Automatic Generation of the Consumption for Temporary Construction Structures Using BIM: Applications to Formwork

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Abstract –

Temporary construction structures (TCSs), such as formwork and scaffolding, attract a lot of attention due to their impact on the schedule and cost of construction projects. In many cases, the determination of the consumption (i.e., labor, materials, and equipment) of TCSs is a complex process subject to errors. This paper presents a general framework to automatically generate the consumption of TCSs based on the geometry and quantification of building elements in the BIM model, coupled with applicable building codes and industry standards. The framework has been implemented to automatically generate the consumption required for the formwork in a BIM test model. The findings show that the framework provides an efficient way to determine the consumption requirements for formwork. Compared to the current consumption estimating tools for TCSs typically used, this BIM-based tool improves efficiency, allowing the project participants to account for TCSs during the preparation of the project schedules and cost estimates during the early phases of a project. With small modifications, the proposed framework could be applied to other TCSs.

Keywords –

BIM; Temporary construction structures; Formwork; Consumption; Quantity take-off

1 Introduction

As an indispensable part of construction resources, temporary construction structures (TCSs), such as formwork and scaffolding, play a significant role in the proper planning and smooth progress of construction projects. They are large in quantity and numerous in category, and due to their complex construction process, can take a long time to be built as well as take considerable amounts of labor and equipment [1]. According to Ko et al. [2], formwork alone, generally accounts for approximately 15% of the total construction cost. Therefore, the consumption of TCSs (i.e., the quantity and cost of the TCSs, as well as their accessories, and associated labor and equipment required) is a critical factor in project profitability [2][3]. In the construction industry, there are applicable building codes and industry standards (i.e., consumption standards), such as *RSMeans Building Construction Cost Data* [4] and *Standard for the Consumption of Construction Engineering in Hunan Province of China* [5], that are used to estimate the consumption of TCSs. For example, the consumption standard [5] specifies the consumption of formwork based on the area and type of formwork used, as well as the type and height of the corresponding building elements. Similarly, the consumption of scaffolding depends on the structure type (e.g., frame structure and shear wall structure), as well as on the building height and area. The information required includes the characteristics and dimensions of the building, the characteristics and quantity of the TCSs, and the type and height of each building element. The collection of this information is a tedious and error-prone process, which becomes difficult in large and complex projects.

Traditional 2D estimating tools were developed to assist estimators in the preparation of quantity take-offs by having a visual representation of the materials to be quantify [6]. This quantification could then be used to determine their consumption. Nevertheless, the main challenge remains when quantifying TCSs as they are not shown in the drawings (or models) from the designers. In recent years, with the advancements in 3D technology, the tools have shifted toward 3D-based estimate as they result in reduced errors and time when compared to 2D-based estimate [7]. But they still have a few disadvantages [8][10]. For example, some tools cannot be used with the building information modeling (BIM) model so its industry foundation classes (IFC) file has to be exported to the new platform to recreate the 3D model for further use. This causes unnecessary duplication of work and the loss of model information because many of the features of the original model are lost due to software compatibility issues (i.e., interoperability problems), and creates problems when changes are made at different project phases. In addition, some tools require to manually selecting the items of the consumption standards to connect quantity take-offs, which can easily lead to errors due to the estimators' interpretation of the consumption standards. Currently, BIM technology based on parametric modeling and three-dimensional digital representation has been widely applied to extract information needed to support project management [8]. Users can expediently obtain the information generated through the creation of building elements automatically. For instance, Kim et al. [11] used information such as location, geometry and quantity of building elements stored in the BIM model to automate the generation of construction schedules. Wang et al. [12] proposed the use of building elements to integrate schedule and cost to establish a cost-based progress curve used to control construction project schedules by extracting the quantities of cost items associated with each activity. In order to make BIM models effective, more and more projects strengthen the collaboration amongst participants, and the BIM models provided by the designers are used by the general contractors to support project management [8][9]. However, except for a few proprietary BIM tools, general BIM authoring tools do not have the ability to work with TCSs, including formwork and scaffolding, in the model [1] [6] [13][14][14]. Although it is possible to create TCSs utilizing the functions used when creating building elements, this process is time consuming and inefficient. The study by Monteiro and Martins [14] has shown that the modeling time would double when considering the creation of formwork.

Some researchers have made beneficial efforts to improve the automation level in generating information for TCSs based on BIM. For example, Kim and Teizer [1] developed a rule-based system that automatically plans scaffolding systems in BIM, which can recognize geometric and non-geometric conditions in building models and estimate the required materials for scaffolding. Monteiro and Martins [14] explored the possibility to develop a tool for ArchiCAD that would automatically provide a formwork model based on the building elements. Users could determine the building elements through a selection of Types, IDs and Layers, and then define the formwork parameters, such as thickness and material type. The formwork quantity would be obtained from the formwork model created automatically. Le [15] presented an algorithm to quickly calculate the quantity of formwork using the application programming interface (API) provided by Autodesk Revit. The algorithm accounted for the areas of intersecting faces. Wei et al. [16] proposed a BIM-based method for the calculation and management of temporary materials. They calculated the formwork quantity taking into account the thickness of formwork when different building elements intersect. Kim et al. [17] developed a semi-automated system to select the correct scaffolding. It included a feature lexicon to formalize the representation of factors essential to scaffolding planning. Singh et al. [18] used BIM data as input to compute the quantity of formwork and generate the visualizations and the schedule of quantities for formwork. Formwork elements were developed as parametrically constrained objects, and by using dimensional parameters, their size, number of sub-elements, and alignment can be adjusted. In previous studies, there are two main types of methods to automatically generate TCSs information. One is to create TCSs elements through a developed BIM-based tool, and the other one is to generate TCSs information directly based on building elements in the BIM model. For the estimate of the consumption of TCSs, the characteristics and quantity of TCSs needs to be determined [5]. Therefore, the latter method is better suited to obtain the information from the TCSs required by the consumption standards while minimizing unnecessary manual operations to generate it.

To address the shortcomings of current estimating tools, this paper presents a general framework that integrates BIM and consumption standards to automatically generate the consumption of TCSs. The framework uses the generation of the consumption required for formwork based on the geometry and quantification of building elements in the BIM model as an example. Compared to previous related studies, this study accounts for the location relationship of different categories of building elements, making the generation results of the formwork more accurate, and the generation process more efficient. A Revit-based tool to generate the consumption required for the formwork is developed and tested by a BIM structural model. By using Revit API [19] and MySQL [20], the whole generation process reaches a high level of automation.

2 General Framework

This section presents a general framework for integrating BIM and consumption standards to automatically generate the consumption of TCSs, which consists of four parts (Figure 1), and uses formwork as an example for its implementation.

The first part is to obtain a BIM design model. The

Table 1. Formwork consumption according to [5]

			Item		
			A 13-20	A 13-21	A 13-22
			Rectangular Column	Special-Shaped Column	Column Height Exceeds 3.6 m
			Bamboo Plywood Formwork		Excess Part is Within 3 m
			Steel Shoring		
Category		Unit	Usage Amount (Per 100 m² Formwork Area)		
Labor	General Labor	Man-day	34.8	51.64	9.42
Material	Sporadic Fixture	kg	-	27.94	-
	Steel Pipe and Coupler	kg	45.94	59.53	10.11
	…	…	…	…	…
Equipment	Truck Crane (5 Tons of Loading Capacity)	Machine-team	0.18	0.18	0.012
	Truck (6 Tons of Loading Capacity)	Machine-team	0.28	0.28	0.03
	…	…	…	…	…

model should include basic building elements such as columns, walls, beams, slabs and stairs, without creating temporary construction structures directly. In addition, the naming of the same type of building elements should be distinguished from other types, so that the consumption of different types of building elements can be calculated according to the corresponding rules of the consumption standards. For example, the consumption standard [5] classifies structural columns into rectangular columns and special-shaped columns in the section of formwork consumption, so different naming is needed to distinguish between these two types.

The second part is to extract and integrate building information required by the consumption standards. As previously indicated, the information required by the consumption calculation of different TCSs is not the same, and specific information needs to be extracted according to the corresponding requirements. For instance, the consumption of formwork is determined by the area and type of formwork used, as well as the type and height of the corresponding building elements [5]. Therefore, this information should be extracted and integrated. It is worth noting that information that is not automatically generated in the BIM model requires additional provisions. In this instance, the area and type of formwork is not readily available, so they need to be determined in this part so that they can be stored in the database for further use, as explained in the next section.

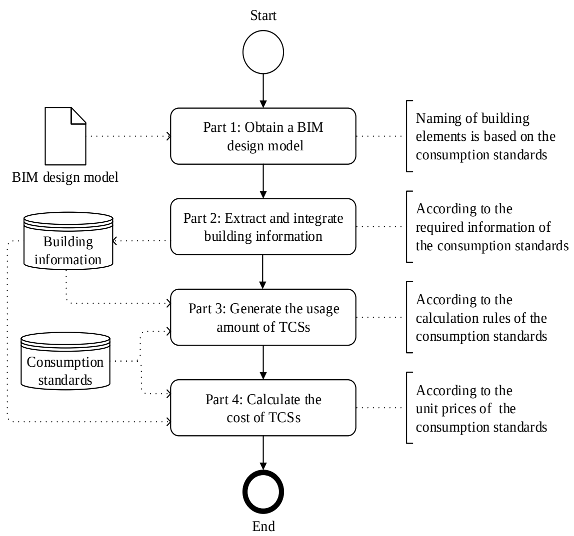


Figure 1. General framework

The third part is to generate the usage amount of TCSs according to the calculation rules provided by the consumption standards, including their quantity, as well as their accessories, how much labor is needed, and which and how much equipment is required. The associated consumptions are coded for a given work and they are accounted in the consumption standards into different items. The applicable items are used based on the information provided in part 2. For example, according to [5], for a rectangular column using bamboo plywood formwork with steel shoring, the usage amount of formwork is defined in item “A13-20” (Table 1). Similarly, for a special-shaped column using bamboo plywood formwork with steel shoring, the usage amount of formwork is defined in item “A13-21” (Table 1).

The fourth part is to calculate the cost of TCSs based on their unit price. With the generated usage amount of TCSs from part 3 and the unit price provided by the consumption standards, the cost of TCSs, including labor, materials, and equipment, can be calculated.

3 Adaptation of the General Framework: Using Formwork as an Example

This section shows the process to automatically generate the consumption of formwork using the general framework presented in Section 2. The process is shown in Figure 2.

In part 1, building elements of every type for which its material is cast-in-place concrete is classified (i.e., giving a specific name) during the modeling to identify the applicable items in part 3. The classification of the types of building elements such as columns, walls, beams, slabs and stairs should be done in accordance with the requirements of the consumption standards.

Part 2 determines the formwork area of the building elements, the projected area of the stair elements, and the formwork type required by the consumption standard [5]. First, the formwork area of the building elements with a material classified as cast-in-place concrete is calculated without considering intersection among building elements. The calculation rules are different based on the real construction situation. For example, the formwork area of columns and walls only calculates the side areas of the building elements, while that of beams, floors and stairs includes the bottom and side areas. The direction of the element surface can be judged by obtaining the vector of the max point of the bounding box of each surface in the elemental solid. If the vector is (0, 0, 1) and (0, 0, -1), it is shown that the surface is the top and bottom of the element. Then obtain the bounding boxes of the solids from the building elements and the midpoint of their surfaces, and convert bounding boxes into new outlines. Two building elements intersect when the midpoint of the surface of a building element is contained within the outline of another building element (to within a predefined tolerance). The tolerance depends on the thickness of the formwork used. The area of the intersecting surface is deducted from the formwork area of the building element.

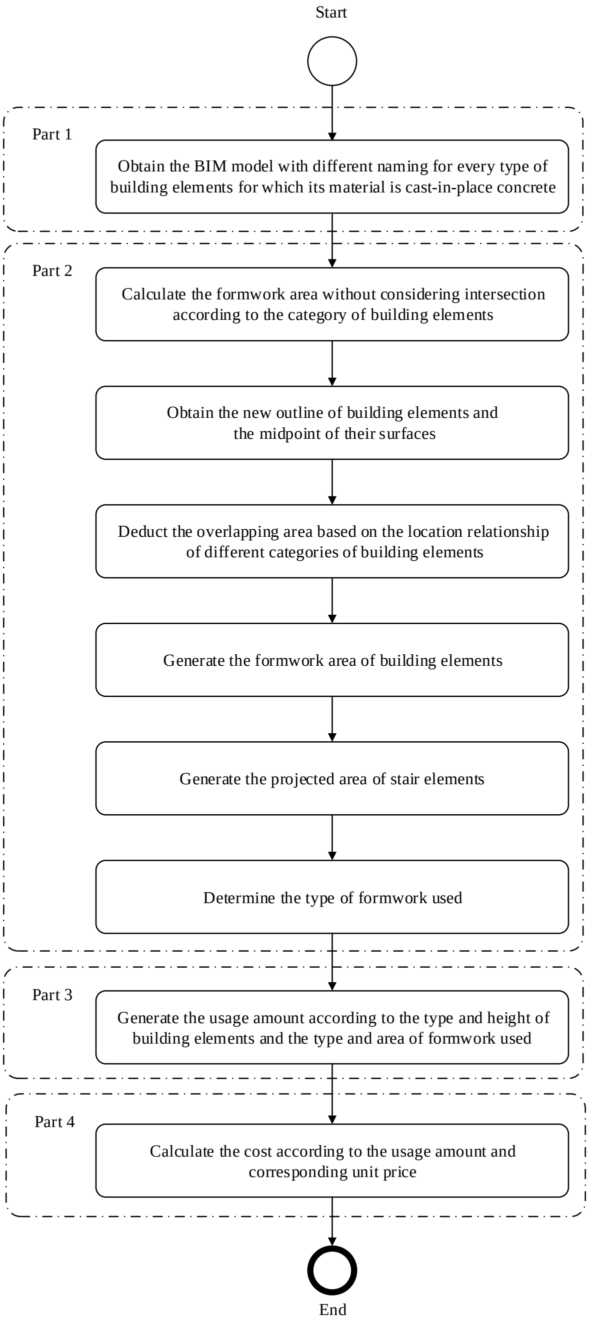


Figure 2. Process to automatically generate the consumption required for formwork

According to the location relationship of different categories of building elements, it is not necessary to judge whether a building element intersects all the other building elements of the BIM model, and it can be summed up as three types of rules. Firstly, intersection is only carried out in building elements including columns, walls, beams and slabs of the same floor. Stairs are the exception because they connect adjacent floors. Secondly, a certain category of building element would selectively judge the intersection with other types of building elements. For example, when a column intersects a beam, the intersection rule is required. On the other hand, when a column intersects a slab, no intersection rule is required because the top and bottom of the column have been previously deducted. Thirdly, a certain category of building elements has a specific intersection judgement process when it intersects with different categories of building elements. For instance, when judging whether a column intersects with a wall, the midpoint of the column surface and the outline of the wall would be retrieved; however, when judging whether a column intersects with a beam, the outline of the column and the midpoint of the beam surface would be retrieved. Through the selective intersection rule based on the consideration of the location relationship of different categories of building elements, the calculation results of formwork area would be more accurate and the calculation would be more efficient. Once the building elements are calculated in accordance with the above rules, the formwork area of those building elements is generated. The consumption of stairs depends on their projected area, and the projected area is generated based on the area of surfaces with vectors that are (0, 0, 1) from stair element. After that, the type of formwork, including material and its shoring (according to the actual situation), is determined.

The last two parts are to generate the consumption of formwork, which represents the usage amount and cost of labor, materials, and equipment that need to be consumed to complete the work content of the formwork including production, installation, maintenance, demolition, stacking and transportation. The consumption value depends on the type and height of the building elements, and the area and type, including material and shoring, of the formwork [5]. For example, a rectangular column using 100 m^2 of bamboo plywood formwork with steel shoring requires 34.8 man-days, 45.94 kg of steel pipes and couplers, and 0.28 machine-team of a truck with a loading capacity of 6 tons (Table 1). When the height of the column exceeds 3.6 m and the excess part is within 3 m, then the excess part requires 9.42 man-days, 10.11 kg of steel pipes and couplers, and 0.03 machine-team of a truck with a loading capacity of 6 tons (Table 1). The type and height of the building element can be obtained from the BIM model, and the area and type of the formwork has been determined in part 2.

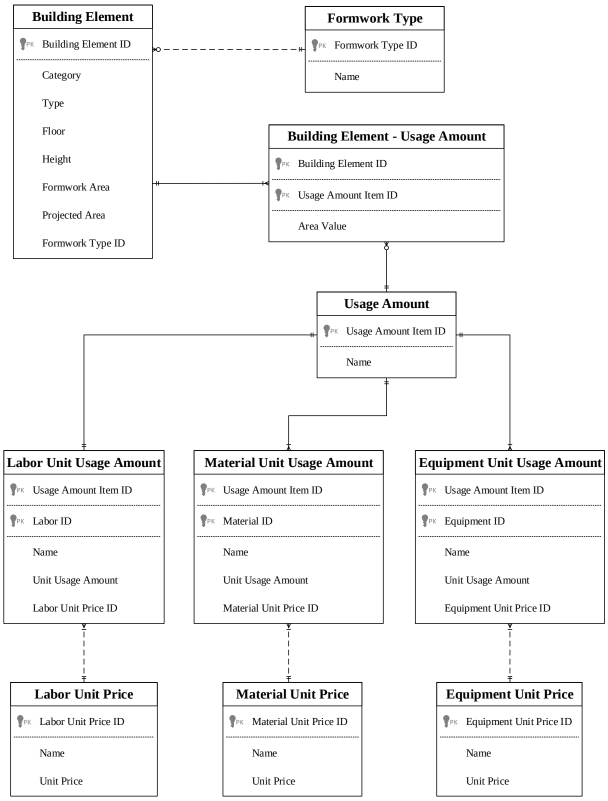


Figure 3. Entity relationship diagram of database structure

To store and manage data efficiently, a database structure containing 10 tables was designed to be used by the BIM-based tool (Figure 3). Using the reference IDs, the tool could parse attribute information from tables by following the paths from the reference IDs to the attributes. Thus, the consumption of formwork can be generated.

4 Case Study

Based on the presented framework, a Revit-based tool was developed to automatically generate the consumption required for the formwork, and was tested using the BIM model of a four-story cast-in-place concrete frame structure. The structure is 17.1 m high and has a building area of 5,028 m^2, which includes concrete columns, concrete walls, concrete beams, concrete slabs and concrete stairs (Figure 4).

All building elements have been named separately according to the classification of the consumption standard [5]. For example, rectangular columns are named “RC”, when the developed tool searches for the building elements with this name, only the consumption of rectangular columns is used.

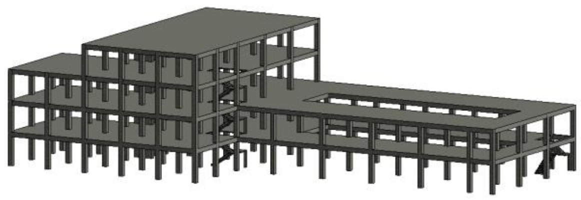
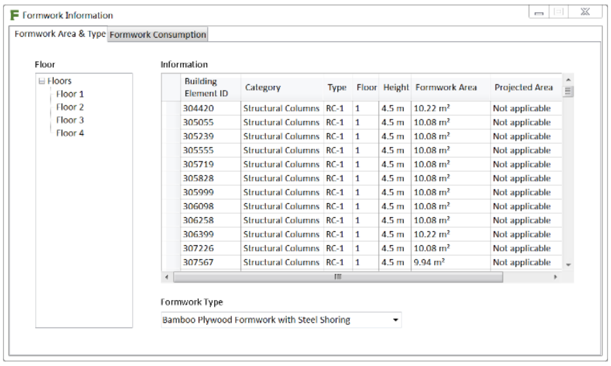


Figure 4. A BIM structural model

The formwork area of each building elements has been calculated using the adapted framework shown in Section 3, the output is shown in Figure 5. The total area calculated for the formwork is 8,436.46 m^2. The type of formwork is selected as the bamboo plywood formwork with steel shoring in the user interface (Figure 5).

After generating the formwork area of the building elements and the projected area of the stair elements, and determining the formwork type, the tool generates the usage amount and cost of labor, materials, and equipment. An example of the output is shown in Figure 6, Figure 7, and Figure 8. Figure 6 and Figure 7 show for each floor the labor usage amount, and cost and their percentage respectively. From the first floor to the fourth floor, it takes 1,509, 1,481, 800 and 623 man-days respectively. The cost per floor is 105,600, 103,659, 55,998 and 43,631 Chinese Yuan (1 CNY = 0.15 USD), also shown as a percentage of the selected cost for each floor; in this case 34.19%, 33.56%, 18.13%, and 14.13%. It can be clearly seen that the first and second floors have the highest labor consumption, while the fourth floor has the lowest. Different categories of total cost and their percentage are shown in Figure 8. The labor cost amounts to 308,888 CNY, which accounts for 64.41%, almost two-thirds of the total cost; while the cost of materials and equipment amounts to 142,470 and 28,222 CNY, or 29.71% and 5.88% of the total cost respectively.



Building Element ID	Category	Type	Floor	Height	Formwork Area	Projected Area
304420	Structural Columns	RC-1	1	4.5 m	10.22 m²	Not applicable
305055	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
305239	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
305555	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
305719	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
305828	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
305999	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
306098	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
306258	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
306399	Structural Columns	RC-1	1	4.5 m	10.22 m²	Not applicable
307226	Structural Columns	RC-1	1	4.5 m	10.08 m²	Not applicable
307567	Structural Columns	RC-1	1	4.5 m	9.94 m²	Not applicable

Figure 5. Generation of formwork area and determination of formwork type

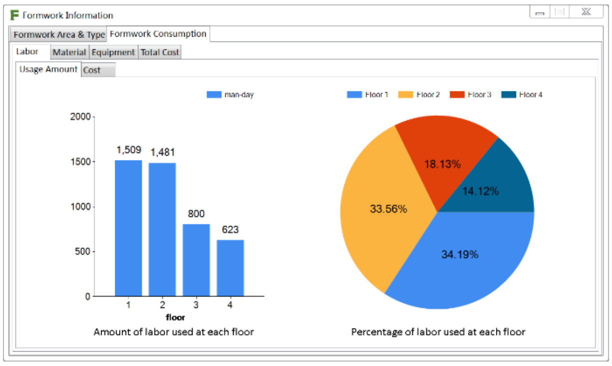


Figure 6. Amount (man-days) and percentage of labor used at each floor

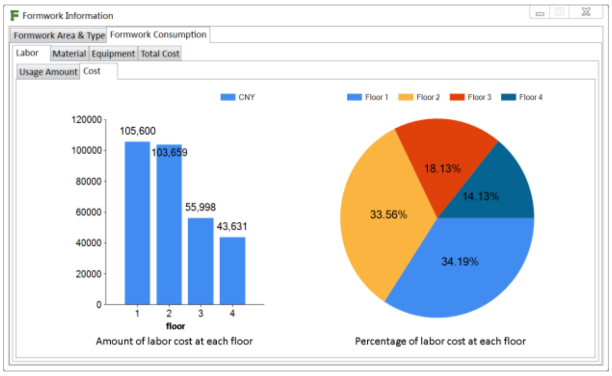


Figure 7. Labor cost (CNY) and percentage at each floor

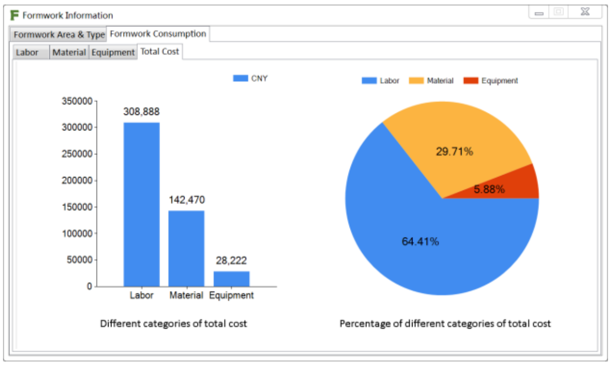


Figure 8. Different categories of total cost (CNY) and their percentage

5 Discussion

The current 3D estimating tools for TCSs typically used in construction projects have a few disadvantages (e.g., some tools cannot be used with the BIM model and/or require to manually selecting the items of the consumption standards to connect quantity take-offs). The framework proposed in this paper only needs the

Table 2. Scaffolding consumption according to [5]

			Frame and shear wall structures	
			24 m < BH* ≤ 30 m	30 m < BH ≤ 50 m
			A 12-12	A 12-13
Category		Unit	Usage Amount (Per 100 m^2 Building Area)	
Labor	General Labor	Man-Day	22.06	17.78
Material	Bamboo Scaffold Floor	m^2	19.56	18.38
	Steel Pipe (Ø 48*3.5)	kg	144.16	149.71
	Sleeve Coupler (1.4 kg)	-	3.87	4.9
	Right Angle Coupler (1.4 kg)	-	19.58	21.96
	Protective Net	m^2	45.01	45.01
	Base (1.71kg)	-	0.43	0.46
	Rotary Coupler (1.4 kg)	-	6.54	6.03
Equipment	Truck (6 Tons of Loading Capacity)	Machine-Team	0.32	0.24

**BH: Building height*

BIM model provided by the designer to automatically generate the consumption of TCSs, which improves efficiency. Although this study adopted proprietary API for Revit, this limitation can be removed by using the IFC compliant BIM model. When comparing the total area of formwork calculated by the presented algorithm to the one calculated by hand, it was found that the difference was negligible (about 0.02% difference). The algorithm considers the general sense of the location relationship of different categories of building elements, though it is not absolute accuracy to every project, it provides a sufficiently accurate way to estimate the formwork area at the early stage of the project. The calculation time using the proposed framework is less than one minute, far less than the time of the hand calculation. In addition, when changes are made to the building elements (i.e., new building elements are added, existing building elements are reduced or the dimensions of the building elements are modified), the TCSs could be recalculated effortlessly using the proposed algorithm.

The presented general framework has lots of potential with respect to other types of temporary construction structures such as scaffolding, which has some differences from the formwork. Fox example, in part 1, the BIM design model should include the area elements in addition to the basic building elements (e.g., columns, walls, beams, slabs and stairs). The consumption of general scaffolding is determined by the structure type (e.g., frame structure and shear wall structure), height and building area [5], therefore, part 2 should extract and integrate the values of the level elements and the area elements, and determine the structure type of the building.

In addition, there is also different in the classification criteria for items. For a building with a frame structure and a total height of 30 m, the usage amount of general scaffolding is defined in item “A12-12” (Table 2). Similarly, for a building with a shear wall structure and a total height of 50 m, the usage amount of general scaffolding is defined in item “A12-13” (Table 2).

6 Conclusions

TCSs is not only critical for the successful completion of construction projects, but is also one of the most significant cost factors in the construction projects. This paper presents a general framework to automatically generate the consumption of TCSs integrating BIM and consumption standards and shows an application to determine the consumption of formwork in a sample project. Information about the amount of resources needed, as well as the cost breakdown, was generated in an efficient manner. The output of the presented framework includes the usage amount and cost of labor, materials, and equipment that need to be consumed to complete the work content of the TCSs. The information provided allows project participants to focus on planning and logistics of the procurement of TCSs as well as having reliable information about their consumption to be accounted during the preparation of the construction schedule and cost estimates during the early phases of a project, rather than spending valuable time in their quantification. Future research will combine schedule information with the consumption, making it a more beneficial tool to the project management team, and more sophisticated algorithms should be developed to provide more accurate results in a more efficient way.

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