An Automated BIM-based System for Generating Shop Drawings and Material Takeoffs: A Case Study of Ceiling Work

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Abstract

During the construction phase, the detail shop drawing and material takeoff are required for supporting construction operations. These processes are labor intensive and take longer time. Recently, the implementation of Building Information Modeling (BIM) technology is an approach that can be used to assist in shop drawing and accurate material takeoff. However, the traditional method of using two-dimensional drawings is still extensively applied to various current practices, which is time-consuming and error prone. Furthermore, previous BIM technology was limited to performing material takeoff for building elements consisting of multiple material layers. This paper proposes a BIM-based automated system for generating detailed shop drawings and material quantities. This research focuses on developing systems for ceiling work. To develop the system, the design algorithm for the ceiling frame and fixed light system is formalized according to the provided construction layout plan. Then, the concept of BIM-based clash detection is applied to automatically detect the overlap between the fixed light system and ceiling frame. A prototype system is being developed in BIM technology that is integrated with Dynamo. An apartment room ceiling layout is utilized to determine the feasibility and effectiveness of the proposed system. The result indicates that the proposed system can automatically generate clear shop drawings in accordance with the designed standard, which provides more accurate material takeoff for C-line and gypsum board in the ceiling system. Moreover, the system will assist engineers in resolving purchase order conflicts during the construction stage as it can automatically generate the quantity of materials based on standard material product sizes.

Keywords: Building Information Modeling, shop drawing, material takeoff, clash detection, ceiling system

1. Background of the research

Quantity take-off is fundamental to ensuring that the entire construction process runs smoothly and efficiently. The quantity take-off is the first intentional endeavor to estimate the cost of a project and is important during the construction project's initial decision-making [1]. This estimate frequently serves as the benchmark from which subsequent estimating stages deviate. Besides that, if the quantity take-off is not done appropriately, the estimations in each construction stage will deteriorate, affecting the project's duration, cost escalation, claims, and amendments [2]. Insufficient material takeoff on material quantities for purchase orders is the root cause of inefficient material management on construction sites [3]. Moreover, the material quantity has a substantial impact on the project's total cost [4]. Shop drawing, on the other hand, is an essential component of the construction process as it provides detailed information on the materials, quantities, and specifications required for the construction project [5]. Shop drawings have a real impact on the cost estimation process at an early stage and improve the accuracy of material quantification during constructability, which may lead to a decrease in the final cost of the project [6].

An efficient method for improving the detail of the material takeoff and shop drawing during the construction process must be implemented. Many technologies have been applied for material takeoff, the most commonly used being 2D-CAD, PlanSwift, Onscreen Takeoff, Bluebeam, and Timberline [7]. These techniques rely on 2D drawings, which leads to inefficiency for quantity takeoff. However, building information technology (BIM) is the newest technology and trend in the ACE industry, which is a high-efficiency tool and demands information integration. This technology is one of the most useful tasks that can be automatically implemented for the quantity takeoff [8]. It has the potential to access virtual building models throughout the construction process to perform quantity takeoff [9]. With the implementation of BIM-based quantity takeoff, there is a significant opportunity to substantially improve the efficiency and accuracy of cost estimation [10]. Because the initial estimate does not consider the quantity of material in the work element, which contains multiple layers (like walls, which consist of core structure layers and finish layers), separate measurements are required to get the exact quantities for purchase orders during the construction stage [11]. In addition, BIM technology can execute clash detection to enhance the multilayered structure's quantity takeoff accuracy [12]. For example, BIM can be used to visualize and identify the clash of the elements, then automatically deduct or modify the overlapped areas to extract the accurate material quantity [13]. Furthermore, a BIM-based approach for material takeoff has emerged as an effective method not only for accurately quantifying materials but also for quickly automating the generation of shop drawings [14].

The importance of material takeoff and shop drawing in construction cannot be overstated. These processes are crucial for improving the efficiency of construction performance and addressing issues related to material quantities. To achieve this, it is essential to use effective methods and appropriate technology. Therefore, the focus of this research is on improving shop drawing and material takeoff processes by leveraging BIM technology. This technology will support the identification of constructability issues and ensure clash detection. By doing so, this research aims to enhance the construction process by reducing material waste, improving accuracy, and increasing overall efficiency.

2. Research problems

Despite its immense significance, material takeoff has not been explicitly researched. The transition from conventional material quantity takeoff to newer methods has been slow due to the risks involved with the adoption of new technology. Material takeoff adopting BIM has been researched limited. Moreover, less research has been focused on material takeoff in the works of elements with multiple layers.

The utilization of conventional quantity takeoff is a major cause of material procurement issues. But this method is still extensively used in most construction projects because adopting new technology is always a risky investment of time and money [15]. The traditional approach is done by working on two-dimensional drawings, which is time-consuming and error-prone due to human interpretation [13]. The conventional method is practically based on CAD drawings, which are carried out on scanned drawings and manually interpreted to calculate quantities that are required for cost estimating and cost planning, the production of bills of quantities, contractual claims, and construction cost evaluation [16]. It has been identified that employing the traditional method makes it difficult to identify clashes, errors, omissions, intersection points between multiple elements, and cascading problems [8]. These drawbacks have a significant impact on determining the material quantities to be purchased as well as the need for construction work. Moreover, conventional quantity takeoff generates a large amount of waste during the construction phase since it should be performed every time the design is revised or when quantities need to be estimated at different levels of detail [17]. Therefore, the quantity of material taken off using this approach through the 2D drawing is inaccurate and ambiguous [10].

There is a limitation on separating the material quantity of the work elements that contain multiple material layers, such as architectural work (ceilings, floor tiles, walls, and roofs). For example, ceiling work is one of the elements that contains multiple material layers, like gypsum board and c-line. To proceed with the purchase order, the quantity of these materials needs to be determined separately. However, the previous research has focused on BIM-based material quantity takeoff for one layer of material in the work element. A prototype system to automatically generate and optimize floor tile layouts using BIM and parametric design (PD) techniques has been developed [18]. The system could reduce material waste by 3.43%–5.50%, improve the accuracy of the estimation of the number of tiles required, and provide a shop drawing on how to cut tiles. However, this approach was unable to determine tile quantities in different sizes, as well as quantities of other material layers such as tile mortar. With the adoption of ArchiCAD (BIM) and Grasshopper (PD platform), the improvement of tile layout is conducted, as it can result in a reduction in tile waste rate of 14.58%, improved calculation efficiency, and reduced computation time compared to the automatically developed system previously [19]. But the system was specific to determining the quantity of just tiles and no other material type, such as mortar quantity.

Another research has found that the accurate shop drawing generated by the system of the BIM model's integration with FRAMEX can acquire final takeoffs and cutting lists while minimizing material waste, but the developed system is not fully automated, and the generated shop drawing is limited to wooden framing [20]. Moreover, by utilizing a method of BIM-based clash detection, the accuracy of the material quantity for wall framings was significantly improved, and it was effective for purchase orders during the construction phase [21]. The study used wall framing spacing values to calculate the positions and lengths of the vertical and horizontal wall framing members, and the result was more accurate than the detailed BIM model and manual method, but their system cannot separate the quantity of material contained in the works of elements with multiple layers. Thus, it is critical that the material quantity be precisely calculated for the requirements of construction activities in order to avoid inadequate purchasing [22].

Material takeoff is indispensable in improving the efficiency of the material order, and there is a need for a better method. Therefore, this research aims at proposing a design system to automatically calculate the precise material quantity by adopting BIM technology. The system will assist the contractors in resolving the conflict of material takeoffs for the purchase order during the construction stage, as the system can automatically generate the quantity of multiple materials by reducing the waste of material and decreasing the time required.

3. Research methodology

The research methodology consists of conceptual design, data collection, and a framework for system development. The details of each section are discussed as follows:

3.1 Conceptual design of system

The concept of BIM-based material takeoff can be classified into two categories: specific material takeoff and multiple material takeoff. Specific material takeoff uses generative design to determine one specific quantity of material, while multiple material takeoff quantifies the material quantity of building elements with different layers of material using visual programming and clash detection. The system automatically generates shop drawings and material quantities for each layer. This research focuses on architectural elements that have multiple layers of materials and uses BIM-based multiple material takeoff, aided by BIM clash detection, to prevent overlapping elements during construction.

3.2 Data collection

To develop a comprehensive system for automatically determining the quantity of materials and generating clear shop drawings, it is necessary to collect relevant data prior to initiating the system development process. The collected data should be based on the specific types of building elements and materials that will be used in the project. This research is primarily focused on developing a ceiling system to test the proposed system.

The development of the ceiling design requires the collection of both external and internal data. Internal data refers to information gathered from the architectural model in Autodesk Revit, such as the layout plan and lighting system layout. On the other hand, external data includes information obtained from the designs and suppliers. The design data, which is a subset of external data, includes the design specifications of the elements and material design specifications. The supplier data, moreover, includes material specifications and installation instructions. Fig. 1 depicts a set of data collection for system development, and Table 1 shows the material specification from a selected supplier.

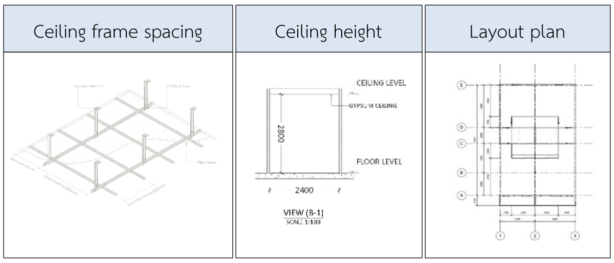

Fig. 1 A set of data collection

Table 1 Material specification from selected supplier

Item	Description	Picture	Supplier
C-line	36x12x4000mm 1.5mm thickness		SCG
L-bar	20x22x4000mm 2mm thickness		SCG
Gypsum Board	1200x2400mm 9mm thickness		SCG

3.3 Framework of system development

The development of an automated system requires three major phases. First, the development of Model I, which implied generating a preference model. This model serves as the foundation for the subsequent phases. Second, Model II is developed using a clash detection process that identifies potential overlaps between building elements. This step is vital for avoiding rework and ensuring compliance with construction standards. Lastly, shop drawings and the required materials are generated. Figure 4.8 depicts the proposed system development framework.

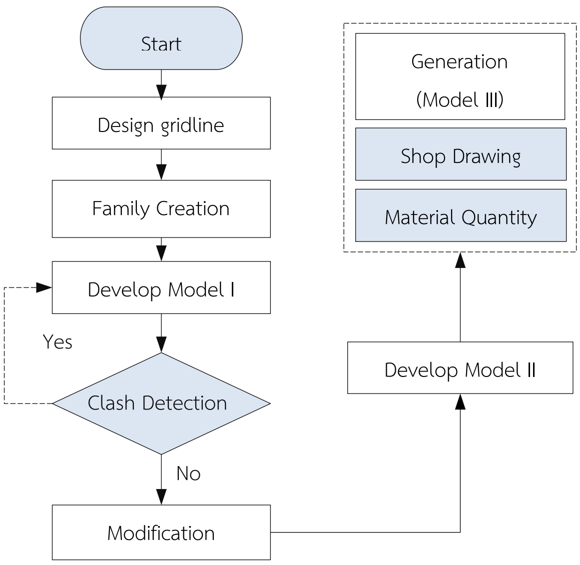

Fig. 2 Proposed system development framework

4. Developing of an automated shop drawing and material takeoff generation of ceiling system

The proposed framework consists of three main models. Model I is focused on the design gridline and family creation, whereas Model II is responsible for clash detection and the subsequent modification of identified clashes. Lastly, model III aims to generate shop drawings and material takeoff. In the following sections, each of these components will be discussed in detail.

To test the system, sample data from apartment rooms has been gathered for initial testing. The development of the system was aided by computer software, including Microsoft Excel, Autodesk Revit, and Dynamo Software.

4.1 Design gridline

In this stage, the design algorithm for generating the gridline is developed. The design aims to determine the reference of start points and endpoints for ceiling framing. Each section is divided into three major steps: data required, process, and output, as shown in fig. 3.

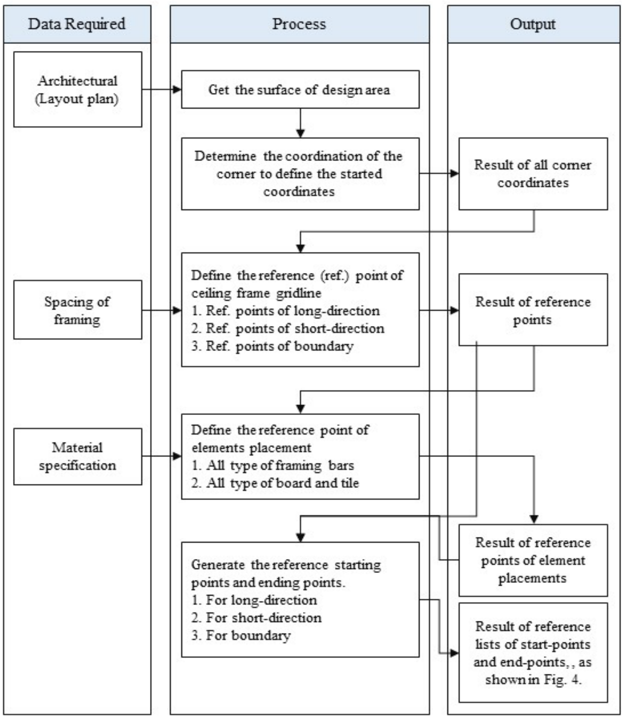

Fig. 3 Design algorithm for generating the design gridline

During the processing, the surface of the design area is determined using information from the architectural layout plan. Next, the system automatically identifies whether the selected surface is rectangular or L-shaped. Once the surface shape is selected, the coordinates of every corner are determined to define the starting points. Then, the reference points for generating gridlines are defined, including the long direction, short direction, and boundary, based on the design spacing specification. The resulting reference points and material specification information are used to define the reference points for element placement. Finally, the start points and endpoints are generated using the resulting reference points and the reference element placement points, as illustrated in Fig. 4.

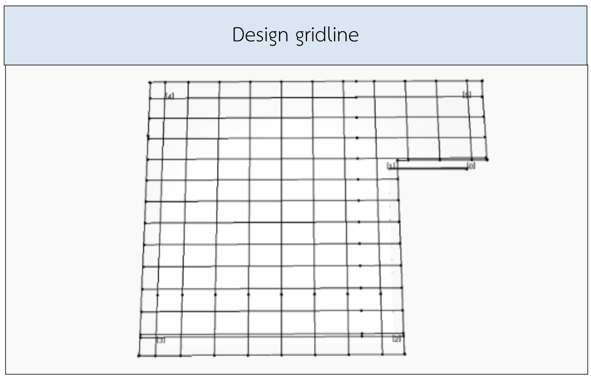

Fig. 4 The coordinates list of start points and endpoints and design gridline

4.2 Design family type

The design family type was created to improve the process of developing automatic ceiling design. It allows the creation of customized elements that can be utilized throughout the design process. To develop the ceiling design system, two types of families are created, each representing a ceiling frame. First, C-section studs are created for both long and short directions of ceiling framing. Second, an L-section stud is created for edging studs to support long and short direction studs. Fig. 5 shows the types of families needed using the information from Table 1.

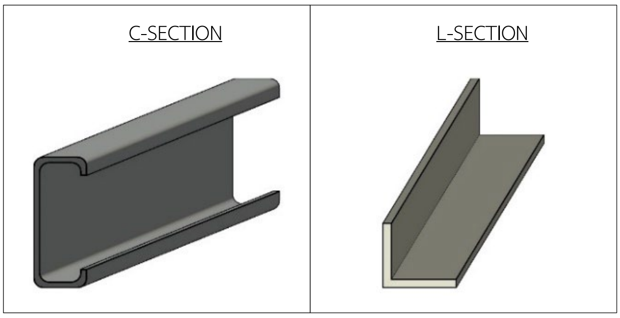

Fig. 5 Two types of families needed

Once the reference start points and endpoints are generated, the element placement process is executed to develop Model I, utilizing the family types created. The process involves selecting appropriate family types and defining the building level using the generated reference lists and design height. Once all requirements are in place, the Model I design is executed.

4.3 Clash detection

During the process of constructible problem detection, a careful inspection of the ceiling building component is essential to identify potential constructible issues that may arise between the framing studs and lighting fixtures. Clash problems and spacing problems are the two types of constructible problems that need to be considered. Fig. 6 illustrates the detection between the framing studs and lighting fixtures. A clash problem occurs when two or more elements intersect, while a spacing problem refers to the maximum allowable spacing between each of the framing studs.

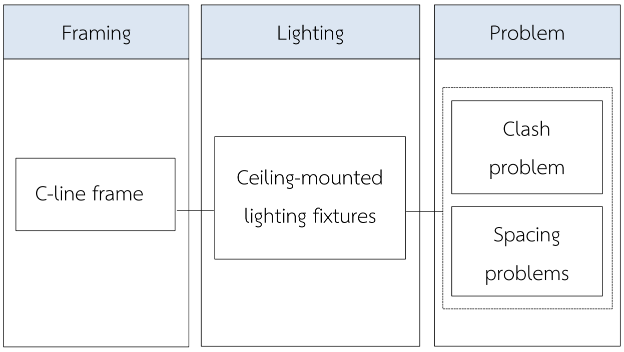

Fig. 6 The detection between framing studs and lighting fixtures

In this research, the primary objective of developing Model II is to address constructible problems between ceiling framing studs and ceiling-mounted lighting fixtures. Fig. 7 shows the constructible problems between framing studs and ceiling-mounted lighting fixtures.

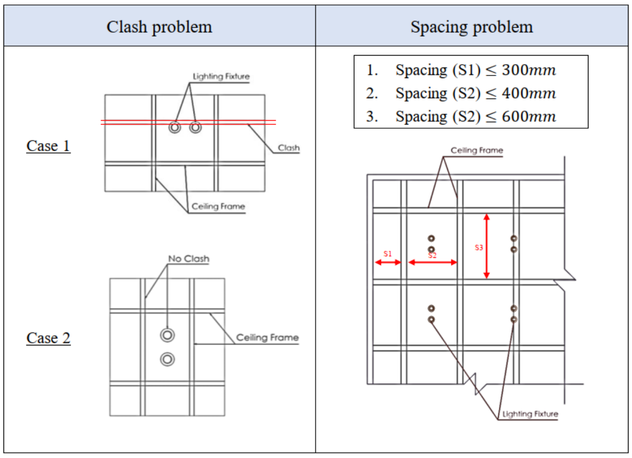

Fig. 7 Constructible problems between framing studs and ceiling-mounted lighting fixtures

To detect clashes between framing studs and ceiling-mounted lighting fixtures, Autodesk Dynamo Software was utilized to develop algorithms that determine intersection elements and points. The results include detected areas, clash points, clash views, and embedded thickness of clashes. The framing studs and lighting fixtures are colored in the 3D model, and the detected information is exported into a Microsoft Excel spreadsheet file. The exported information includes the clash number, stud framing type, stud framing ID, lighting fixture type, lighting fixture ID, point coordinates, and embedded thickness value. Fig.9 shows a summary of the ceiling framing clash detection and development process.

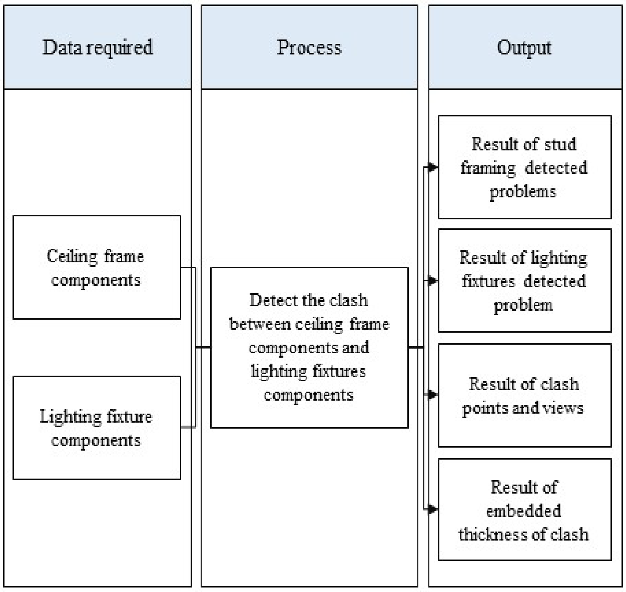

Fig. 8 A summary concept of ceiling framing clash detection development

4.4 Modification of clash

The stud modification is developed to solve the constructability problems of framing stud detection. This modification aims to solve the problems with an automated method. The automated stud modification tries to automatically move the framing stud to another location to solve the clash problems and adds an allowance spacing number between stud-to-stud, which is 300mm, 600mm, and 400mm for edge, long direction, and short direction, respectively.

4.5 Shop drawing and material takeoff generation

After Model II has been developed, the system generates the shop drawing and material takeoff. The shop drawing includes the stud spacing and cutting length for each stud for the construction process. Furthermore, the material takeoff is generated in Microsoft Excel, providing essential information such as the type of material used, material specification, required quantity, and selected supplier.

5. Testing automated system and its result

5.1 System implementation

The implementation of automated systems is done using an apartment building consisting of three floors as a case study. An L-share bedroom room with a 33.8 m^2 ceiling area is utilized to verify the proposed system framework. Fig. 9 illustrates the prototype building used to test the system. To develop an automated system of the ceiling, it is necessary to combine the data collection discussed in Section 4 with Building Information Modeling software such as Autodesk Revit 2021, and Autodesk Dynamo.

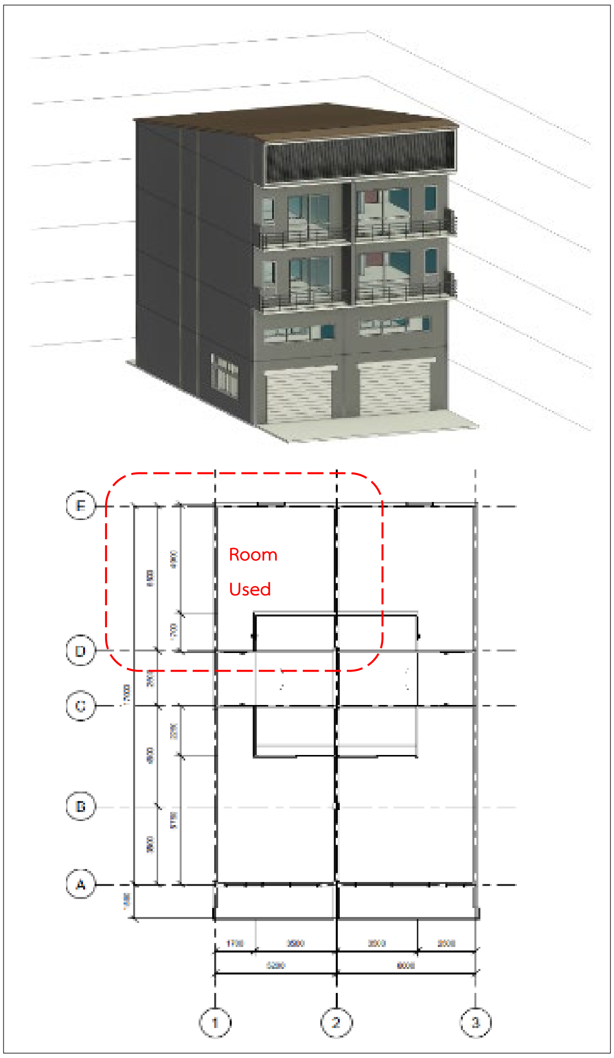

Fig. 9 Accommodation building for implementing the prototype

5.2 Results of the system

The primary aim of developing this system is to automatically extract required materials from ceiling building components in each layer and generate the shop drawing of the ceiling frame with no clashes between lighting fixtures. As elaborated in the preceding sections regarding the process and the implementation of the system, the results of the required materials utilized for the ceiling and its corresponding shop drawing are obtained and discussed in the following.

The ceiling frame shop drawing is automatically generated in Revit, which details the spacing from stud-to-stud. It provides automatic pre-modification of the detected clashes before site implementation. As shown in Fig. 10, the system provides three types of framing placement detail, including C-section for long direction, C-direction for short direct, and L-section for boundary supported frame. Moreover, as illustrated in Table 3, the system provides a cutting schedule for the ceiling frame, which assists in the cutting process before installation. Table 2 shows the stud length cutting schedule for the ceiling frame.

Fig. 10 The design shop drawing of ceiling frame

Table 2 Stud schedule of ceiling frame for site implementation

Type	Stud Shape	W	H	B	THK	Length	Number
Unit		mm				mm	pcs
C-Section		36	14	5	1.5	4000	21
C-Section		36	14	5	1.5	2450	4
C-Section		36	14	5	1.5	1050	8
C-Section		36	14	5	1.5	1550	3
C-Section		36	14	5	1.5	750	9
L-Section		22	20		2.5	4000	3
L-Section		22	20		2.5	3700	1
L-Section		22	20		2.5	2450	1
L-Section		22	20		2.5	1700	1
L-Section		22	20		2.5	1550	1
L-Section		22	20		2.5	1050	1
L-Section		22	20		2.5	1050	1

In Table 3, the results of the ceiling frame material quantity are automatically extracted into Microsoft Excel files. The result indicates the element position, section type, element type, element ID, and element length for both types of studs: C-section and L-section.

Table 3 Result of ceiling frame material quantity in Excel files

Ceiling Frame Generation	Result in Excel files				
L-section studs	Element Position	Section Type	Element Type (mm)	Element ID	Element Length (mm)
	Boudary supported	L-section stud	L22x20x2.5	468115	1700
	Boudary supported	L-section stud	L22x20x2.5	468117	3500
	Boudary supported	L-section stud	L22x20x2.5	468119	4000
	Boudary supported	L-section stud	L22x20x2.5	468121	750
	Boudary supported	L-section stud	L22x20x2.5	468123	4000
	Boudary supported	L-section stud	L22x20x2.5	468125	1050
	Boudary supported	L-section stud	L22x20x2.5	468127	4000
	Boudary supported	L-section stud	L22x20x2.5	468129	2450
	Boudary supported	L-section stud	L22x20x2.5	468131	1550
C-section studs	Element Position	Section Type	Element Type (mm)	Element ID	Element Length (mm)
	Long direction	C-section stud	C36x14x5	468077	4000
	Long direction	C-section stud	C36x14x5	468079	4000
	Long direction	C-section stud	C36x14x5	468081	4000
	Long direction	C-section stud	C36x14x5	468083	4000
	Long direction	C-section stud	C36x14x5	468085	4000
	Long direction	C-section stud	C36x14x5	468087	4000
	Long direction	C-section stud	C36x14x5	468089	4000
	Long direction	C-section stud	C36x14x5	468091	4000
	Long direction	C-section stud	C36x14x5	468093	1050
	Long direction	C-section stud	C36x14x5	468095	1050
	Long direction	C-section stud	C36x14x5	468097	1050
	Long direction	C-section stud	C36x14x5	468099	1050
	Long direction	C-section stud	C36x14x5	468101	1050
	Long direction	C-section stud	C36x14x5	468103	1050
	Long direction	C-section stud	C36x14x5	468105	1050
	Long direction	C-section stud	C36x14x5	468107	1050
	Long direction	C-section stud	C36x14x5	468109	1550
	Long direction	C-section stud	C36x14x5	468111	1550
	Long direction	C-section stud	C36x14x5	468113	1550
C-section studs	Element Position	Section Type	Element Type (mm)	Element ID	Element Length (mm)
	Short direction	C-section stud	C-14x36x5	468025	4000
	Short direction	C-section stud	C-14x36x5	468027	4000
	Short direction	C-section stud	C-14x36x5	468029	4000
	Short direction	C-section stud	C-14x36x5	468031	4000
	Short direction	C-section stud	C-14x36x5	468033	2450
	Short direction	C-section stud	C-14x36x5	468035	2450
	Short direction	C-section stud	C-14x36x5	468037	2450
	Short direction	C-section stud	C-14x36x5	468039	2450
	Short direction	C-section stud	C-14x36x5	468041	4000
	Short direction	C-section stud	C-14x36x5	468043	4000
	Short direction	C-section stud	C-14x36x5	468045	4000
	Short direction	C-section stud	C-14x36x5	468047	4000
	Short direction	C-section stud	C-14x36x5	468049	4000
	Short direction	C-section stud	C-14x36x5	468051	4000
	Short direction	C-section stud	C-14x36x5	468053	4000
	Short direction	C-section stud	C-14x36x5	468055	4000
	Short direction	C-section stud	C-14x36x5	468057	4000
	Short direction	C-section stud	C-14x36x5	468059	750
	Short direction	C-section stud	C-14x36x5	468061	750
	Short direction	C-section stud	C-14x36x5	468063	750
	Short direction	C-section stud	C-14x36x5	468065	750
	Short direction	C-section stud	C-14x36x5	468067	750
	Short direction	C-section stud	C-14x36x5	468069	750
	Short direction	C-section stud	C-14x36x5	468071	750
	Short direction	C-section stud	C-14x36x5	468073	750
	Short direction	C-section stud	C-14x36x5	468075	750

Moreover, the primary aim of material takeoff in this research is to assist the engineer in resolving purchase-order conflicts during the construction stage. As illustrated in Table 4, the developed system automatically generates the required material list for the purchase order. The ceiling work requires three types of materials: C-line, L-bar, and gypsum board, and the generated list includes material type, size, thickness, length, supplier, quantity, and unit.

Table 4 Material list for purchase order

Material Type	Size (mm.)	THK. (mm.)	Length (mm.)	Supplier	Quantity	Unit
C-Line	36x14x5	1.5	4000	ISI	28	Pcs
L-Bar	22x20	2.5	4000	ISI	6	Pcs
Gypsum Board	1200x2400	9		GYPRO	19	Pcs

Basically, to perform material takeoff, two popular approaches are commonly used in most construction projects: traditional and BIM-based methods [23]. Traditional material takeoff relies on two-dimensional drawings, which can be time-consuming and prone to human error during interpretation. This method also presents challenges in identifying clashing elements, errors, and omissions, and requires separate calculations for quantity takeoff and material takeoff to proceed with the purchase order [24]. Regardless of the method used, it is necessary to account for additional material quantities due to potential wastage and material contingencies. Typically, 5% to 10% is added for wastage, and up to 3% for material contingency to ensure enough materials are available in case of breakage, mistakes, or changes to the construction plans [25].

On the other hand, BIM-based approach for material takeoff has emerged as an effective method for accurately quantifying materials and generating shop drawings [20]. Unlike traditional methods, which rely on two-dimensional drawing, BIM-based material takeoff works with three-dimensional modeling, enabling the users to detect the potential clashes between building components before construction. This feature helps avoid costly delays and rework caused by errors and omissions [26]. Furthermore, BIM adoption can automatically generate material takeoff and clear shop drawings, reducing the likelihood of human error and timesaving. Waste optimization is also achievable with BIM-based method, as it allows users to plan materials more precisely and minimize waste in construction [19]. Therefore, BIM-based approach offers significant advantages over traditional methods and is increasingly becoming the industry standard for material takeoff in construct projects. Table 5 outlines the differences in material takeoff capabilities between traditional and the developed system.

Table 5 The differences in material takeoff capabilities between traditional and the developed system

Function	Traditional Method	System Development
Takeoff Type	Quantity Takeoff	Material Takeoff
Drawing-Based	Two-dimensional drawing	3D drawing
Clash checked	Separated drawings	Clash detection
Wastage	5% - 10% added	0% added
Shop Drawing	Manually arrange	Automatically generate
Data generation	Manually calculate	Automatically generate

6. Discussion and conclusion

The results of the study demonstrate that BIM-based clash detection can be effectively utilized to detect overlaps between the ceiling framing and lighting fixtures and that the material takeoff design algorithm can accurately calculate the building components with multiple layers of materials. Moreover, the proposed system can automatically generate the cutting length of the ceiling frame, facilitating the construction process and reducing waste during the cutting stage. The provision of a shop drawing ensures the accuracy of the material takeoff, enabling specific purchase orders to be processed with minimal waste. Compared to the traditional method of calculating material quantity based on the amount of work and on-site arrangement of the ceiling frame, the proposed system is more effective in accurately calculating and generating detailed drawings with consistency.

However, the system has some limitations that need to be addressed, including the inability of the Dynamo script to generate arc shapes and detect corner points exceeding six points. Furthermore, the overall results show that the proposed system can improve the process of BIM-based material takeoff by providing an automated system that can reduce the time spent on material quantification. This automated system allowed practitioners to generate clear shop drawings in accordance with the designed standard, resulting in more accurate material generation. Our research conclusions demonstrate that the proposed system can be implemented, although it requires improvement to overcome its limitations and achieve more variety in shape and fully automated clash detection.

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