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BIM-Based Automatic Extraction of Daily Concrete and Formwork Requirements for Site Work Planning

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Abstract: Material planning is important in construction, for it affects procurement, cost, and schedule. Proper planning of material supply and logistics helps streamline the performance of all tasks through the avoidance of excessive or insufficient material supply. Material planning relies on quantity takeoff (QTO) and project schedules. Conventionally, quantity takeoff was a manual process based on 2D drawings and human interpretation and was error-prone. Presently, with the popularity of Building Information Modelling (BIM), in BIM-based projects, using inbuilt quantity takeoff functions, quantities of work can be generated automatically from BIM models to aid the quantity takeoff. However, if those inbuilt QTO solutions are object-based, then the quantities of works extracted may not meet the requirements of the users in selected cases, e.g., in zone-based construction projects. Also, for estimating daily material requirements, the accuracy of the quantities of work becomes more important, not only for the purpose of efficient planning but also for reducing construction waste. Since works using the same type of material can go overlapping, in addition to estimating the amount of material for each work, the total amount of material for a day must also be calculated. Thus, this research aims to develop a framework for automatic extraction of zone-based concrete volumes and formwork positions for cast-in-place concrete structures using the data in BIM models, followed by linking them with project schedules for estimating daily concrete and formwork requirements. This framework extends the body of knowledge by introducing an innovative algorithm for automatically calculating overlapped areas between concrete members and a rule for naming tasks in the schedule, followed by evaluating the formwork requirements without drawing formwork in a 3D model. A software tool will be developed to achieve the aim, and a case study will be used to validate the proposed framework.

Keywords: BIM; quantity takeoff; concrete and formwork; construction schedule

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1. Introduction

1.1. The Role of Quantity Takeoff in Construction

It is estimated that the cost of materials represents 50% to 60% of what of a construction project [1], in which formwork and concrete might cost up to 15% and 33% of the total construction budget, respectively [2]. Material planning heavily depends on the quantity takeoff result and its schedule. Inadequate material planning, supply, and management could lead to problems in costs, schedules, and quality management of the project [3], and also the environment (construction waste generation). Quantity takeoff plays a crucial role in construction project management.

Inaccurate quantity takeoff is likely to result in problems pertaining to costs, schedule, quality of the project, and environmental protection. For instance, an error in the quantity takeoff process could result in either an oversupply or a shortage of concrete on-site. A lack in quantity could result in issues like cold joints, more time, and the cost of placing fresh orders; an excess will result in material waste and additional expenses. According to earlier research, waste from freshly mixed concrete can reach 13.2% by weight [4], which is a major source of financial and environmental issues.

1.2. Challenges in Quantity Takeoff

Practically, there are three ways for quantity takeoff (QTO) calculation: (1) the manual method using paper drawings; (2) the semi-automated method, leveraging on CAD drawings that are usually presented in the PDF form; and (3) the automated or BIM-based method. Quantity takeoff was conducted manually or semi-automatedly based on 2D drawings and the experience and knowledge of estimators doing the quantity takeoff work [5]. This approach might lead to errors due to insufficient information on 2D drawings or wrong human interpretation. Some potential issues indicated by Monteiro and Martins [5] were problems in detecting classes, errors or omissions, overestimation, and occurrences of cascading problems. In addition, the manual process usually takes a lot of time due to frequent occurrences of human mistakes [6]. Therefore, BIM-based QTO attracts more and more attention nowadays.

1.3. BIM-Based Approach for Constructors

In view of the benefits brought by BIM, more and more constructors were applying BIM for two major purposes: (1) For visualization, as a 3D model could easily represent a complex structure and help with quality assessment; and (2) for quantity takeoff, as a 3D model could quickly extract quantities for tasks like cost estimation, construction planning, tendering, and production control [6,7].

Extracting measurements and material quantities directly from a Building Information Modeling (BIM) model can reduce the time required and is more reliable than traditional methods using 2D drawings [6,8]. With BIM, the time needed for quantity takeoff could be saved up to 80%, and the corresponding accuracy would be at least 97%, as indicated by Olsen and Taylor [9]. However, existing BIM-based QTO solutions, including inbuilt functions of BIM software such as Autodesk Revit 2019, may not be helpful enough in a number of circumstances, such as in schedule-based QTO.

Quantity takeoff serves different purposes in a typical construction project. The relations between quantity takeoff and other major tasks in a construction project lifecycle are shown in Figure 1. For clients and consultants, "Quantity Takeoff for Estimation" only focuses on the total volume for overall project cost estimation. For constructors, "Quantity Takeoff for Construction" provides schedule-based quantity results, which are required for material planning, construction planning, and cost estimation.

Quantity Takeoff for Estimation and Quantity Takeoff for Construction are different because the latter is strongly dependent both on the construction methods used and construction processes, while the former only needs to take into account the construction methods. Therefore, Quantity Takeoff for Construction may require a different measuring approach to reflect the construction processes applied, such as the construction joint for concrete, which must be taken into consideration. Also, Quantity Takeoff for Estimation can help generate the total amount of materials consumed for the components/the whole project, while Quantity Takeoff for Construction must allow the estimation of the materials to be consumed daily.

An illustrative example is presented in Figure 2, including a floor plan (Figure 2a), a 3D model (Figure 2b), a North View (Figure 2c), and a West View (Figure 2d). In order to construct the example building, the process should be divided into two stages: (1) Stage 1: Construction of columns; and (2) Stage 2: Construction of beams and slabs. The height of each column is 3.9 m, as in Figure 2c,d. Considering the difference in the height of the

beams (600 mm and 400 mm) that contact the columns, the concrete pouring height of each column at stage 1 should stop at 3.3 m.

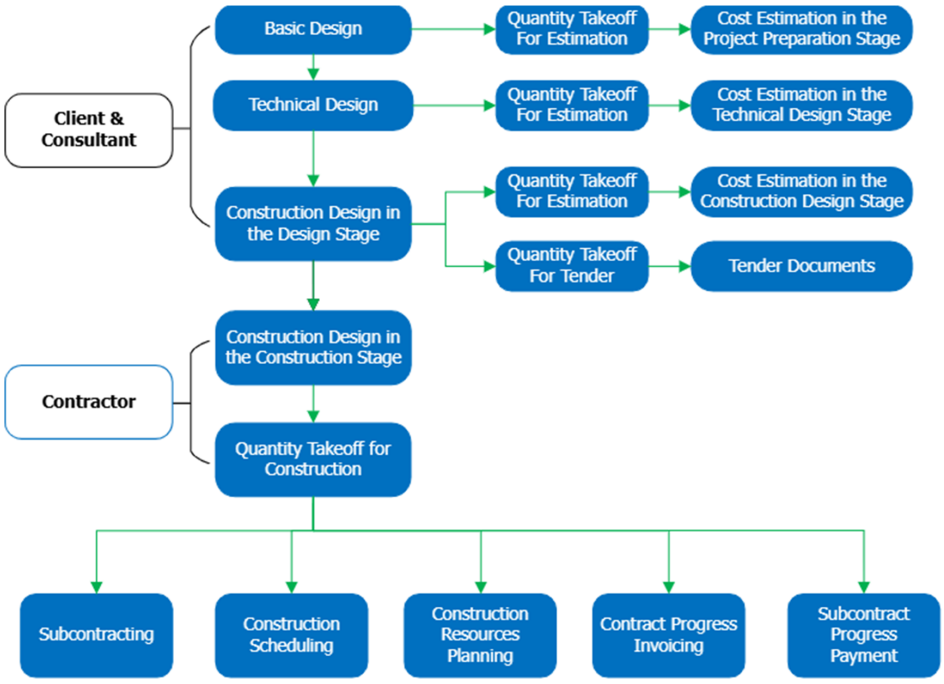
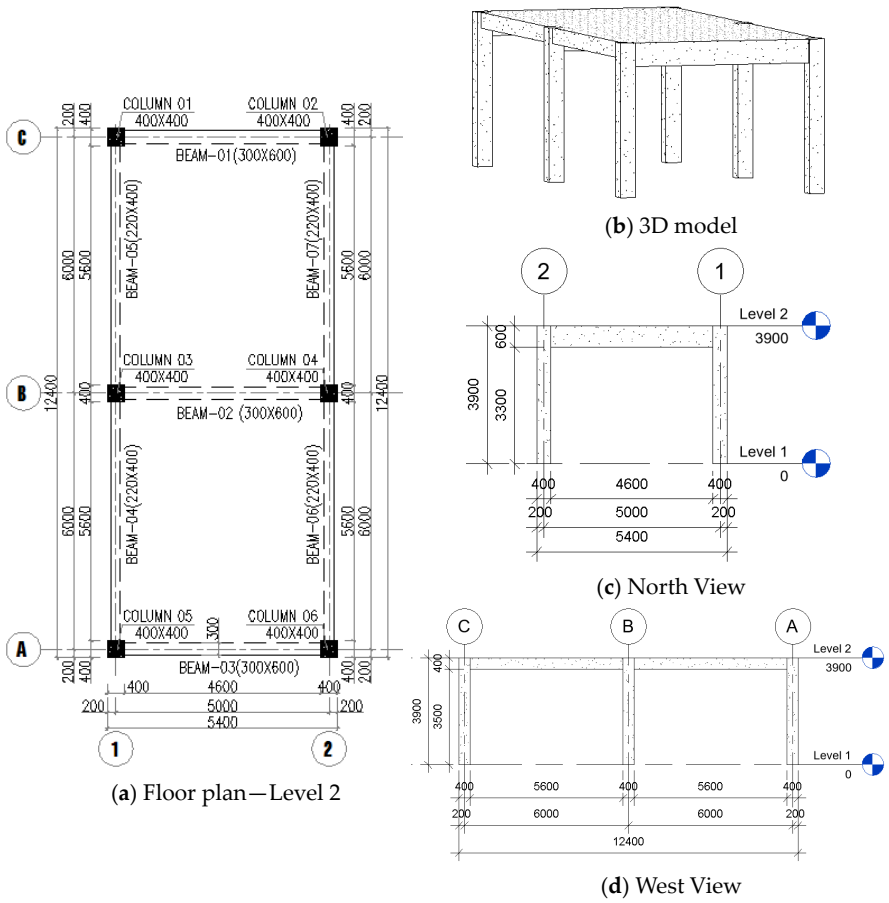


Figure 1. The relations between quantity takeoff and other major tasks in a project lifecycle.



(**a**) Floor plan—Level 2

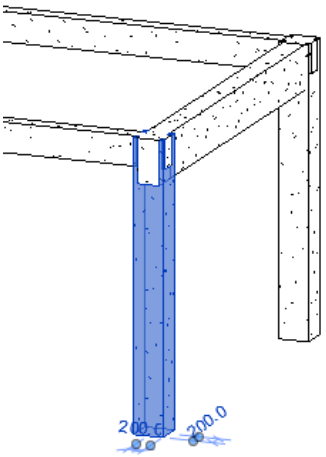
(**b**) 3D model

(**c**) North View

(**d**) West View

Figure 2. An illustrative example.

With regard to concrete volume calculation, the concrete volume for six columns needed for stage 1 is 6 × 0.4 × 0.4 × 3.3 = 3.168 (m^3). The overlapped concrete between columns and beams will be poured at stage 2. The software's functions are not able to simulate this process and then provide inaccurate results. For example, Autodesk Revit 2019 software, a popular BIM software, provides a join command in which concrete at the intersection could be assigned to a single component to avoid duplication. In this case, the result for columns concrete will be 3.240 (m^3) (Figure 3c) and 3.744 (m^3) (Figure 3d) if the overlap concrete is assigned to beams (Figure 3a) and columns (Figure 3b), respectively. Both results are inappropriate for calculating concrete quantity takeoff following stages.

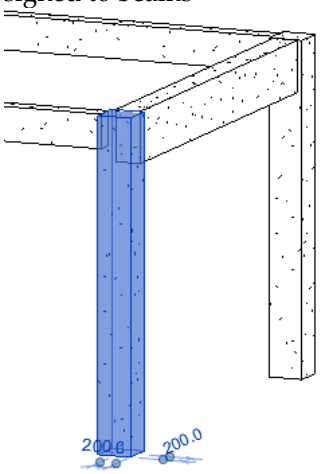


(**a**) The overlap concrete assigned to beams

<Column Material Takeoff>

A	B	C	D	E
Base Level	Top Level	Type	Family and Type	Material: Volume
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.54 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.54 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.54 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.54 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.54 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.54 m³
Grand total: 6				3.24 m³

(**c**) Column Material Takeoff from Revit software if assigning the overlap concrete to beams



(**b**) The overlap concrete assigned to a column

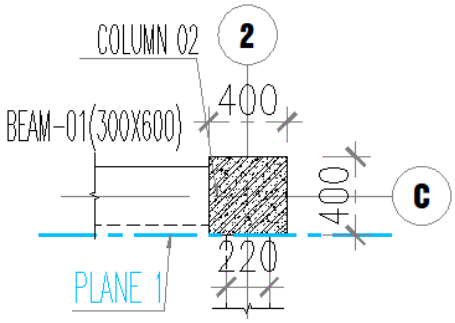
<Column Material Takeoff>

A	B	C	D	E
Base Level	Top Level	Type	Family and Type	Material: Volume
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.624 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.624 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.624 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.624 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.624 m³
Level 1	Level 2	400 x 400mm	M_Rectangular Column: 400 x 400mm	0.624 m³
Grand total: 6				3.744 m³

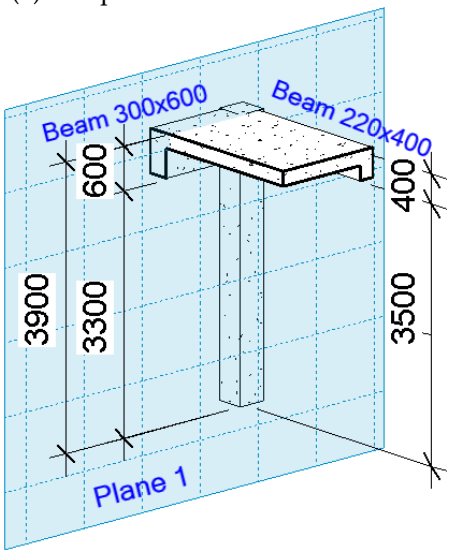
(**d**) Column Material Takeoff from Revit software if assigning the overlap concrete to columns

Figure 3. Quantity takeoff off concrete after using Join command in Revit.

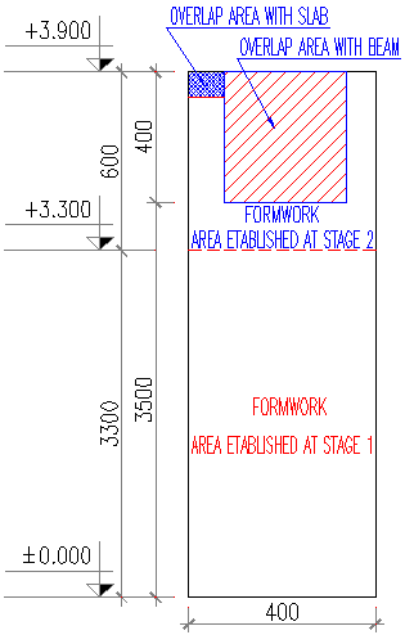
For formwork estimation, a column is retrieved to analyze in Figure 4a, and an imaginary plane (Plane 1) is drawn coincident with a column face (Figure 4b). To establish formwork, in stage 1, the formwork of columns should be installed to a height of 3.3 m, and the rest should be performed in stage 2. Some researchers [10,11] have used Dynamo to discover the overlap area between items, as shown in Figure 4c. Afterward, they calculated the total area of the surrounding faces minus the overlapping area. However, besides the overlap area being deducted at the site, engineers still need to calculate the formwork area established at each stage. Therefore, a new algorithm should be proposed to solve all issues mentioned above.



(**a**) The position of Plane 1 on level 2



(**b**) Plane 1 in the 3D model



(**c**) Formwork area on column face

Figure 4. An illustrative example for formwork estimation.

1.4. Zoning in Construction

Construction zoning is frequently employed as an effective method to conserve direct materials (such as formwork and scaffolding) and distribute human resources [7]. Upon completion of tasks in a zone, resources (e.g., formwork or workers) may be relocated to subsequent zones. This method can diminish the contractor's initial investment. Project work zones are often organized to maintain uniform work spaces and construction elements. If the project contains many slabs at varying elevations, the zoning regulations for each level should remain consistent. The zoning of a construction project facilitates a more rational and effective project timeline. The procedure for zoning is shown in Figure 2.

In Figure 5, it can be seen that zoning can start after a building model is available, followed by calculating the zone-based works/materials (e.g., concrete volume, formwork positions, scaffolding, cranes, etc.) and task durations. If the obtained schedule can meet all the required project requirements, it is finalized. Otherwise, the zoning process will start all over again.

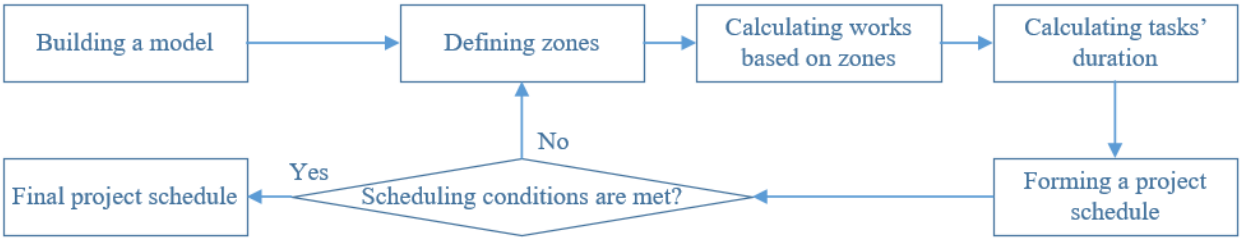


Figure 5. The procedure for zoning.

1.5. Motivation and Significance of This Research

A quick search on the Scopus database, the largest source of indexed scientific publications [12], in November 2024 brings in 198 documents with the search keywords [BIM AND ("quantity take-off" OR "quantity takeoff")]. A thorough review of the abstracts of such publications shows that there is no single publication addressing the BIM uses for time-based quantity takeoff. The popular topics include quantifying carbon emissions [13], rebar cutting [14], estimating [15] cash flow, progress payment [16], taking quantity for building components [17], discussing the Methods of Measurement in relation to BIM-based quantity takeoff [18], etc. A recent review paper entitled "BIM-based quantity takeoff: Current state and future opportunities" published in 2024 never mentioned any papers containing completely relevant topics. There is only one conference paper dated back in 2017 discussing the BIM-based QTO for daily reporting by a simple mechanism of integrating the timemark into each project component [19] and another paper published in 2021 proposing an API for automatic extraction of daily concrete requirements from 3D BIM and project schedules [19], but the latter was just at an early stage of research. The literature shows the gap for a complete solution for daily material planning on construction sites.

Although construction zoning is common nowadays, there is hardly any user-friendly tool that could extract material quantity data on a daily basis for on-site logistics planning found in the market. In addition, there is still a lack of research on calculating the daily required material volumes according to the schedule (mentioned in Section 1.3) to help manage materials on the construction site.

To bridge the gap, this research proposed an approach that could handle overlaps between structural elements and automatically extract zone-based concrete volume and formwork data on a daily basis using the BIM model. Autodesk Revit 2019 was adopted in this research as the BIM software, and a plugin was developed using the Revit Application Programming Interface (API) and the C# programming language. The plugin can achieve the following purposes:

- To segment structural components based on zones on a BIM model;
- To handle zone-based quantity takeoff for concrete and formworks. In order to obtain that, innovative algorithms are introduced to calculate the overlapped areas; and
- To import the schedule from an Excel file and calculate daily required quantities for concrete and formwork.

2. Literature Review

A more thorough review of 198 publications found in the Scopus database provides a more insightful picture of BIM-based quantity takeoff in general and BIM-based quantity takeoff for daily planning, especially for the two most popular materials of concrete and formwork.

2.1. Conventional Quantity Takeoff vs. BIM-Based Quantity Takeoff

Quantity takeoff, a process in which building elements are measured and counted, is popularly considered important in construction projects since it provides crucial data for other tasks [5,20]. The output of the quantity takeoff process has been confirmed to be used for various purposes, including cost estimation, calculation of the construction activities, project management, material procurement [21], and contract progress payment.

Conventionally, there are two ways for quantity takeoff (QTO) calculation: (1) the manual method using paper drawings; (2) the semi-automated method that leverages CAD drawings. Some previous research strives to improve the efficiency of quantity takeoff using 2D and 3D CAD. Jadid and Idrees introduced a method to estimate the required material for beams, columns, slabs, and foundations by using layer computation of AutoCAD drawings [22]. Automatic extraction of material quantities required for wall assembly was proposed by Manrique et al. in a 3D CAD model [23]. A specialized technique for placing formwork panels around columns was suggested by Lee et al. [24], enabling ideal formwork placements even for intricate floor plans with numerous columns. The harmony

search optimization algorithm is used to rapidly and automatically determine cohesive and ideal layouts. The case study indicated that the proposed method dropped 56% in the nonstandard pannel-covered area. Following conventional quantity takeoff methods, a cascade of errors is likely to occur when quantity takeoff is carried out manually [5].

The literature has provided proof that BIM-based quantity takeoff increases productivity, accuracy, and completeness of cost-estimating tasks [12] in comparison to the traditional approach. Lots of recent publications have supported this statement [25] by providing some practical [26,27] evidence or discussing featured factors [28]. Proposed solutions for BIM-based quantity takeoff include the usage of 3D authoring or 4D software, including Autodesk Revit and Navisworks [29], specific software such as Cubicost [25,27] and/or Allplan [30], or using solutions such as IFC-based BIM [31], ontological algorithms [32], a data-driven framework based on BIM and knowledge graphs [33], or other digital technologies such as scan-to-bim [34], virtual reality [35], to facilitate automated quantity takeoff. Some papers stopped developing theoretical frameworks without validating them in practical cases [16]. However, previous publications have revealed that there are some high-level automated solutions for BIM-based quantity takeoff, including an integrated framework to automatically extract and visualize construction quantities from BIM models. The system includes a Quantity Precision Check (QPC) module for automating more accurate QTO outputs. These outputs are then automatically transferred to an external database and visualized through a user-friendly dashboard on the Microsoft Power BI platform [36].

2.2. BIM-Based Quantity Takeoff for Daily Planning of Construction Materials

Material quantity can be automatically calculated by extracting geometric data and semantic properties of each building part from the building's BIM models [6]. This method is called BIM-based quantity takeoff, which is faster, more accurate, and more efficient than conventional quantity takeoff [37]. Sheikhkhoshkar et al. developed a structural model in Revit to extract spatial information, including all construction joints, and link them to other tools for automatically generating concrete joint layouts and daily concrete volumes [38]. Kim et al. retrieved spatial and geometric data, quantities, relationships, and material layer set information from BIM models through ifcXML for automatic schedule generation [39]. Kannan and Santhi defined concrete formwork components and applied them to the BIM model of a high-rise building [40]. The drawback of these formwork components is that the opening is overlooked in structural concrete elements, causing the inaccuracy of calculation. Khosakitchalert et al. presented a method that could automatically calculate formwork quantities using reinforced concrete elements' surfaces through a function library that might not be used in other BIM software [10]. Cepni et al. [11] represented a method to calculate the formwork of objects with complex geometries based on Autodesk Revit Dynamo, then conducted a comparison time between manual quantity takeoff and automated quantity takeoff. In these two studies [10,11], the authors primarily focused on calculating the total formwork volume instead of the schedule-based formwork volume. Therefore, additional manual effort is needed to calculate the required daily quantity of formwork. A new algorithm with a higher level of automation to handle this process may help resolve the issue. In order to calculate auxiliary materials (e.g., formwork), Wei et al. [41] had to define a template as a temporary structure, then construct formwork following the design requirement. The drawn formwork data would be used to calculate after that. But modeling tasks could be time-consuming and error-prone because it is conducted manually.

Singh et al. proposed a framework using BIM data as input to compute the quantity of formwork generate visualization and prepare a schedule, but the framework is only applicable to formwork elements of cast-in-situ walls [42]. Hanna et al. [43] developed a tool to assist the designer in making the decision to select and optimize formwork. Automated optimization of formwork design is suggested by Hyun et al. [44]. It seeks to select the optimal formwork option and optimize the formwork design. The wall data from a 3D model, including size, shape, and coordinates, are extracted to an IFC file; then, the authors

applied formulas to design formwork for a concrete wall. The limitation of this paper is only focused on calculating formwork for wall components.

A prototype that can automatically design formwork for walls and deck was proposed by Lee et al. [45], demonstrating the viability of software development. In this prototype, a library of aluminum formwork is collected and simulated. The application was developed using Unity 3D and Blender 3D, which are utilized for meshing and pre-processing the BIM 3D rendering data. In this work, the meshes were transformed into a constant form by utilizing an algorithm that populates a 3D model with meshes that are all the same size and shape.

Reusing formwork is a crucial issue because it reduces the initial investment for the constructors. Mansuri et al. [46] created a cascading method to retrieve data from BIM to manage the inventory of formwork. The stripped formwork at an earlier stage would be used at a later stage, reducing formwork costs. Mei et al. suggest a system based on building information modeling (BIM) to help site managers automatically receive precise requirements for concrete formwork in order to save waste and expenses [47]. In order to retrieve the dimension of concrete elements (i.e., columns, walls, slabs, and beams), the authors extract these dimensions directly from the component in the 3D model. After that, the authors assumed that columns and floors have four-face contact and five-face contact, respectively. These dimensions would be used to create and optimize formwork. However, the formwork results extracted directly from the 3D model cannot be used unless some additional adjustments are added [48]. For instance, beams often serve as boundaries for the surrounding faces of floors; as a result, the requirement for additional formwork can be minimized. Furthermore, for the column, the formwork should be divided into two phases to construct; thus, the column formwork dimension could not take the whole dimension of the surrounding face contact. In addition, the framework has not considered the material dissipation of formwork panels.

When working with other components in the structure skeleton, the overlap between the other parts is an indispensable issue that has to be addressed. BIM software developers have tried to create BIM tools to automate extracting the quantity takeoff. One major disadvantage of BIM tools is their inability to work with formworks in the model [5]. Many BIM tools do not have a built-in function for modeling formworks, including the popular Revit [4,6]. Although some software products like Tekla Structures have presented a function enabling formwork modeling, they do not provide the contractor with scheduled-based quantity outputs. Furthermore, a significant drawback in calculating formwork requirements is an overestimation of formwork quantities at structural joints (Figure 3). In Figure 6, it can be seen that the formwork is usually double-counted in the joint of two adjacent structural elements, like a beam and a column, etc.

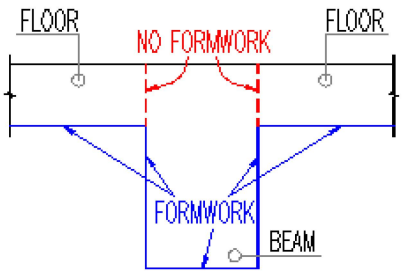


Figure 6. Issues in extracting formwork quantities from a BIM model.

2.3. Zone-Based Applications

Construction zoning is a regulatory framework used in urban planning to designate specific areas for particular types of land use and construction activities. It involves dividing a region into zones, each with prescribed rules governing the type, scale, and purpose of buildings that can be developed. Construction zoning is frequently utilized in large projects as an effective strategy to organize human resources and save direct materials

(such as formwork and scaffolds) [7,49]. After the activities in a zone are finished, the resources (e.g., personnel or formwork) can be moved to the following zones. This method can mitigate the contractor's initial investment. Following this, some similar tasks (i.e., pouring concrete or formwork erection) are performed simultaneously in different zones or levels. Therefore, the engineers need to handle all these tasks simultaneously and have planning material appropriately. The division of a construction site into zones is influenced by multiple factors, including the construction team's capacity, material supply capabilities, and project schedule. This process is typically overseen by an experienced site manager to ensure optimal efficiency and coordination. The issue of zone division is beyond the scope of this study and will not be addressed further. Although construction zoning is common nowadays [7,49,50], there is hardly any user-friendly tool that could extract material quantity data following the zone and the construction process presented above.

3. Framework for Zone-Based Quantity Takeoff

A framework for the zone-based generation of daily concrete and formwork requirements is shown in Figure 7, which comprises six phases: (A) BIM model preparation; (B) defining zones; (C) calculating concrete volume for each zone; (D) calculating formwork quantity for each zone; (E) reading schedule information from an Excel file and calculating quantity takeoff; (F) daily concrete and formwork requirement.

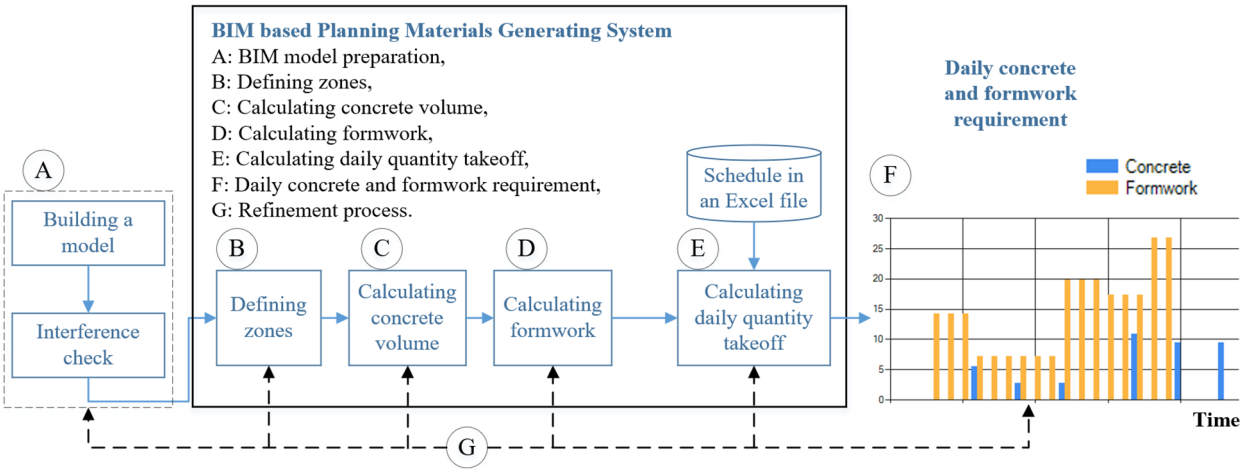


Figure 7. Framework for zone-based quantity takeoff.

Zones are delineated according to task similarity, work nature, and work sequence, facilitating optimal resource usage. Afterward, the quantities required for concrete and formworks are calculated based on the zones and the construction joints between columns, beams, walls, and slabs, as elaborated in Sections 3.3 and 3.4. Finally, the project schedule in an Excel file is imported to conduct daily quantity takeoff, followed by the generation of daily material requirements.

3.1. BIM Model Preparation

3.1.1. Steps for Preparing a 3D BIM Model

Preparing a suitable 3D BIM model plays a vital role because it will directly affect the quantity takeoff results. BIM model preparation includes four major steps (Figure 8). The first step is to determine the project baseline. The project basepoint should coincide with the model origin point O(0,0,0) in the coordinate system Oxyz, which would serve as the reference point for the calculation of all the coordinates in the various zones (Figure 9). The zone definition is presented in Section 3.2.

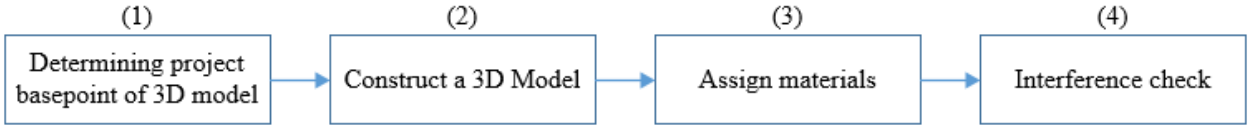


Figure 8. Steps of BIM model preparation.

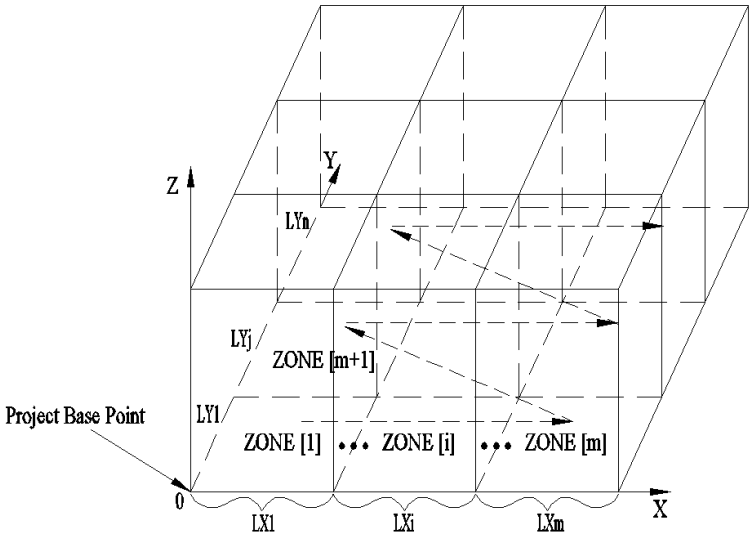


Figure 9. An example of locating a project basepoint.

The second step is to construct a 3D model using BIM software, which should contain basic construction elements, including beams, slabs, and columns. After designing these elements, materials will be assigned to these elements to calculate the concrete volume. The final step is interference checking, which prevents overlaps between elements in the model by comparing 3D solid models of building elements. The purpose of this step is to increase the accuracy of the QTO job.

3.1.2. The Rule for Preparing a 3D BIM Model

In fact, there are many ways to create a 3D model, which can lead to differences in mass calculation results. However, in order to calculate exactly the daily quantity takeoff, some rules applying Quantity Take-off (RQT) are proposed as follows to make sure that this approach comes with an accurate result.

- Columns are created from one level to the next level (Figure 10).

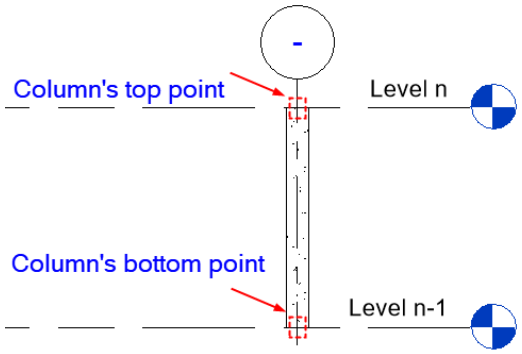


Figure 10. Draw a column in a 3D model.

- Beams are established from one column's edge to the edge of another column (Figure 11).

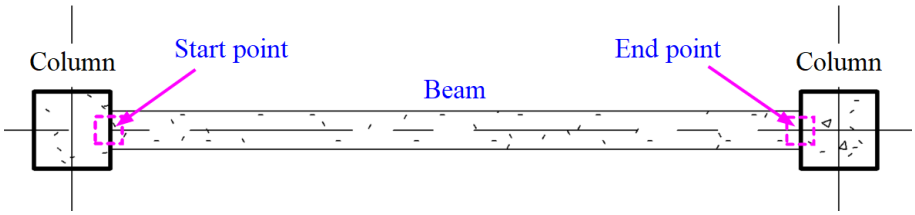


Figure 11. Draw a beam in a 3D model.

- Slabs are formed by the contacting edges of the beams and columns that surround the slabs (Figure 12).

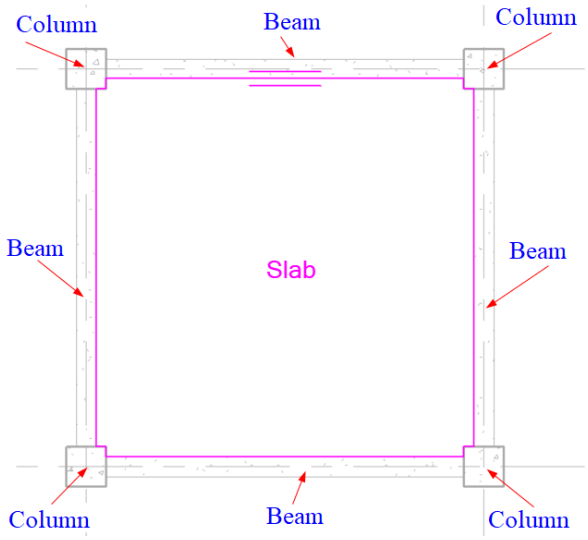


Figure 12. Draw a slab in a 3D model.

3.2. Defining Zones

To facilitate efficient project planning and resource allocation, extensive construction projects are typically segmented into manageable sections, referred to as zones. The engineers often determine these zones during the planning phase, and the entire building timetable is developed accordingly. In standard multi-story or high-rise building projects, zones are established on a horizontal plane, so all vertical levels within the designated area are classified under the same zone. Four primary steps exist for delineating zones: (1) Obtain input data, such as X and Y dimension values; (2) define zones based on these values; (3) identify elements that belong to each level and zone; (4) verify that each element belongs to a particular zone; and (5) extract concrete volume based on zones and levels. The process of defining zones is illustrated in Figure 13.

Step 2 involves using user input and the decomposition approach proposed by Heigermoser et al. [7] to divide a 3D BIM model into zones, levels, and elements. Figure 14 illustrates the tree-views of the decomposition of the model that adapted from [7].

A class "Zone" was established to systematically organize data, with building elements regarded as the objects within that class. According to the principles of object-oriented programming, a class serves as the blueprint for an object, which, containing variables, data structures, and functions, is an instance of that class [51]. Consequently, the data inside the "Zone" class were further disaggregated into levels and elements. Each zone comprised a list of levels, and each level encompassed lists of columns, beams, and slabs, along with their respective element properties, including location, volume, and ID. Figure 15 depicts the data arrangement within a zone of a three-dimensional architectural model. There are "k" levels, each comprising structural elements such as columns, beams, and slabs.

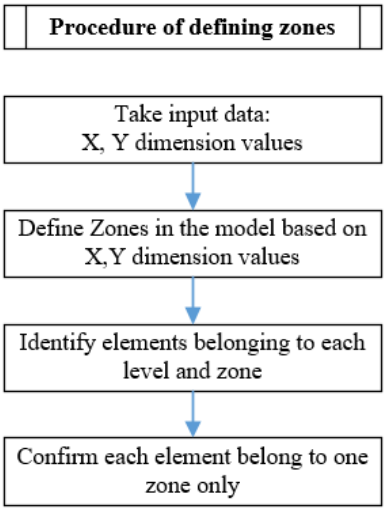


Figure 13. The procedure of defining zones.

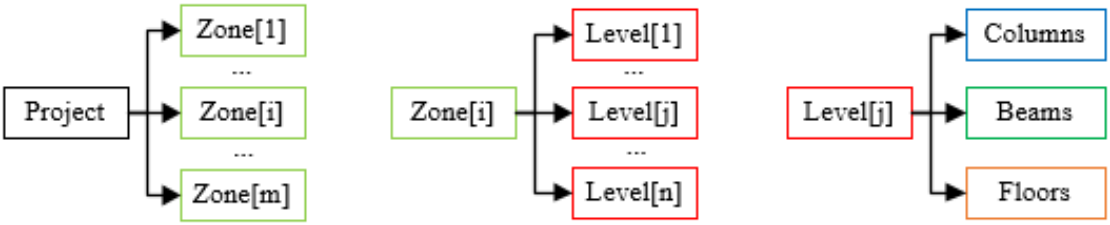


Figure 14. Tree-views of 3D model decomposition.

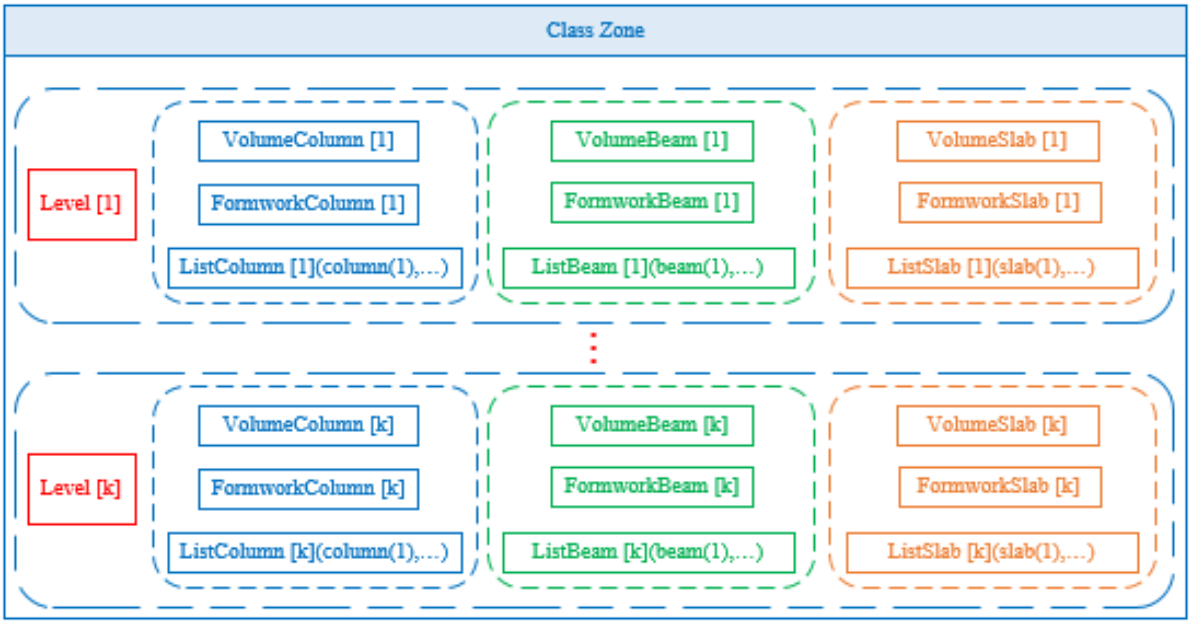
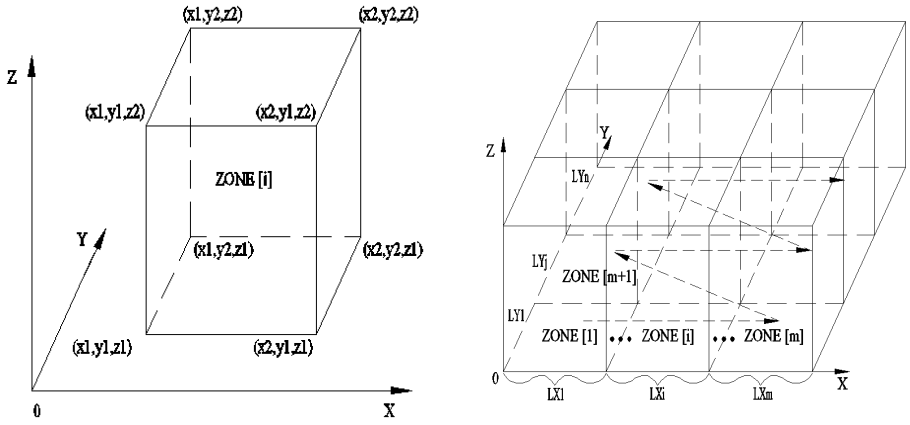


Figure 15. Data organization in a typical zone of a building with multiple levels.

To define a zone within a 3D model, a bounding box is generated using two primary corner points: (x1, y1, z1) and its diagonally opposite corner (x2, y2, z2), as depicted in Figure 16a. The remaining six vertices of the bounding box (x2, y1, z1), (x2, y2, z1), (x1, y2, z1), (x1, y1, z2), (x2, y1, z2), and (x1, y2, z2) are automatically derived from these two key points. The coordinates of the key corner points are determined by the user-defined dimensions of the zone, denoted as Lx, Ly, and Lz along the X, Y, and Z axes, respectively. Zones are primarily indexed along the *X*-axis, as illustrated in Figure 16b.



(**a**) The bounding box of a zone (**b**) Multiple zones in the 3D space

Figure 16. Representation of the bounding box and multiple zones.

In Step 3, elements within a bounding box or zone were identified utilizing the "template" function of the Revit API. Elements entirely contained within a zone or intersecting its boundary were classified as part of that zone. Since each zone encompassed multiple levels, the elements were further categorized based on their specific positions within the zone. The "level" information was obtained directly from the element's properties in the Building Information Modeling (BIM) model.

When an element intersects with the boundaries of multiple zones, repetition in counting might occur. To overcome this problem, the ID of the element that appeared in multiple zones would be checked in this step to avoid repetition. Such an element is assigned to the zone with the lowest index number and removed from the other zones to avoid duplication. To ensure that each element only belongs to one zone, two consecutive zones in the 3D model, Zone A and Zone B, are used to explain how this is achieved (Figure 17). The first step is to take an element in Zone A to be checked. This element's ID will be compared with all elements' IDs in Zone B. If there is any element in Zone B that has the same ID as the element in Zone A, the element in Zone B will be deleted.

3.3. Calculating Concrete Volume

Due to several factors, including size or complexity of structures, material supply restrictions, permissible working times and conditions, and human resources limitations, uninterrupted concrete pouring is sometimes impractical [52]. Therefore, construction joints allow the resumption of work after a period of time [53]. Sheikhkhoshkar et al. presented a table of various guidelines for construction joint placement in concrete, which suggested skilled designers define the positions of joints and establish a precise pouring schedule [38].

During construction, the concrete volumes and formwork quantities are mostly calculated based on schedules rather than the total amount. Considering columns, beams, and slabs are the three major components in a building's superstructure, their concrete volumes and formwork quantities should be calculated in an efficient and effective way. When constructing columns, formworks are usually set up from the bottom of the column to the bottom face of the beam (Figure 18). Therefore, in practice, the concrete volume of the column should be divided into two parts: V_{column} and $V_{Overlap}$. V_{column} denotes the volume from the bottom of the column to the bottom face of the beam; $V_{Overlap}$ denotes the overlapping volume between the column and the beam. Figure 19 shows the flow of calculating the concrete volume of a column, with relevant information extracted from the BIM software.

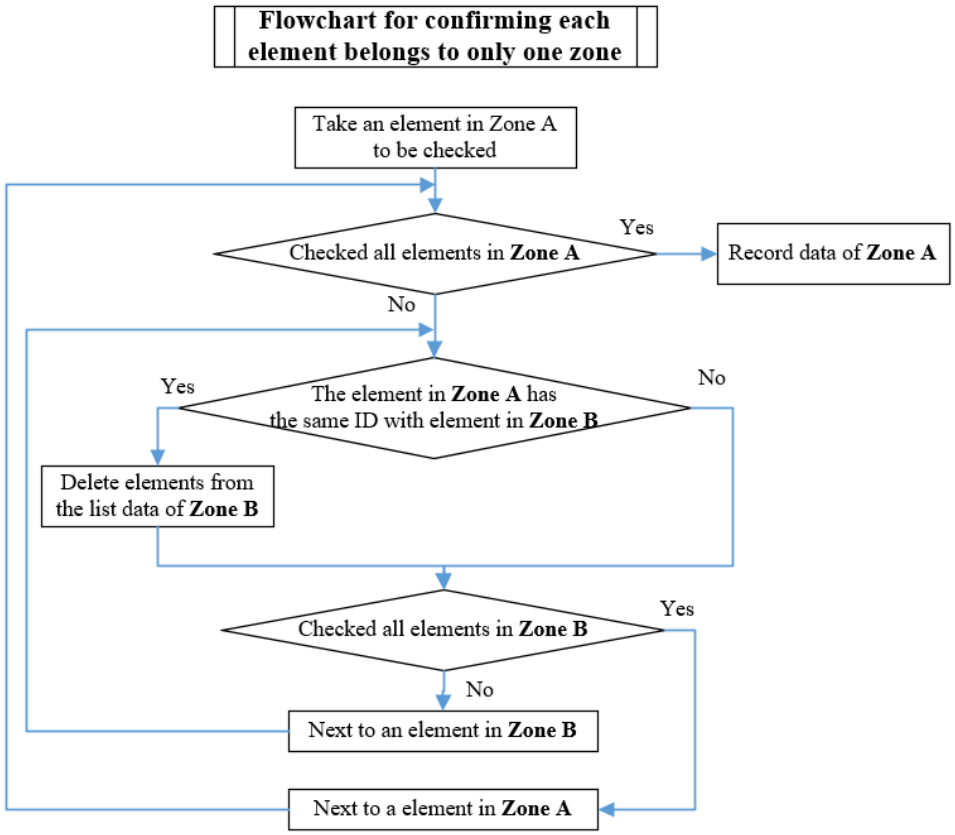


Figure 17. Flowchart for confirming each element belongs to only one zone.

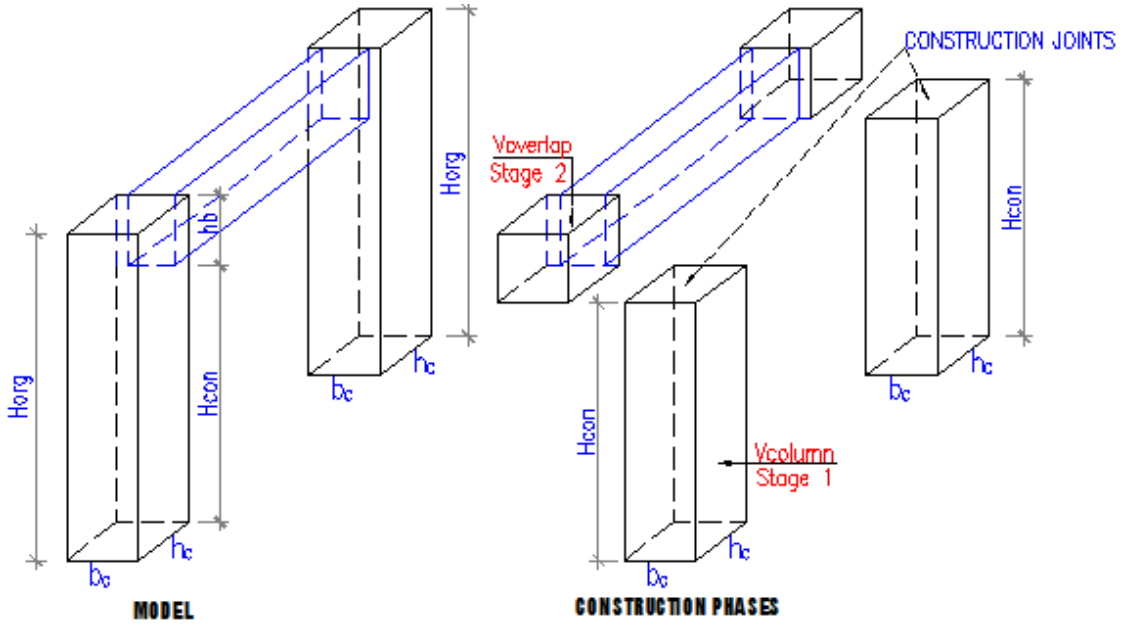


Figure 18. Differences in beam volume segmentation: model representation vs. construction practice.

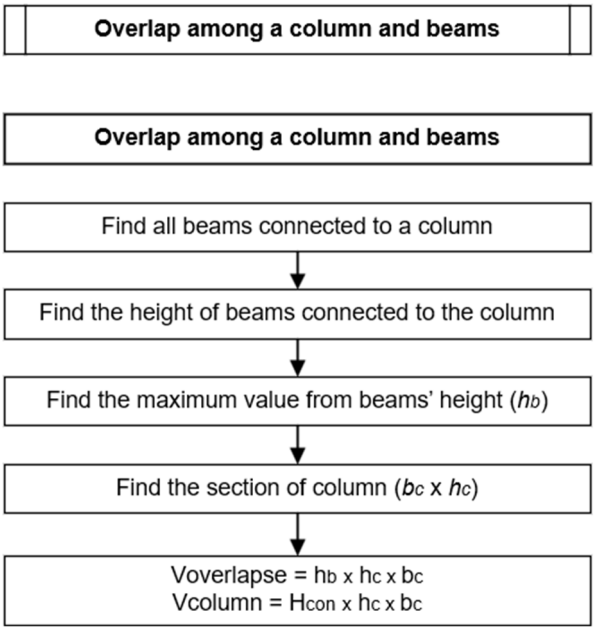


Figure 19. The flow of calculating the concrete volume of a column.

The first step is to identify all the beams connected to the column, which are elaborated in Figure 20, followed by extracting the dimensions associated with the column from the BIM model. These dimensions are h_c (height of the column section), b_c (width of the column section), H_{org} (height of the column), and h_b (maximum of the height of the beam).

$$V_{Overlapse} = h_b \cdot h_c \cdot b_c \quad (1)$$

$$V_{column} = H_{con} \cdot h_c \cdot b_c \quad (2)$$

$$\text{where } H_{con} = H_{org} - h_b \quad (3)$$

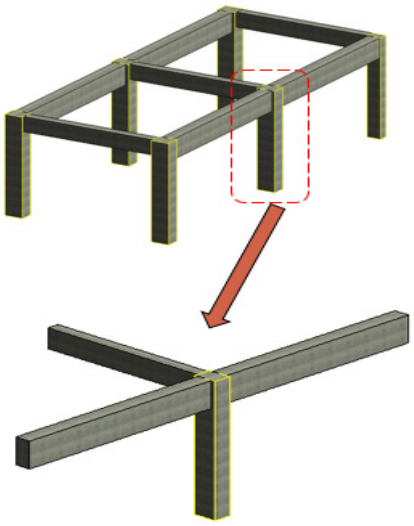


Figure 20. An example of the beams connected to the column.

3.4. Calculating Formwork Quantity

To determine the formwork quantity, the overlaps between a beam and a column, a beam and a slab, a column and a slab, and adjacent beams will be calculated.

3.4.1. Assumptions

In this research, it is assumed that structures have rectangular plans, and columns and beams have rectangular cross-sections. Although these assumptions apply to a large number of building projects, plans and cross-sections of different shapes will be considered in future research.

3.4.2. Considering Overlaps

When handling overlaps between two structural members, each face of a structural member is checked against each face of the other structural member to see if there is an intersection. The flow of checking overlaps between structural members is shown in Figs. 21, 22, and 23 to illustrate how overlaps are handled. The "object" in Figures 21–23 refers to the structural member of concern.

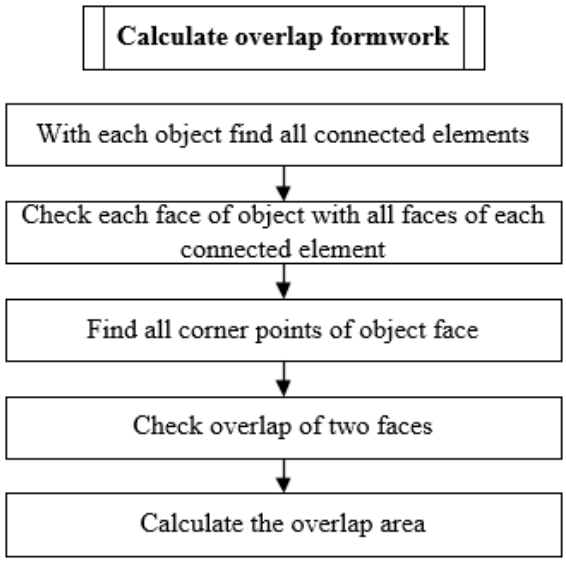


Figure 21. The flow of checking overlaps between structural members.

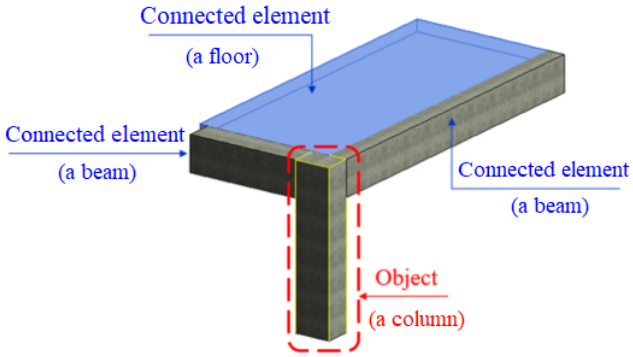


Figure 22. Find all structural members connected to the object.

First, find all structural members that are connected to the object. For example, in Figure 18, the connected structural members are beams and slabs.

Then, each face of the object is considered with all the faces of each connected structural element, and an example is elaborated in Figure 19.

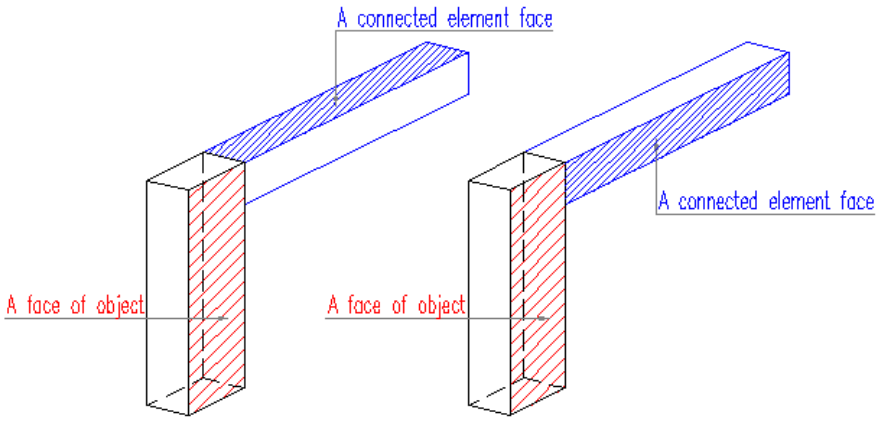


Figure 23. Consider each face of the object against all the faces of a connected structural member.

Find all corner points of a face

The next step is to find all corner points of each face. In a BIM model, each structural member is formed by faces, each face is created by edges, and each edge has two endpoints. To find the corner points of each face, it is necessary to ensure the sum of two edges in a triangle is greater than the third edge (Equations (4)–(6)).

Assume Point A (xA, yA), Point B (xB, yB), and Point C (xC, yC) are on a plane (Figure 24). Characters a, b, and c denote the length of the B-C segment, C-A segment, and A-B segment, respectively. The value of a, b, and c is calculated as follows:

$$a = \sqrt{(\mathrm{xB} - \mathrm{xC})^2 + (\mathrm{yB} - \mathrm{yC})^2} \tag{4}$$

$$b = \sqrt{(\mathrm{xC} - \mathrm{xA})^2 + (\mathrm{yC} - \mathrm{yA})^2} \tag{5}$$

$$c = \sqrt{(\mathrm{xA} - \mathrm{xB})^2 + (\mathrm{yA} - \mathrm{yB})^2} \tag{6}$$

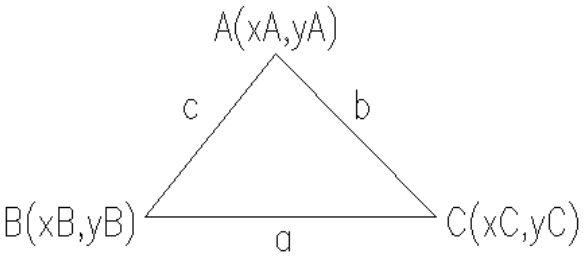


Figure 24. Find all corner points.

If (($a + b > c$) and ($b + c > a$) and ($c + a > b$)) is true, it means that A point is a corner point.

Checking overlaps between two faces

Following the assumptions in Section 3.4.1, it is assumed that the structural members are rectangular cross-sections. Therefore, the overlaps between a column and a beam, a beam and a slab, and a column and a slab could be considered as the overlaps between two rectangles. After finding all the corner points of the two faces, e.g., Face A and Face B in Figure 25, an algorithm is used to check whether there is an overlap between these two faces. Assume that FaceA has four corner points: PA1, PA2, PA3, PA4, and FaceB has corner points PB1, PB2, PB3, and PB4.

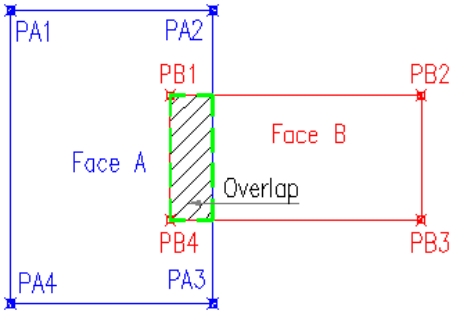


Figure 25. The overlap between Face A and Face B.

The main idea of the algorithm is to check if there exists a line that separates a point on Face A from all the points on Face B. If such a line exists, there is no overlap between Face A and Face B. To start, draw a line, d1, connecting PA1 and PA2 as shown in Figure 26a. Assume the coordinates of PA1, PA2, PB1, PB2, PB3, and PB4 are: PA1 (xA1, yA1), PA2 (xA2, yA2), PB1 (xB1, yB1), PB2 (xB2, yB2), PB3 (xB3, yB3), and PB4 (xB4, yB4). Equation (7) shows the linear equation connecting PA1 and PA2:

$$(x - xA1)\cdot(yA2 - yA1) - (y - yA1)\cdot(xA2 - xA1) = 0 \quad (7)$$

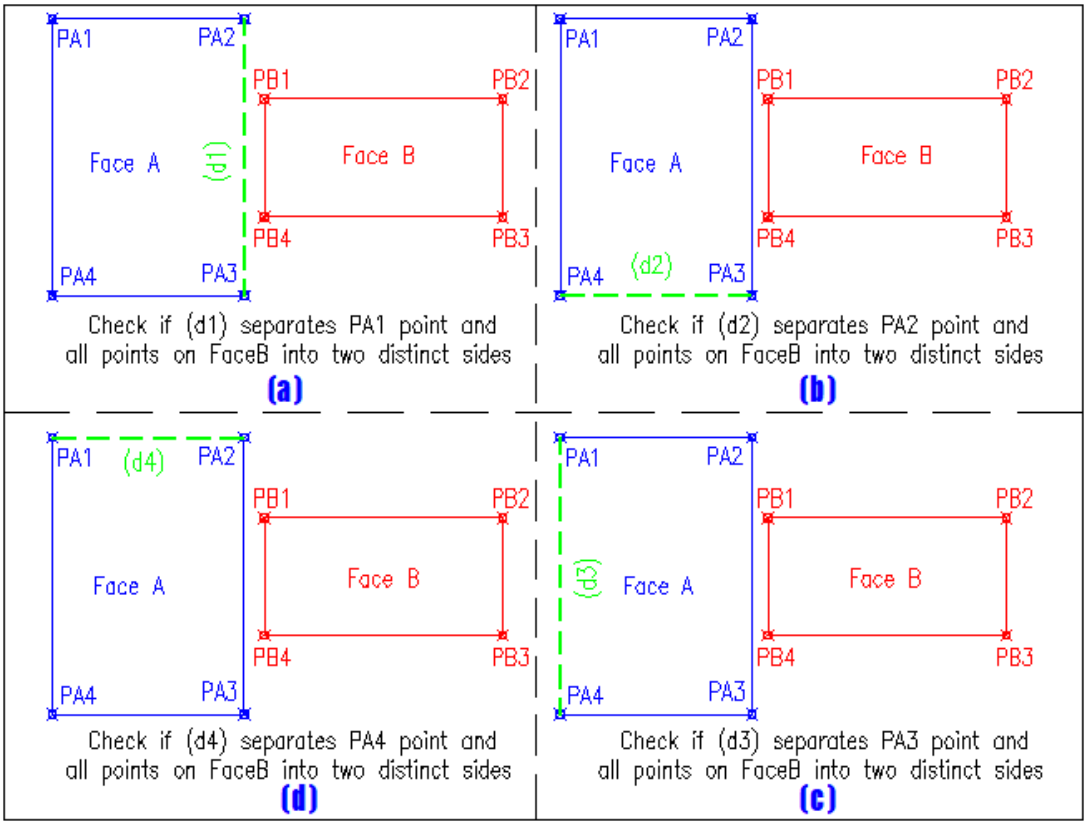


Figure 26. The flow to check whether an overlap exists between Face A and Face B.

Afterward, check whether PA3 is on the opposite side of PB1, PB2, PB3, and PB4.

$$[(xA3 - xA1)\cdot(yA2 - yA1) - (yA3 - yA1)\cdot(xA2 - xA1)]\cdot[(xB1 - xA1)\cdot(yA2 - yA1) - (yB1 - yA1)\cdot(xA2 - xA1)] < 0 \quad (8)$$

$$[(xA3 - xA1)\cdot(yA2 - yA1) - (yA3 - yA1)\cdot(xA2 - xA1)]\cdot[(xB2 - xA1)\cdot(yA2 - yA1) - (yB2 - yA1)\cdot(xA2 - xA1)] < 0 \quad (9)$$

$$[(xA3 - xA1)\cdot(yA2 - yA1) - (yA3 - yA1)\cdot(xA2 - xA1)]\cdot[(xB3 - xA1)\cdot(yA2 - yA1) - (yB3 - yA1)\cdot(xA2 - xA1)] < 0 \quad (10)$$

$$[(xA3 - xA1)\cdot(yA2 - yA1) - (yA3 - yA1)\cdot(xA2 - xA1)]\cdot[(xB4 - xA1)\cdot(yA2 - yA1) - (yB4 - yA1)\cdot(xA2 - xA1)] < 0 \quad (11)$$

If all the results from Equations (8)–(11) are all valid, Face A and Face B do not overlap. Otherwise, continue checking using lines d2, d3, and d4 as shown in Figure 26b, c, and d, respectively.

Calculating the overlap area

In order to calculate the overlap area between two faces, all the points of Face B placed inside Face A should be known first. In the first step, a center point ceP, the intersection point of two diagonal lines connecting PA1 and PA3 and PA2 and PA4, respectively, should be found (Figure 27). Assume that points have coordinates as follows, with ceP at (xA, yA):

$$xA = \frac{A}{B};\ yA = \frac{(xA - xA1)\cdot(yA3 - yA1)}{xA3 - xA1} + yA1 \quad (12)$$

where:

$$A = \frac{xA1\cdot(yA3 - yA1)}{xA3 - xA1} - yA1 - \frac{xA2\cdot(yA4 - yA2)}{xA4 - xA2} + yA2 \quad (13)$$

$$B = \frac{yA3 - yA1}{xA3 - xA1} - \frac{yA4 - yA2}{xA4 - xA2} \quad (14)$$

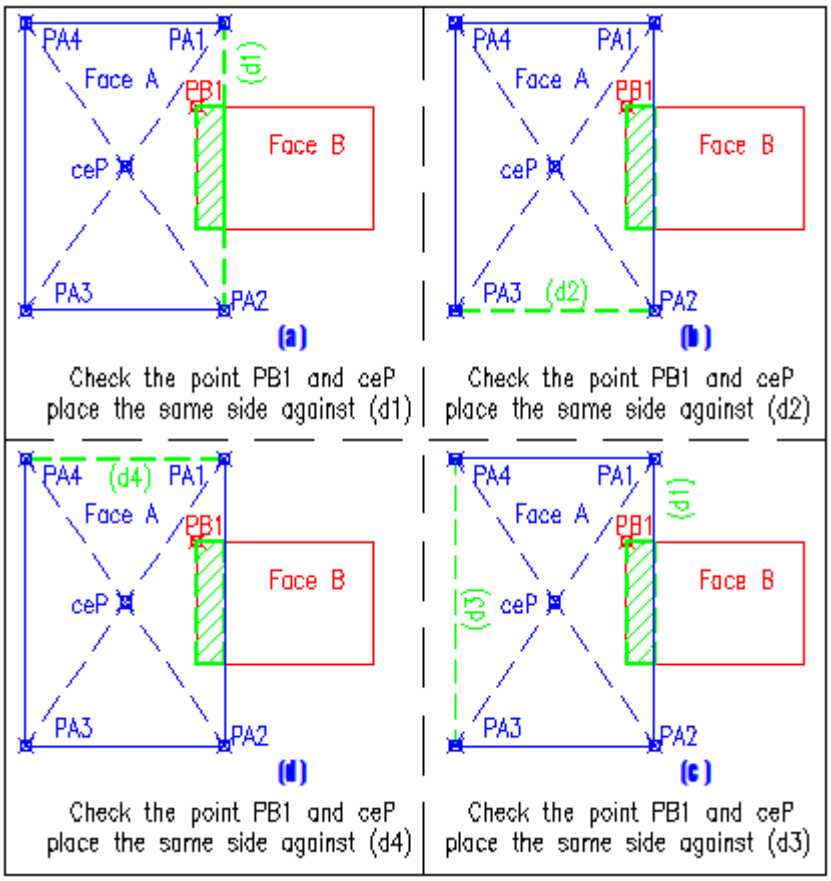


Figure 27. The flow to check if one point is inside a rectangle.

Next, each corner point of the FaceB is checked against ceP to see if it is on the same side as ceP.

$$[(xA - xA1)\cdot(yA2 - yA1) - (yA - yA1)\cdot(xA2 - xA1)]\cdot[(xB1 - xA1)\cdot(yA2 - yA1) - (yB1 - yA1)\cdot(xA2 - xA1)] \geq 0 \quad (15)$$

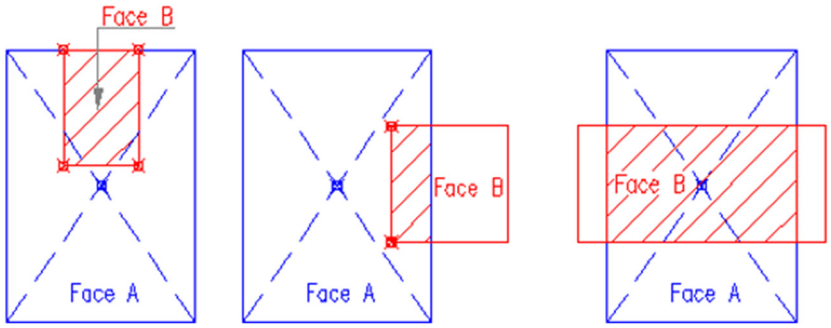
$$[(xA - xA2)\cdot(yA3 - yA2) - (yA - yA2)\cdot(xA3 - xA2)]\cdot[(xB1 - xA2)\cdot(yA3 - yA2) - (yB1 - yA2)\cdot(xA3 - xA2)] \geq 0 \quad (16)$$

$$[(xA - xA3)\cdot(yA4 - yA3) - (yA - yA3)\cdot(xA4 - xA3)]\cdot[(xB1 - xA3)\cdot(yA4 - yA3) - (yB1 - yA3)\cdot(xA4 - xA3)] \geq 0 \quad (17)$$

$$[(xA - xA4)\cdot(yA1 - yA4) - (yA - yA4)\cdot(xA1 - xA4)]\cdot[(xB1 - xA1)\cdot(yA1 - yA4) - (yB1 - yA4)\cdot(xA1 - xA4)] \geq 0 \quad (18)$$

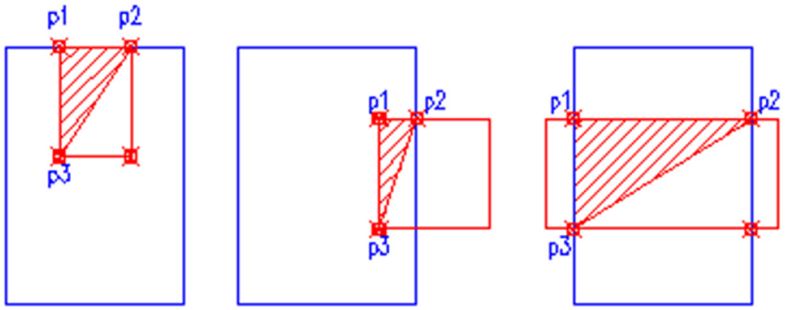
If the calculated results of Equations (15)–(18) are all true, the point PB1 is inside Face A. Similarly, apply Equations (15)–(18) to PB2, PB3, and PB4 to find all points of Face B that are inside Face A.

Figure 28 shows three possible overlap scenarios, with the number of corner points of Face B inside Face A indicated, respectively. "n" is denoted as the number of points of Face B that are inside Face A. Three scenarios n = 4, n = 2, and n = 0 are shown in Figure 29.



(**a**) n = 4 (**b**) n = 2 (**c**) n = 0

Figure 28. Calculating the number of corner points of Face B inside Face A.



(**a**) n = 4 (**b**) n = 2 (**c**) n = 0

Figure 29. Calculating overlap formwork flowchart.

In each case, the overlap area can be calculated using Heron's formula (Equation (19)).

The area of the triangle p1p2p3, in Figure 30, can be calculated using the following Heron's formula (Equation (19)):

$$S = \frac{\sqrt{(a+b+c)(a+b-c)(b+c-a)(c+a-b)}}{4} \quad (19)$$

$$\text{The overlap area} = 2 \times S = \frac{\sqrt{(a+b+c)(a+b-c)(b+c-a)(c+a-b)}}{2} \quad (20)$$

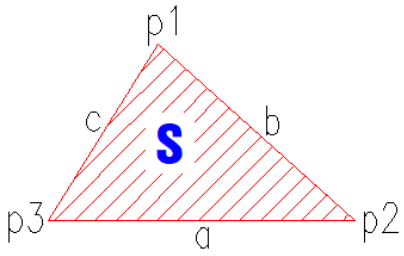


Figure 30. Calculating the area from 3 points.

3.4.3. Calculating Formwork Requirements for Each Structural Member

The way to calculate the formwork area for a slab is to sum up all the surrounding faces and a bottom face, minus the slab overlaps (Figure 31).

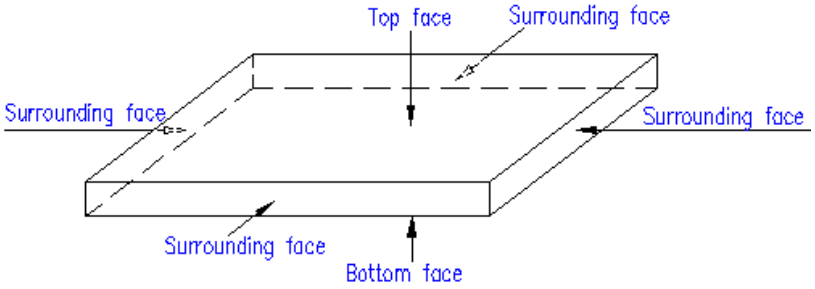


Figure 31. Calculating slab's formwork area.

The way to calculate the formwork area for a beam is to sum up all the surrounding faces and a bottom face, minus the beam overlaps (Figure 32).

$$S_{Beam} = \sum S_{Surrounding\ face} + S_{Bottom\ face} - S_{Beam\ Overlaps} \quad (21)$$

$$S_{Floor} = \sum S_{Surrounding\ face} + S_{Bottom\ face} - S_{Floor\ Overlaps} \quad (22)$$

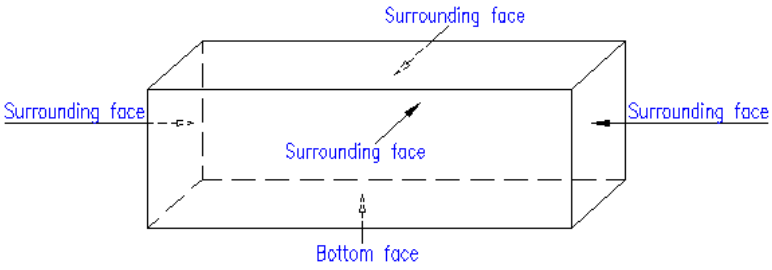


Figure 32. Calculating beam's formwork area.

For a column, the formwork area could be divided into two parts: (1) The formwork area below the beam's bottom face, $S_{ColumnUnder}$, and (2) the formwork area above the beam's bottom face, $S_{ColumnAbove}$, (Figure 33). $S_{ColumnUnder}$ would be handled first, followed by handling $S_{ColumnAbove}$ together with the beams and slab. $S_{ColumnAbove}$ is calculated by summing up all the surrounding faces and minus the slab overlap. This could be used for calculating the formwork areas for beams and slabs at the construction stage.

$$S_{ColumnAbove} = 2 \times (b_c + h_c) \times h_b - S_{ColumnOverlap} \quad (23)$$

$$S_{ColumnUnder} = 2 \times (b_c + h_c) \times H_{construction} \quad (24)$$

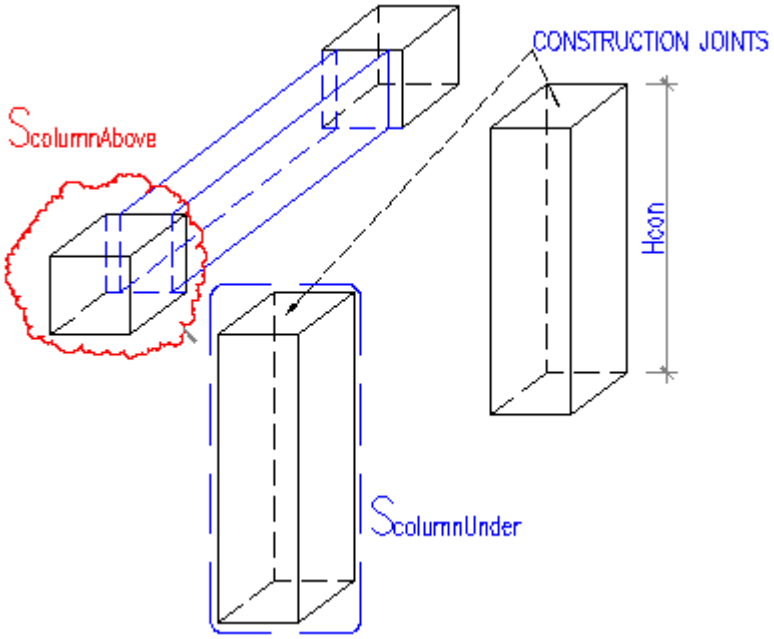


Figure 33. Calculating column's formwork area.

Afterward, concrete volumes and formwork areas are summed up and stored under a class Quantity, which contains data on the zone, level, structural member (i.e., element), concrete, and formwork (Figure 34).

```
public class Quantity
{
    //Quantity Object (concrete, formwork) theo zone, level, element, date
    public string zone;
    public string level;
    public string element;
    public DateTime date;
    public double concrete;
    public double formwork;
}
```

Figure 34. A class Quantity.

3.5. A Rule for Preparing Schedule Excel File and Calculating Daily Quantity Takeoff

3.5.1. A Rule for Preparing a Schedule Excel File

To link a BIM model to its corresponding project schedule for extraction of daily concrete and formwork requirements, an Excel file with schedule information is used to facilitate the calculation of daily quantity takeoff. Each recorded activity in the Excel file would come with the task name, duration, and start and finish times (Figure 35).

A	B	C	D	E
ID	**Task Name**	**Duration**	**Start**	**Finish**
1	**Superstructure**	**23 days**	**16/11/20**	**8/12/20**
2	Steel erection of column in zone 1 level 1	2 days	16/11/20	17/11/20
3	Formwork erection of column in zone 1 level 1	3 days	18/11/20	20/11/20
4	Pouring concrete of column in zone 1 level 1	1 day	21/11/20	21/11/20
5	Steel erection of column in zone 2 level 1	2 days	18/11/20	19/11/20
6	Formwork erection of column in zone 2 level 1	3 days	21/11/20	23/11/20

Figure 35. A screenshot of a project schedule presented in Excel.

In order to automatically calculate quantity takeoff, this paper proposes a rule naming the tasks as follows:

- It should start with "Formwork erection" if engineers are working on a formwork task, or "Pouring concrete" engineers are working on the concrete task, then
- The name of the component should be "column" or "beams and slabs". If they are working with columns, beams, and slabs, respectively, then
- The name of the zone[i] and level[j] must be specified in the task name.

After reading the schedule information from the Excel file, relevant concrete and formwork data will be extracted. At the same time, the "task_name" would be split based on zone, level, and element information (Figure 36). Afterward, all this information is used for deriving quantity takeoff from the BIM model using the class Quantity, as described in Section 3.4.3.

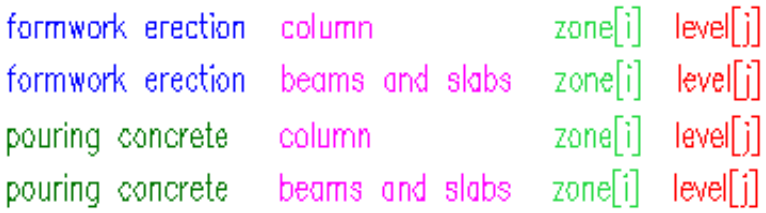


Figure 36. Parsing keywords in the "task_name" field.

In BIM software, objects such as columns, beams, and slabs can be filtered by category. Additionally, the level of information is predefined during the modeling process, enabling efficient filtering and selection. Based on this key information, data can be retrieved directly through programming.

3.5.2. Calculating Daily Quantity Takeoff

When a task's required material quantity is available, an equal allocation of daily material requirements is assumed throughout the task's duration. The amounts of daily material requirements from various tasks are summed up to obtain a grand total for the day. An example is presented in Figure 37. Assume that TASK1 requires five material units and needs five days to complete, from Day 1 (D1) to Day 5 (D5), and TASK2 requires five units within five working days, from Day 4 (D4) to Day 8 (D8). The combined daily material requirements (TASK1+2) are one unit for D1 to D3 and D6 to D8 and two units for D4 and D5.

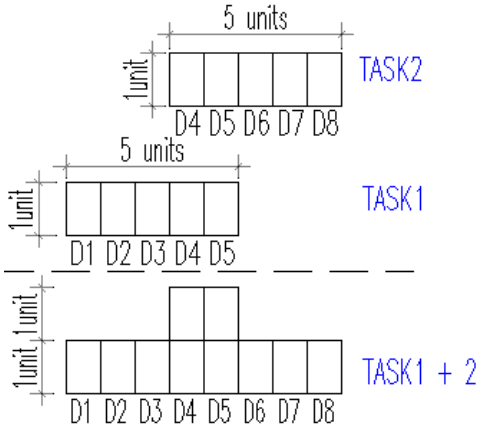


Figure 37. Combined daily material requirements.

4. Validation

A residential building project, the Him Lam Green Park project in Bac Ninh Province in Vietnam (Figure 38), was used as a case study to validate the proposed approach. This

project was selected to validate the results as it represents a common type of construction in Vietnam—adjacent and repetitive buildings—making it well-suited for zone division during the construction process. Moreover, the contractor had already implemented a zone division method for this project.



Figure 38. The resident building in the Him Lam Green Park project, Bac Ninh province, Vietnam.

The project comprises 18 identical housing units, each measuring five meters in width, 15 m in length, and spanning seven levels. The project is organized into six zones, with each zone containing three units, and each zone has 15 m both in length and width (Figure 39).

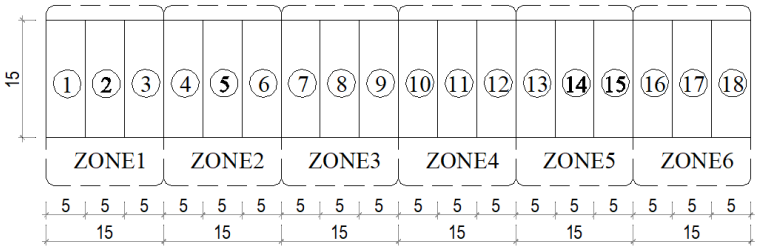


Figure 39. The layout and zones of the building project in Vietnam.

The material quantity estimation of this project was carried out based on 2D CAD drawings. Although the project included a construction schedule, it lacked a detailed plan for the daily concrete requirements. Errors in manual quantity estimation from 2D drawings frequently resulted in over-ordering or under-ordering of materials. Furthermore, inadequate planning of concreting activities and the absence of timely information on daily material needs contributed to delays in the project schedule. For instance, late ordering of concrete often caused supply delays or refusals from ready-mixed concrete (RMC) plants, which were constrained by their busy production and delivery schedules.

To address the issue of inaccurate quantity estimation and streamline the quantity takeoff process, a 3D model of the project's structural components was developed using Autodesk Revit 2019 based on the 2D drawings (Figure 40). In the 3D model, the project base

point was aligned with the model's origin, as this reference point was essential for calculating the coordinates of all zones within the model. The project schedule was organized in an Excel file, which was utilized as input for the daily material quantity takeoff process.

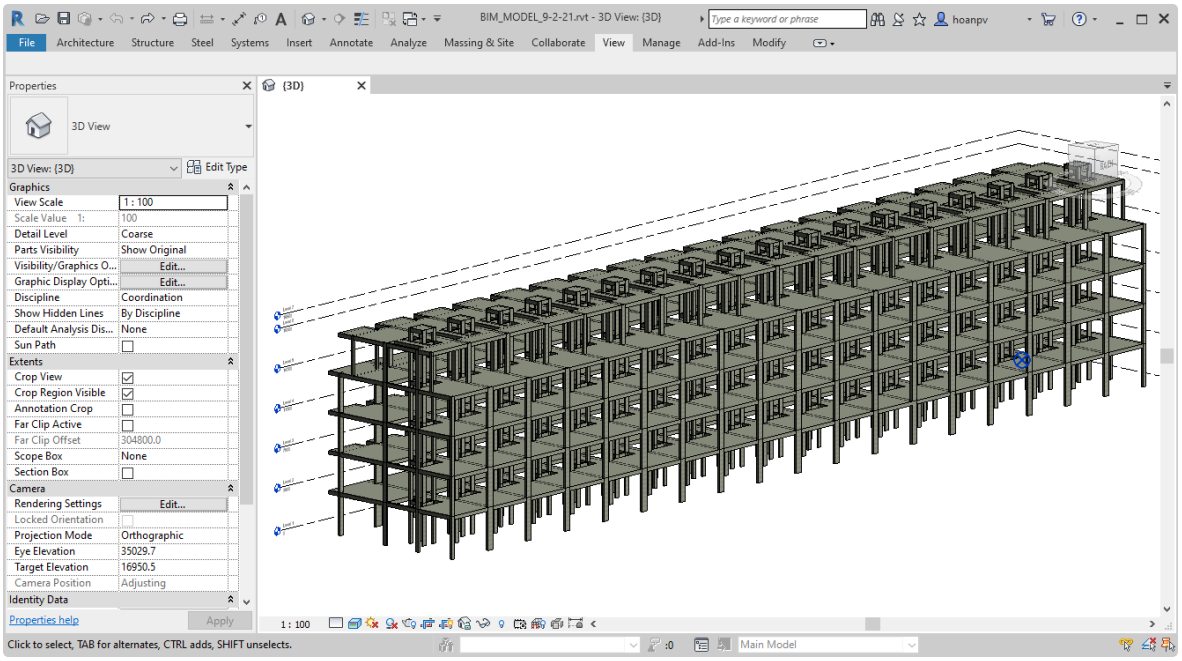


Figure 40. The 3D model of the project.

Figure 41 presents the user interface developed to facilitate user input for defining zones. Since the project was divided into six zones, each with dimensions of 15 m in both the X and Y directions, the same zoning configuration was implemented in the 3D model. To define these zones, the interface prompted users to input the zoning dimensions along the X and Y directions, as well as the minimum and maximum heights along the Z direction.

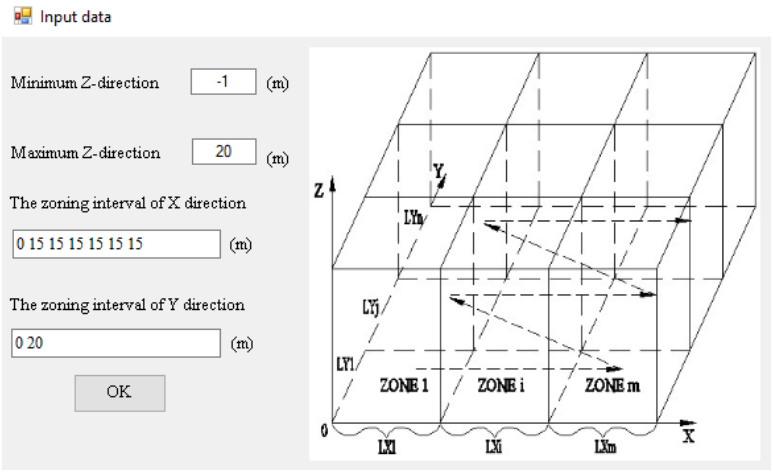


Figure 41. The user interface for defining zones.

To create a project schedule, Microsoft Project software is used. After setting a project start date, all the tasks of the project will be filled in the "Task Name" field. Combined with the task consequence, Microsoft Project will calculate the Start date and Finish date for every task logically (Figure 42). In the next step, the data in the "Task Name", "Duration", "Start", and "Finish" fields are exported to an Excel file to facilitate the calculation of daily quantity takeoff (Figure 43).

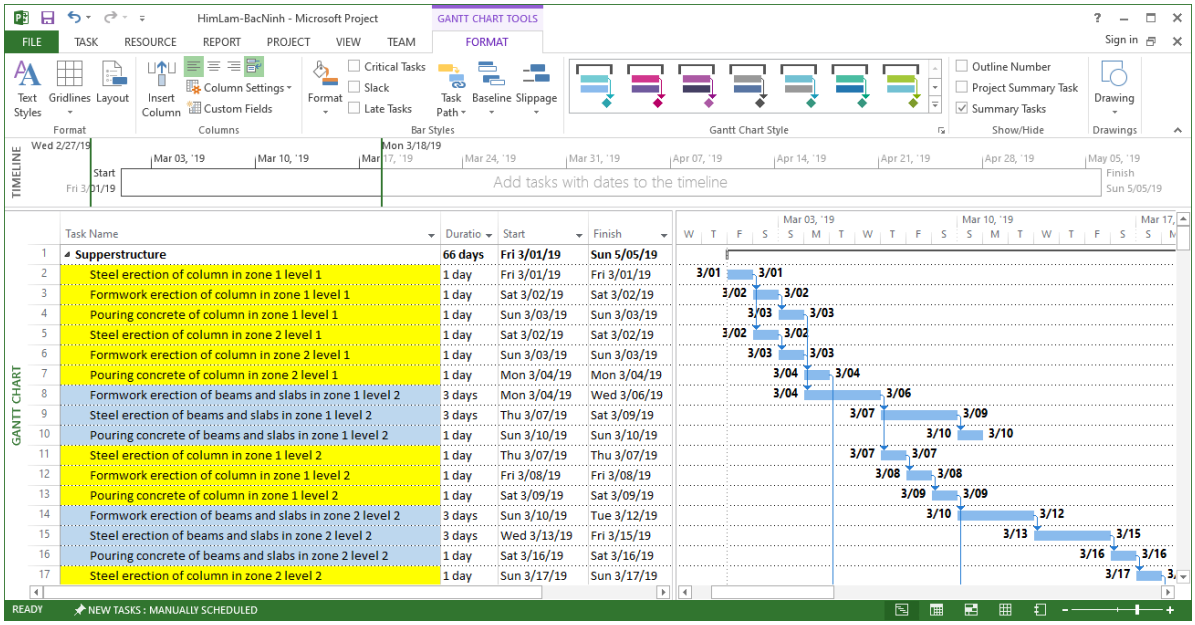


Figure 42. Project schedule in Microsoft Project 2013 software.

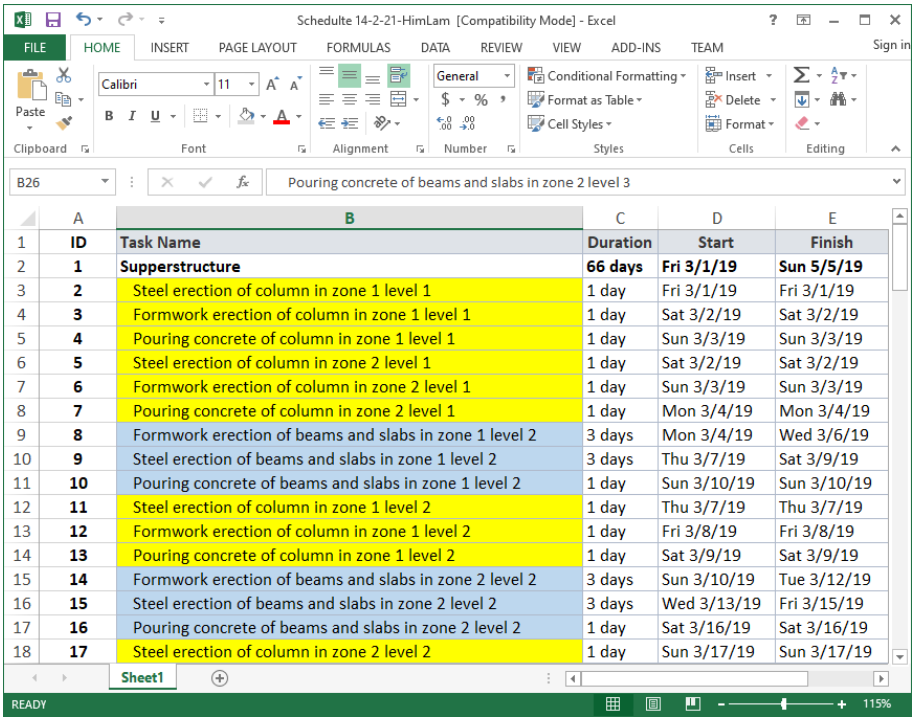
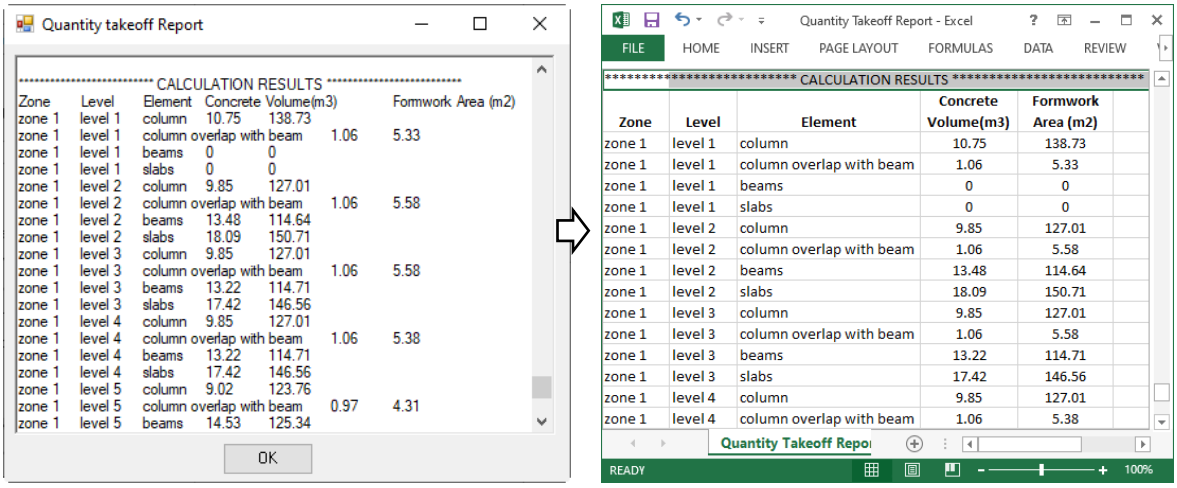


Figure 43. Excel file's project schedule.

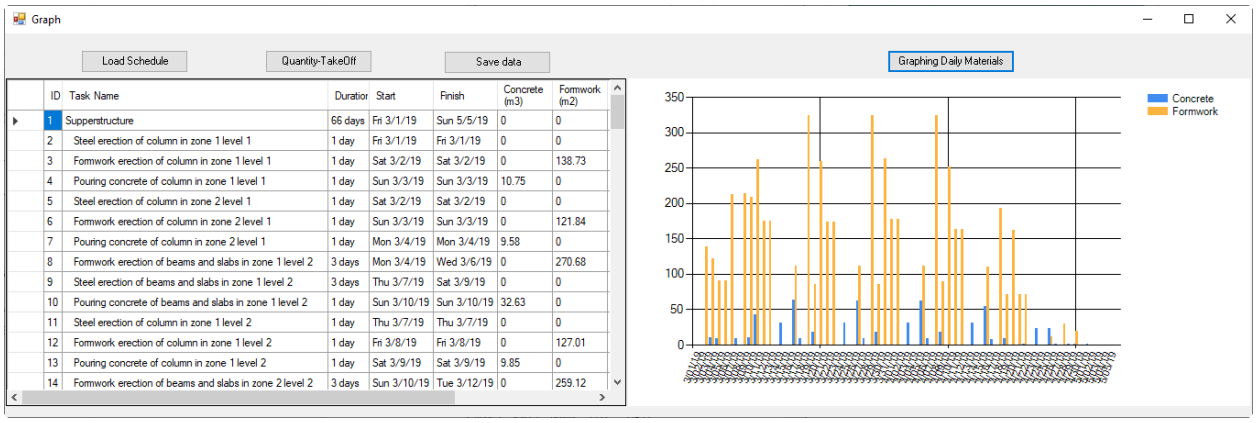
Figure 44a shows the quantity takeoff results on the screen, and Figure 44b presents the quantity takeoff results in the spreadsheet.



(**a**) The on-screen output (**b**) The spreadsheet output

Figure 44. The on-screen and spreadsheet outputs of the advanced quantity takeoff.

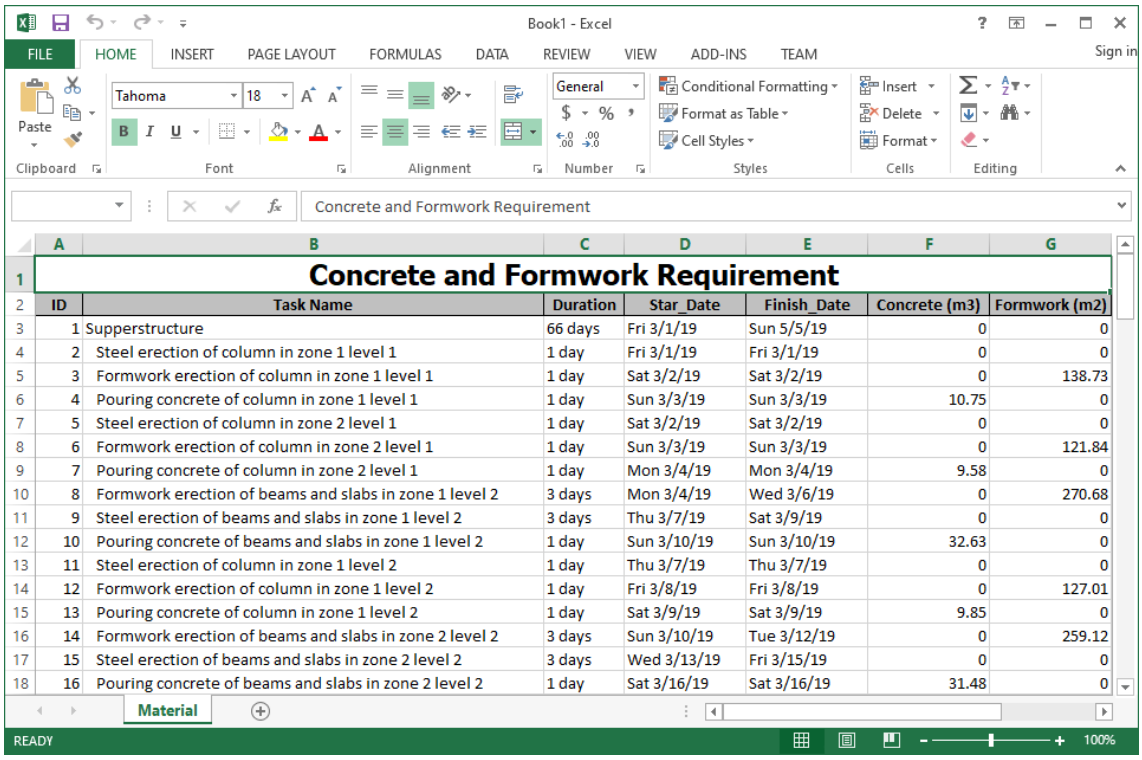
The generated quantity takeoff data would then be used to calculate daily material quantity requirements (Figure 45a), which would be presented in a bar chart (Figure 45b). The horizontal axis of the bar chart shows the dates, and the vertical axis of the bar chart indicates the quantity required.



(**a**) Concrete volume and formwork area requirement (**b**) Volume chart by day

Figure 45. Concrete volume and formwork area requirement schedule and volume chart by day.

The bar chart can help the user notice peak material requirements and facilitate early material arrangements. Furthermore, to mitigate potential delays in material delivery, the schedule can be shared with material providers. The developed tool in this research can generate a spreadsheet containing detailed material requirement information, such as dates, locations, and volumes of concrete and formwork requirements (Figure 46), and is expected to enhance project management through timely material management and reduction of unnecessary material waste and time delay.



	A	B	C	D	E	F	G
1	Concrete and Formwork Requirement						
2	ID	Task Name	Duration	Star_Date	Finish_Date	Concrete (m3)	Formwork (m2)
3	1	Supperstructure	66 days	Fri 3/1/19	Sun 5/5/19	0	0
4	2	Steel erection of column in zone 1 level 1	1 day	Fri 3/1/19	Fri 3/1/19	0	0
5	3	Formwork erection of column in zone 1 level 1	1 day	Sat 3/2/19	Sat 3/2/19	0	138.73
6	4	Pouring concrete of column in zone 1 level 1	1 day	Sun 3/3/19	Sun 3/3/19	10.75	0
7	5	Steel erection of column in zone 2 level 1	1 day	Sat 3/2/19	Sat 3/2/19	0	0
8	6	Formwork erection of column in zone 2 level 1	1 day	Sun 3/3/19	Sun 3/3/19	0	121.84
9	7	Pouring concrete of column in zone 2 level 1	1 day	Mon 3/4/19	Mon 3/4/19	9.58	0
10	8	Formwork erection of beams and slabs in zone 1 level 2	3 days	Mon 3/4/19	Wed 3/6/19	0	270.68
11	9	Steel erection of beams and slabs in zone 1 level 2	3 days	Thu 3/7/19	Sat 3/9/19	0	0
12	10	Pouring concrete of beams and slabs in zone 1 level 2	1 day	Sun 3/10/19	Sun 3/10/19	32.63	0
13	11	Steel erection of column in zone 1 level 2	1 day	Thu 3/7/19	Thu 3/7/19	0	0
14	12	Formwork erection of column in zone 1 level 2	1 day	Fri 3/8/19	Fri 3/8/19	0	127.01
15	13	Pouring concrete of column in zone 1 level 2	1 day	Sat 3/9/19	Sat 3/9/19	9.85	0
16	14	Formwork erection of beams and slabs in zone 2 level 2	3 days	Sun 3/10/19	Tue 3/12/19	0	259.12
17	15	Steel erection of beams and slabs in zone 2 level 2	3 days	Wed 3/13/19	Fri 3/15/19	0	0
18	16	Pouring concrete of beams and slabs in zone 2 level 2	1 day	Sat 3/16/19	Sat 3/16/19	31.48	0

Figure 46. The spreadsheet output of the tool containing the daily concrete requirement.

5. Discussion

In this research, it was assumed that the boundary of a zone is rectangular, and zones propagate in one direction. Also, rectangular cross-sections of structural members were assumed, which reflected the most common cases in practice. Through the presented example, it can be seen that the proposed method and developed tool in this research are of practical value and could facilitate the handling of concrete and formwork quantity takeoff in an efficient and effective way. Besides developing a Revit API tool, the framework and its algorithm could be applied to build a new add-in for other BIM software. This study focuses on the estimation of the superstructure; therefore, grade beams and slabs-on-grade are not considered. In Vietnam and some other Asian countries, it is common to see walls built with bricks, which is not within the scope of this study. Currently, the governments of ASEAN countries are in the process of mandating the implementation of Building Information Modeling (BIM). As a result, companies have established specialized BIM departments, making the application of the BIM tools developed in this paper relatively straightforward and cost-effective. While the reuse of formwork should be considered in materials planning, calculating daily formwork requirements is a fundamental initial step. The optimization of formworks based on the construction schedule will be explored in future research. Also, addressing assumptions related to the boundary of a zone and the characteristics of a rectangular cross-section could be explored in future work.

6. Conclusions

Quantity takeoff is an important aspect of construction project management. Depending on the purpose of the QTO, there are different quantifying approaches used. For example, when it comes to QTO for bidding, general contractors use semi-automated QTO (using CAD and PDFs). For planning purposes, leveraging BIM data are appropriate because it relates to only one entity, which is a contractor. Besides, applying BIM-based quantity takeoff provides accurate data for contractors and saves time. In this research, a BIM-based quantity takeoff framework is presented to calculate zone-based daily quantity requirements for concrete and formworks. A systematic approach was proposed to inte-

grate with BIM for the quantity takeoff of concrete and formwork requirements. The new algorithm developed by the authors to calculate the overlap area between concrete items is applied in Sections 3.3 and 3.4. In addition, this research developed a Revit API tool for zone-based quantity takeoff for building projects.

A building project in Vietnam was utilized to validate the proposed approach and developed tool. Results showed that zone-based quantity takeoff can be quickly and accurately executed to produce daily concrete and formwork requirements. Though the proposed approach is restricted to beams and columns of rectangular cross-sections at this moment, it lays a good foundation for future research on similar tracks.

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References

1. Vipin, V.P.; Rahima Shabeen, S. Factors Affecting Material Management in Construction Industry. *Int. J. Recent Technol. Eng.* **2019**, *8*, 4845–8448. [CrossRef]
2. Ko, C.-H.; Wang, W.-C.; Kuo, J.-D. Improving Formwork Engineering Using the Toyota Way. *J. Eng. Proj. Prod. Manag.* **2011**, *1*, 13–27. [CrossRef]
3. Tserng, H.P.; Yin, S.Y.L.; Li, S. Developing a Resource Supply Chain Planning System for Construction Projects. *J. Constr. Eng. Manag.* **2006**, *132*, 393–407. [CrossRef]
4. Kazaz, A.; Ulubeyli, S.; Er, B.; Arslan, V.; Arslan, A.; Atici, M. Fresh Ready-mixed Concrete Waste in Construction Projects: A Planning Approach. *Procedia Eng.* **2015**, *123*, 268–275. [CrossRef]
5. Monteiro, A.; Poças Martins, J. A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Autom. Constr.* **2013**, *35*, 238–253. [CrossRef]
6. Sacks, R.; Eastman, C.; Lee, G.; Teicholz, P. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*, 3rd ed.; Wiley: Hoboken, NJ, USA, 2018. Available online: https://www.wiley.com/en-us/BIM+Handbook:+A+Guide+to+Building+Information+Modeling+for+Owners,+Designers,+Engineers,+Contractors,+and+Facility+Managers,+3rd+Edition-p-9781119287537 (accessed on 21 December 2020).
7. Heigermoser, D.; García de Soto, B.; Abbott, E.L.S.; Chua, D.K.H. BIM-based Last Planner System tool for improving construction project management. *Autom. Constr.* **2019**, *104*, 246–254. [CrossRef]
8. Sattineni, A.; Bradford, R.H. Estimating with BIM: A Survey of US Construction Companies. In Proceedings of the 28th ISARC, Seoul, Republic of Korea, 29 June–2 July 2011.
9. Olsen, D.; Taylor, J.M. Quantity Take-Off Using Building Information Modeling (BIM), and Its Limiting Factors. *Procedia Eng.* **2017**, *196*, 1098–1105. [CrossRef]
10. Khosakitchalert, C.; Yabuki, N.; Fukuda, T. Automatic concrete formwork quantity takeoff using building information modeling. In Proceedings of the 19th International Conference on Construction Applications of Virtual Reality, Bangkok, Thailand, 13–15 November 2019.
11. Cepni, Y.; Akcamete, A.; Klein, R. Automated bim-based formwork quantity take-off. In Proceedings of the 20th International Conference on Construction Applications of Virtual Reality, Middlesbrough, UK, 30 September–2 October 2020.
12. Alathamneh, S.; Collins, W.; Azhar, S. BIM-based quantity takeoff: Current state and future opportunities. *Autom. Constr.* **2024**, *165*, 105549. [CrossRef]
13. Lou, B.; Barbieri, D.M.; Bohne, R.A. BIM-Based Life Cycle Assessment to Quantify Carbon Dioxide Emissions During Road Construction. In Proceedings of the 5th International Conference on Transportation Geotechnics (ICTG), Sydney, Australia, 20–22 November 2024; Rujikiatkamjorn, C., Xue, J., Indraratna, B., Eds.; Springer: Singapore, 2025; Volume 7, pp. 403–412.
14. Wang, Z.; Jia, L.; Lv, J.; Huang, J. Minimization of Rebar Cutting Waste Using BIM and Cutting Pattern-Oriented Multiobjective Optimization. *J. Constr. Eng. Manag.* **2024**, *150*, 04024166. [CrossRef]
15. Le HT, T.; Cong, T.D. BIM-integrated system: A successful alternative for estimating cash flow in building projects. *ASEAN Eng. J.* **2023**, *13*, 103–112. [CrossRef]
16. Nguyen, T.-Q.; Lou, E.C.W.; Nguyen, B.N. A theoretical BIM-based framework for quantity take-off to facilitate progress payments: The case of high-rise building projects in Vietnam. *Int. J. Build. Pathol. Adapt.* **2024**, *42*, 704–728. [CrossRef]

17. Ren, S.; Qiang, G.; Tang, S.; Zhang, C.; Seo, H.-J.; Wu, K. An automatic design-feedback process for structural prefabricated components quantity take-off calculation using BIM. *Archit. Eng. Des. Manag.* **2024**, *20*, 287–302. [CrossRef]
18. Soon, L.T.; Ng, Z.X.; Kamarazaly, M.A.; Kam, K.J. The Analysis of BIM Based Measurement for the Quantity Surveying Profession. *J. Eng. Sci. Technol.* **2023**, 34–35. Available online: https://jestec.taylors.edu.my/Special%20Issue%20THINK%20SPACE%202022/STAAUH%202022_04.pdf (accessed on 2 December 2024).
19. Pham, V.-H.; Chen, P.-H.; Pal, A.; Christian. Automatic Extraction of Daily Concrete Requirements from 3D BIM and Project Schedules. *AIP Conf. Proc.* **2021**, *2428*, 020009.
20. Liu, H.; Lu, M.; Al-Hussein, M. Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. *Adv. Eng. Inform.* **2016**, *30*, 190–207. [CrossRef]
21. Fırat, C.E.; Arditi, D.; Hamalainen, J.; Stenstrand, J.; Kiras, J. Quantity Take-Off in Model-Based Systems. 2010. Available online: https://itc.scix.net/pdfs/w78-2010-112.pdf (accessed on 21 December 2020).
22. Jadid, M.N.; Idrees, M.M. Cost estimation of structural skeleton using an interactive automation algorithm: A conceptual approach. *Autom. Constr.* **2007**, *16*, 797–805. [CrossRef]
23. Manrique, J.D.; Al-Hussein, M.; Bouferguene, A.; Nasseri, R. Automated generation of shop drawings in residential construction. *Autom. Constr.* **2015**, *55*, 15–24. [CrossRef]
24. Lee, D.; Lim, H.; Kim, T.; Cho, H.; Kang, K.-I. Advanced planning model of formwork layout for productivity improvement in high-rise building construction. *Autom. Constr.* **2018**, *85*, 232–240. [CrossRef]
25. Tamrin, A.G.; Sucipto, T.L.A.; Noviansyah, W.; Sukatiman; Rahmawati, A.; Mar'atussoleha, M. Investigating the benefit and challenges of implementing BIM-based quantity take-off in a grand mosque project. *AIP Conf. Proc.* **2024**, *3145*, 020007. [CrossRef]
26. Wardito, E.; Husin, A.E. Increasing the value of jetty projects based on building information modelling 5D (BIM 5D). *AIP Conf. Proc.* **2024**, *2710*, 090010. [CrossRef]
27. Soon, L.T.; Wong, L.S.; Kamarazaly, M.A.; Saar, C.C.; Ilmi, H.S. Comparison of bim-based quantities take-off in quantity surveying profession. *Plan. Malays.* **2024**, *22*. [CrossRef]
28. Wahab, A.; Wang, J. Factors-driven comparison between BIM-based and traditional 2D quantity takeoff in construction cost estimation. *Eng. Constr. Archit. Manag.* **2022**, *29*, 702–715. [CrossRef]
29. Shick Alshabab, M.; Vysotskiy, A.; Petrichenko, M.; Khalil, T. BIM-Based Quantity Takeoff in Autodesk Revit and Navisworks Manage. In Proceedings of the EECE 2019, St. Petersburg, Russia, 19–20 November 2019; Anatolijs, B., Nikolai, V., Vitalii, S., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 413–421.
30. Saputra, H.; Pratama, R.; Tita, E.E.; Yusa, M. Comparative Analysis of Quantity Take-Off Material Between Conventional Method & BIM Nemetschek Allplan Method on Bridge. *Architecture* **2024**, *12*, 2622–2633. [CrossRef]
31. Yang, F.; Zhang, J.; Wong Chong, O.; Sexton, C. Introducing Computing to Construction Management Undergraduate Students through Automated Quantity Takeoff from IFC-Based BIM. In Proceedings of the ASCE International Conference on Computing in Civil Engineering, Pennsylvania, PA, USA, 28–31 July 2024; pp. 630–638.
32. Ergen, F.; Bettemir, Ö.H. Development of ontological algorithms for exact QTO of reinforced concrete construction items. *Structures* **2024**, *60*, 105907. [CrossRef]
33. Liu, H.; Cheng, J.C.P.; Gan, V.J.L.; Zhou, S. A novel Data-Driven framework based on BIM and knowledge graph for automatic model auditing and Quantity Take-off. *Adv. Eng. Inform.* **2022**, *54*, 101757. [CrossRef]
34. Jamal, K.A.A.; Ee, C.S.; Khiyon, N.A.; Wahab, N.A.A. Scan-to-BIM Approach Towards Producing Quantity Take-Off of Heritage Buildings in Malaysia. *J. Eng. Sci. Technol.* **2021**, *17*, 120–137.
35. Bademosi Fopefoluwa, M.; Tayeh Ralph Issa Raja, R.A. An Immersive Approach to Construction Cost Estimating. In Proceedings of the ASCE International Conference on Computing in Civil Engineering 2019, Atlanta, GA, USA, 17–19 June 2019; pp. 48–54.
36. Valinejadshoubi, M.; Moselhi, O.; Iordanova, I.; Valdivieso, F.; Bagchi, A. Automated system for high-accuracy quantity takeoff using BIM. *Autom. Constr.* **2024**, *157*, 105155. [CrossRef]
37. Bečvarovská, R.; Matějka, P. Comparative analysis of creating traditional quantity takeoff method and using a bim tool. In Proceedings of the Construction Maeconomics Conference, Prague, Czech Republic, 7 November 2024.
38. Sheikhkhoshkar, M.; Rahimian, F.P.; Kaveh, M.H.; Hosseini, M.R.; Edwards, D.J. Automated planning of concrete joint layouts with 4D-BIM. *Autom. Constr.* **2019**, *107*, 102943. [CrossRef]
39. Kim, H.; Anderson, K.; Lee, S.; Hildreth, J. Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Autom. Constr.* **2013**, *35*, 285–295. [CrossRef]
40. Kannan, R.; Santhi, H. Automated Construction Layout and Simulation of Concrete Formwork Systems Using Building Information Modeling. In Proceedings of the 4th International Conference of EACEF (European Asian Civil Engineering Forum), Singapore, 26–28 June 2013. [CrossRef]
41. Wei, H.; Zheng, S.; Zhao, L.; Huang, R. BIM-based method calculation of auxiliary materials required in housing construction. *Autom. Constr.* **2017**, *78*, 62–82. [CrossRef]
42. Singh, M.; Sawhney, A.; Sharma, V. Utilising Building Component Data from BIM for Formwork Planning. *Constr. Econ. Build.* **2017**, *17*, 20. [CrossRef]
43. Hanna, A.S.; Willenbrock, J.H.; Sanvido, V.E. Knowledge Acquisition and Development for Formwork Selection System. *J. Constr. Eng. Manag.* **1992**, *118*, 179–198. [CrossRef]

44. Hyun, C.; Jin, C.; Shen, Z.; Kim, H. Automated optimization of formwork design through spatial analysis in building information modeling. *Autom. Constr.* **2018**, *95*, 193–205. [CrossRef]
45. Lee, B.; Choi, H.; Min, B.; Ryu, J.; Lee, D.-E. Development of formwork automation design software for improving construction productivity. *Autom. Constr.* **2021**, *126*, 103680. [CrossRef]
46. Mansuri, D.; Chakraborty, D.; Elzarka, H.; Deshpande, A.; Gronseth, T. Building Information Modeling enabled Cascading Formwork Management Tool. *Autom. Constr.* **2017**, *83*, 259–272. [CrossRef]
47. Mei, Z.; Xu, M.; Wu, P.; Luo, S.; Wang, J.; Tan, Y. BIM-Based Framework for Formwork Planning Considering Potential Reuse. *J. Manag. Eng.* **2022**, *38*, 04021090. [CrossRef]
48. Cho, J.; Chun, J. Cost Estimating Methods for RC Structures by Quantity Takeoff and Quantity Prediction in the Design Development Stage. *J. Asian Archit. Build. Eng.* **2015**, *14*, 65–72. [CrossRef]
49. Bajpai, A.R. Zone-based Manufacturing. Master's Thesis, The University of Tennessee, Knoxville, TN, USA, 2020.
50. Wu, K.; García De Soto, B.; Adey, B.T.; Zhang, F. BIM-based estimation of vertical transportation demands during the construction of high-rise buildings. *Autom. Constr.* **2020**, *110*, 102985. [CrossRef]
51. Bruce, K.B. *Foundations of Object-Oriented Languages*; The MIT Press: Cambridge, MA, USA, 2002. Available online: https://mitpress.mit.edu/books/foundations-object-oriented-languages (accessed on 24 January 2021).
52. CCAA Offices. *Joints in Concrete Buildings*; CCAA Offices: Mascot, NSW, Australia, 2004.
53. Halvorsen, G.T.; Poston, R.W.; David, W.F.; Harry, M.P.; Keith, A.P.; Will, H.; Andrew, S.; Tony, C.L.; Lewis, H.T.; Edward, G.N.; et al. *Joints in Concrete Construction (ACI 224.3R-95)*; American Concrete Institute: Farmington Hills, MI, USA, 2001.

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