in Chapter 3. Chapter 4 extended the proposed method from Chapter 3 to automatically modify the compound elements in BIM models. Chapter 5 proposed an alternative approach to obtain the correct material quantities from compound elements in a BIM model. In this chapter, all five chapters are concluded. The following sections provide the summary, contributions, and limitations of the research. Furthermore, the recommendations for the future works are suggested at the end.

6.1 Summary

BIM is a technology that has allowed a new approach to quantity takeoff called BIM-based quantity takeoff. All building elements in a BIM model contain computable graphics and data attributes, and hence the quantities of building elements can be obtained directly from a BIM model. BIM-based quantity takeoff reduces the measurement time and delivers more reliable outcomes. However, if building elements in a BIM model are incomplete or incorrect, the material quantities can deviate from actual values or cannot be extracted directly from the model. Therefore, building elements in a BIM model must contain appropriate details to allow accurate quantity takeoff.

Compound elements, such as walls and floors, are building element categories that have complications when performing quantity takeoff. This is because they consist of multiple material layers that may have different sizes and compositions. The LOD of each compound element must be properly defined and the correct modeling method must be executed in order to obtain accurate quantity takeoff from a BIM model. Each material layer of compound elements must be modeled to represent the exact size and composition of the actual construction, and some sub-components, such as wall framings, must be modeled in the compound elements. However, BIM models that are transferred from the design phases are usually incomplete or incorrect for quantity takeoff. The low LOD of compound elements in the design phases causes some sub-components (e.g. wall framings) absent from the compound elements. The modeling methods developed for compound elements also result in inaccurate quantity takeoff. When compound elements are modeled as single model elements with defined material layers, the ability to adjust the size and composition of each material layer is lost, leading to deviations when extracting quantities for each material layer. Furthermore, the compound elements can be created that overlap with other elements, such as columns and beams, resulting in excess material quantities. Therefore, the compound elements must be manually inspected and edited after the design phases for quantity takeoff and other construction tasks. Each layer of the compound element should be separated as an individual model element and the overlapping regions must be eliminated. Also, the sub-components that are necessary for quantity takeoff must be modeled properly. However, the process of manual correcting the BIM models to achieve an accurate quantity takeoff is time-consuming, cost-intensive, and error-prone, especially under a tight schedule in the construction phase.

This study developed three BIM-based quantity takeoff methods for compound elements. Architectural walls and architectural floors (or floor finishes) are the focal compound elements because they are major architectural elements in which each material layer usually has its own distinction.

The first method is the BCEQTI method presented in Chapter 3. This method improves the accuracy of the quantities of compound elements, which are walls and floors, that are modeled as single model elements and overlap with other building elements. The BCEQTI method integrates the concept of BIM-based clash detection to automatically subtract the overlapping quantities and add the missing quantities of each layer of compound elements. The prototype system was developed, and the BCEQTI method was validated with three simple buildings and one actual residential building project. The BCEQTI method effectively decreased the deviation of the material quantities from the BIM model when compared to the accurate detailed BIM models, and the accuracy was stable across all cases. The prototype system takes only a few minutes to execute the scripts. Therefore, the BCEQTI method can also save the time dedicated to making or editing a BIM model that is incorrect or incomplete for quantity takeoff. However, this method does not edit the original BIM models. Thus, the BIM models still provide inaccurate quantity takeoff results.

The second method is the ACEM method presented in Chapter 4. This method improves the accuracy of the quantities of compound elements (walls and floors) by correcting the BIM models. The ACEM method automatically modifies compound elements in BIM models by separating each layer into an individual model element and eliminating the overlapping regions of the compound elements. The prototype system was developed, and the validation was conducted using a residential building and an office building. The material quantities of compound elements from the BIM models modified by the ACEM method are equivalent to the baseline from the manually modified BIM models. Furthermore, the prototype system modified compound elements in BIM models in much less time than that required for the manual method. Therefore, the working time, cost, and error associated with editing BIM models can be reduced. However, modifying BIM models approach increases geometries in the models, which can slow down the performance of the software, especially in large-scale buildings.

The third method is the BWFQT method presented in Chapter 5. This method proposes an alternative approach to obtain the correct material quantities from compound elements in a BIM model without modifying the BIM model. This chapter focuses on wall framings in drywalls, which are usually absent from a BIM model transferred from the design phases. The BWFQT method automatically calculates quantities of wall framings from drywalls in a BIM model and embedding them into the drywall properties in the BIM model. The quantities of wall framings can be obtained from the BIM model that does not contain wall framing models. The prototype system was developed, and the validation was conducted using an actual interior project. The BWFQT method can provide accurate quantities of wall framings compared with the complete detailed BIM model in which the wall framings were modeled manually. The execution time of the prototype system is faster than the modeling time of the complete detailed BIM model. Therefore, this method can reduce the time and cost of creating wall framings in a BIM model for quantity takeoff. Furthermore, the geometries in the BIM model do not increase, which stabilizes the performance of the software.

6.2 Research Contributions

This research contributes to the understanding of the deviations when extract quantities of compound elements from incomplete or incorrect BIM models and to develop the methods that can improve the accuracy and efficiency of the BIM-based quantity takeoff for compound elements.

The BCEQTI method presents a new approach for BIM-based quantity takeoff by using the concept of BIM-based clash detection to assist the process of BIM-based quantity takeoff. The ACEM method presents an approach to automatically correct compound elements in BIM models. The BWFQT method presents an approach to calculate material quantities and embed them into the properties of compound elements in the BIM model.

All proposed methods in this research can deliver accurate material quantities of compound elements from the incomplete or incorrect BIM models in much less time than the manual modification of BIM models and the manual calculation methods. The working time, cost, and human error associated with the manual works can be reduced. The proposed methods can also be applied to compound elements other than walls and floors, such as ceilings and roofs. However, a specific system for each compound element must be developed because the input BIM model elements are different. The accurate material quantities from the proposed methods improve the execution of other tasks in the design and construction process, such as a precisely detailed cost estimation in the pre-construction phase and precise material purchase in the construction phase. The proposed methods are platform independent, except the parts that relate to Revit API. Therefore, they can be applied to develop automatic quantity takeoff systems in any BIM platform.

6.3 Limitations and future research

The proposed methods have some limitations that should be addressed in future studies or developed in commercial products. The limitations of each method are highlighted as follows.

The BCEQTI method cannot separate different kinds of materials in some conditions, such as the exterior wall finish surfaces that consist of multiple materials and the interior wall finish surfaces that consist of multiple materials in any given room.

The ACEM method was not designed for cases with multiple wall types or floor types in the same room, multiple wall finishes covering the exterior of a building, and complex wall types such as slanted walls, stacked walls, and curtain walls. Moreover, the ACEM prototype system limits the numbers of wall layers and floor layers and cannot create walls that are exterior and interior wall finishes in some places.

The BWFQT method cannot calculate quantities of wall framings in slanted walls and curved walls and cannot calculate wall framings for different drywall types simultaneously. In addition, other wall openings shapes than rectangular cannot be used in this method because it uses bounding boxes for doors and windows in the calculation.

Furthermore, the accuracy and speed of all methods could be validated by further case studies and various quantity surveyors and BIM modelers that have different levels of experience and expertise.

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