Automatic Generation of the Vertical Transportation Demands During the Construction of High-Rise Buildings Using BIM

K. Wu[a,b], B. García de Soto[c,d], B.T. Adey[a], and F. Zhang[b]

[a] Institute of Construction and Infrastructure Management, ETH Zurich, Switzerland
[b] School of Civil Engineering, Central South University, China
[c] Division of Engineering, New York University Abu Dhabi (NYUAD), UAE
[d] Department of Civil and Urban Engineering, Tandon School of Engineering, New York University (NYU), USA
E-mail: keyi-wu@hotmail.com, garcia.de.soto@nyu.edu, adey@ibi.baug.ethz.ch, zfl@csu.edu.cn

Abstract –

The explosion of high-rise building projects has increased the awareness on the importance of the planning and management of vertical transportation systems (i.e., tower cranes, construction elevators and concrete pumps). Although researchers have made beneficial efforts in several aspects of vertical transportation systems (e.g., optimal design capacities and layouts), the estimation of demands on vertical transportation systems (i.e., the quantity of construction resources associated with location, trip date and vertical transportation mode) has not been fully integrated. Currently, this process is still done manually. Building information modeling (BIM) provides the possibility to automate this process, decreasing the time it takes to gather that information and reducing errors associated with manual collection and quantification. This paper proposes a BIM-based framework to generate the vertical transportation demands during the construction of high-rise buildings. It consists of six parts: (1) determine the vertical transportation information of building materials, (2) generate the vertical transportation information of temporary construction materials, (3) link the project schedule with construction materials, (4) generate the vertical transportation information of construction workers, (5) determine the vertical transportation mode for construction materials, and (6) generate the vertical transportation demands. A prototype tool, in the form of an add-in using Revit API, has been developed to demonstrate the functionality of the proposed framework through testing the BIM model of a 36-story high-rise building. The findings show that the framework allows to exploit BIM to generate the information needed to determine the vertical transportation demands quickly and effortlessly.

Keywords –

BIM; Vertical transportation demands; Vertical transportation systems; High-rise buildings

1 Introduction

In recent years, the number and height of high-rise buildings have increased significantly [1]. According to the Council on Tall Buildings and Urban Habitat (CTBUH) [2], the total number of 200-meter-plus buildings in the world was 263 in 2000. This number increased to 1,319 in 2017, a 402% increase from 2000. The average height of the world's 100 tallest buildings increased from 285 meters in 2000 to 372 meters in 2017, a 31% increase.

The vertical transportation of resources required in construction projects is becoming increasingly important, especially in the case of high-rise buildings [3]. During the construction of high-rise buildings, there are not only more resources to be transported, but also transportation distances are longer, making the vertical transportation efficiency an important factor when considering the progress of construction projects [1]. For this reason, vertical transportation systems, including tower cranes, construction elevators and concrete pumps (Figure 1), are attracting more and more attention from both academia and industry.

Figure 1. Tower cranes and concrete pumps used in the early stages of the construction of a high-rise building (source: the authors)

Some researchers have made beneficial efforts in several aspects of vertical transportation systems, such as optimal design capacities [1] [3] [4] and layouts [6] [7] [8]. These studies require vertical transportation demands (i.e., the quantity of construction resources (e.g., weight and volume of materials, number of workers) associated with location, trip date and vertical transportation mode) as the basis for analysis and calculation. However, a main challenge is to obtain the required information because the current estimation process is still being done manually, making this process time consuming, tedious, and prone to errors [1] [9].

As a rapidly developing digital technology in the AEC industry, building information modelling (BIM), has made it possible to solve some of the above problems due to its rich information stored (e.g., quantity and location of building elements), with the potential of automating the estimation process [10] [11]. Some researchers have made beneficial attempts to estimate the vertical transportation demands using BIM. In their research, the quantity, weight, dimension, coordinate and level of building elements in the BIM model were extracted to determine the load and destination of each transportation for tower cranes [4] [9] [12]. Each building element was categorized according to its material under the same family name and associated with schedule information [4] [9]. In order to estimate the vertical transportation demands of temporary construction materials, formwork and scaffolding were created in the BIM model [9]. However, these studies still have some application limitations. First, manually creating temporary construction materials is inefficient, it has been showed that the total modelling time doubles or more according to previous project experience [14]. Second, the researchers have not yet developed a method to link the objects explicitly according to their characteristics due to the discrepancy between the model break down structure in the BIM model and the work break down structure in the project schedule [13]. Although some BIM tools, such as Autodesk Navisworks, can link project schedule information with building elements semi-automatically [5], they are still inconvenient due to the need to create the corresponding collection of building elements in the BIM model according to tasks in the project schedule. Third, construction workers have a greater impact on the transportation performance of construction elevators than construction materials [1], nevertheless, construction workers are difficult to capture in the BIM model, and have not been included yet in the previous studies. Fourth, there is a variety of vertical transportation modes (e.g., tower crane, construction elevator, and concrete pump) to be used in high-rise building construction, the researchers have not yet allocated transportation resources to different vertical transportation modes available.

In order to address these limitations, this paper proposes a BIM-based framework to generate the vertical transportation demands during the construction of high-rise buildings. The remainder of the paper is organized as follows. First, each part of the framework is explained in detail. Subsequently, an example is tested using a prototype tool to validate this framework. Furthermore, the benefits and limitations of the framework are discussed. Finally, conclusions and ongoing work are provided.

2 Proposed Framework

Based on the use of BIM authoring tools (e.g., Autodesk Revit), a framework to generate the vertical transportation demands is proposed (Figure 2). It consists of the following six parts: (1) determine the vertical transportation information of building materials, (2) generate the vertical transportation information of temporary construction materials, (3) link the project schedule with construction materials, (4) generate the vertical transportation information of construction workers, (5) determine the vertical transportation mode for construction materials, and (6) generate the vertical transportation demands. These six parts are explained in the following subsections.

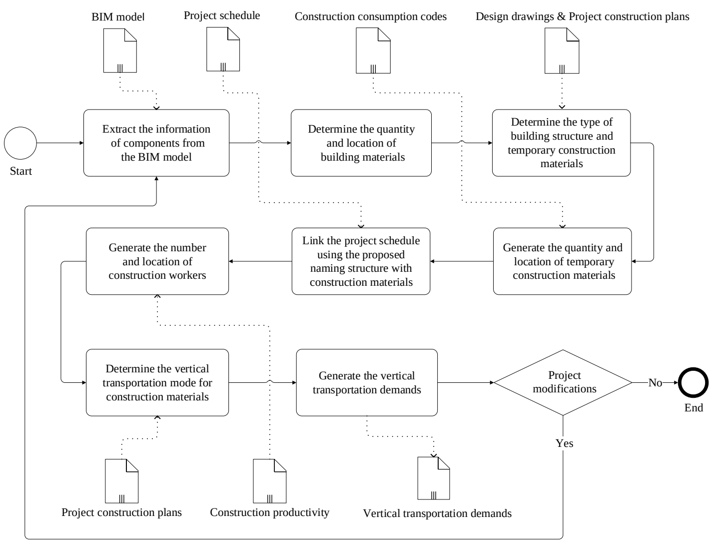

Figure 2. A BIM-based framework to generate the vertical transportation demands

2.1 Part 1: Determine the vertical transportation information of building materials

In Part 1, the information of components is extracted from the BIM model, including building elements (ID number, category (e.g., columns, walls, beams, slabs, stairs), type (e.g., rectangular beam, special-shaped beam), floor, material property (e.g., material quality, density) and dimension (e.g., height, length, width)), building areas (ID number, floor and area), and building levels (ID number, level and elevation). This information is used to determine the quantity (i.e., weight and volume) and location of building materials, and to gather the information required to generate the vertical transportation information of temporary construction materials in the next part.

2.2 Part 2: Generate the vertical transportation information of temporary construction materials

During the construction of high-rise buildings, the quantity of temporary construction materials (i.e., formwork and scaffolding) to be transported is large. It becomes critical when deciding vertical transportation cycle-time [15]. Part 2 is to generate the vertical transportation information of temporary construction materials, including quantity and location.

In the construction industry, there are existing construction consumption codes to estimate the quantity of temporary construction materials. For example, according to the consumption code [16], the quantity of formwork is based on the type (e.g., rectangular beam, special-shaped beam, lintel) and dimension (e.g., height, length, width) of building elements to be constructed, as well as the type of formwork to be used (e.g., bamboo plywood formwork with steel shoring). Similarly, the quantity of scaffolding is based on the building structure type (e.g., frame structure, shear wall structure), building height and area, as well as the type of scaffolding to be used (e.g., steel pipe scaffolding). In this part, the construction consumption codes are used. Figure 3 shows the process to estimate the quantity of temporary construction materials using the consumption codes. It consists of three steps. First, obtain the information required by the consumption codes from the BIM model and project construction documents (i.e., design drawings and project construction plans). Then, determine the unit quantity of the corresponding items in the consumption codes according to the information obtained, including the unit quantities of formwork for different building elements and the unit quantities of scaffolding for different building areas. Finally, calculate the quantity of temporary construction materials. Meanwhile, the location of temporary construction materials is determined from that of corresponding building elements (in the case of formwork) and building areas (in the case of scaffolding). Through using the BIM model and applicable consumption codes, the vertical transportation information of temporary construction materials is generated without creating them directly in the BIM model.

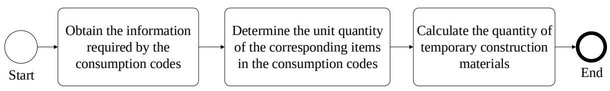

Figure 3. Process to estimate the quantity of temporary construction materials

2.3 Part 3: Link the project schedule with construction materials

Part 3 is to link the information from the project schedule (i.e., start and finish dates) with construction materials. This information will be used to quantify the number of construction workers and determine the trip date of construction materials and workers in the subsequent parts (Part 4 and Part 6).

The work break down structure of the project schedule typically has four levels (Figure 4 (a)), including sub-projects (e.g., foundation, main structure,

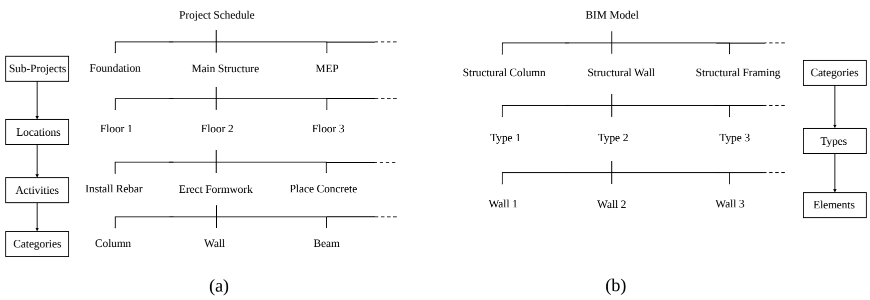

Figure 4. Work break down structure of the project schedule (a) and model break down structure of the BIM model (b)

MEP), locations (e.g., floors), activities (e.g., install rebar, erect formwork, place concrete), and categories (e.g., column, wall, beam). While the BIM model is generally broken into three levels (Figure 4 (b)), with categories, types, and elements. The discrepancy between the work break down structure in the project schedule and the model break down structure in the BIM model, leads to considerable time and efforts spend in matching and linking construction tasks and building elements [13]. To address that, a naming structure for tasks of the project schedule is proposed, as shown in Figure 5.

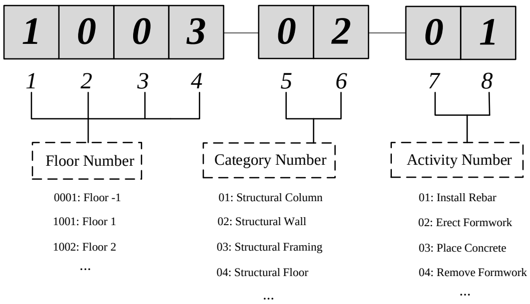

Figure 5. Proposed naming structure for tasks of the project schedule

The naming structure consists of three parts, namely (1) floor number, (2) category number, and (3) activity number. The floor number indicates the location of tasks. The category number is defined based on building element categories in the BIM model. The activity number represents the work scope of tasks. For example, a task with a "1003-02-01" name, as shown in Figure 5, means (read backwards) installing rebar for the structural walls in floor 3. According to this information, the task links all the structural wall rebar located on floor 3, meanwhile, the construction workers installing the structural wall rebar will also be connected in Part 4.

2.4 Part 4: Generate the vertical transportation information of construction workers

Ensuring that construction workers can be transported to destination floors on time, has a great influence on the construction progress, in some cases, it is more critical than transporting construction materials [1] [17]. Therefore, having a good understanding on the vertical transportation demands of construction workers is very important. In Part 4, the number and location of construction workers are generated.

The number of construction workers are calculated based on the quantity of construction materials, the duration of tasks (i.e., start and finish dates), and the construction productivity (Equation (1)).

$$N = \frac{Q}{(F - S + 1) \times P} \tag{1}$$

Where, N represents the number of construction workers per day for a given task; Q indicates the quantity of construction materials, with units depending on the type of materials (e.g., rebar (kg), formwork (m^2), concrete (m^3)); S and F are the start and finish dates, respectively, of the task evaluated; and P, namely the construction productivity, refers to the construction quantity per worker per day (e.g., for concrete: m^3/worker/day). For example, if the concrete volume of a structural column is 17.5 m^3, the start and finish dates of placing concrete are the same day, and the construction productivity is 35 m^3/worker/day, the construction worker number, using Equation (1), is 0.5. Meanwhile, the construction worker location is determined based on that of the column. The total number of construction workers required at a given date and location will be aggregated in Part 6.

2.5 Part 5: Determine the vertical transportation mode for construction materials

In the construction of high-rise buildings, different types of construction materials are usually transported through specific vertical transportation modes, for example, rebar is generally transported using tower cranes. But in some cases, some types of construction materials may also use different vertical transportation modes, for instance, concrete is usually transported by concrete pumps, but sometimes tower cranes are also used to lift it using concrete buckets. Therefore, Part 5 is to determine the vertical transportation modes for all construction materials taking into account actual planning defined by the project team.

Figure 6 shows the process to specify the vertical transportation modes to be used for different construction materials. It consists of the following three steps: (1) select the material to be transported (e.g., rebar, formwork, concrete); (2) choose the location to which the material will be transported (e.g., floor 1, floor 2, floor3); and (3) specify the vertical transportation mode to be used (e.g., tower crane, construction elevator, concrete pump).

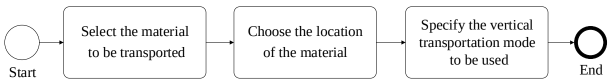

Figure 6. Process to specify the vertical transportation modes to be used for different construction materials

Table 1. Quantity output of construction resources using different vertical transportation modes

Vertical transportation mode	Quantity output		
	Material weight	Material volume	Worker number
Tower crane	✓		
Construction elevator	✓	✓	✓
Concrete pump		✓	

2.6 Part 6: Generate the vertical transportation demands

After the implementation of Part 1 through Part 5, the quantity, location, trip date, and vertical transportation mode of different construction resources have been determined. In Part 6, this information is compiled to display the vertical transportation demands for each type of vertical transportation systems. If there are any modifications to the project, the vertical transportation demands will be regenerated according to the updated BIM model and construction documents.

In general, the transportation volume of vertical transportation systems is limited by their loading capacities and space constraints. For tower cranes, the loading capacity is the main limiting factor. With respect to construction elevators, cages impose constraints on the dimensions of the object being transported, hence, construction elevators are limited by both the loading capacity and space constraint simultaneously. Concrete pumps are different from the above two types of vertical transportation systems since their transportation volume is based on the volume of concrete transported per hour. Thus, the quantity output of materials to be transported by tower cranes is weight, that of materials to be transported by construction elevators is weight and volume, that of materials to be transported by concrete pump is volume, and workers are output by number (Table 1).

3 Example

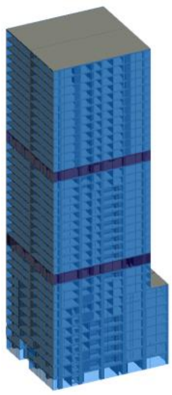

Figure 7. 3D view of the BIM model used in the example

A BIM model developed using Autodesk Revit 2017 [18] was used to test the proposed framework. The BIM model consists of a 36-story high-rise building with a height of 149.6 meters (Figure 7), which contains columns, walls, beams, slabs, stairs, wall finishes, doors, windows and glass curtain walls. For simplicity, the MEP system was excluded. The rebar information was generated using the Glodon software (GGJ 2013) [19]. Based on the framework, a prototype tool was developed in C# by using Revit API [20]. A database containing 14 tables was created using MySQL [21] (Figure 9), it can be divided into 4 parts, the blue table information (i.e., “Building Element”, “Building Area”, and “Building Level”) was from the BIM model, the green table information (i.e., “Consumption Code”, “Construction Productivity”, and “Formwork Content) was from the construction codes, the yellow table information (i.e., “Project Schedule”, “Vertical Transportation Mode”, “Formwork Type”, “Scaffolding Type”, and “Building Characteristic”) was from the project construction documents, and the red table information (i.e., “Formwork”, “Scaffolding”, and “Construction Worker”) was from the generated information. A use interface (Figure 8) was developed to determine the formwork type (i.e., bamboo plywood formwork with steel shoring), building structure type (i.e., frame-shear wall structure), scaffolding type (i.e., steel pipe scaffolding) and vertical transportation mode (e.g., tower crane, construction elevator, concrete pump) used for construction materials. Microsoft Project was used to develop the project schedule. The vertical transportation demands were generated as the Microsoft Excel files (Figure 10 to Figure 14).

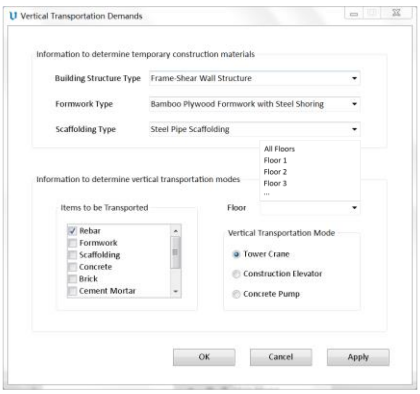

Figure 8. Developed user interface

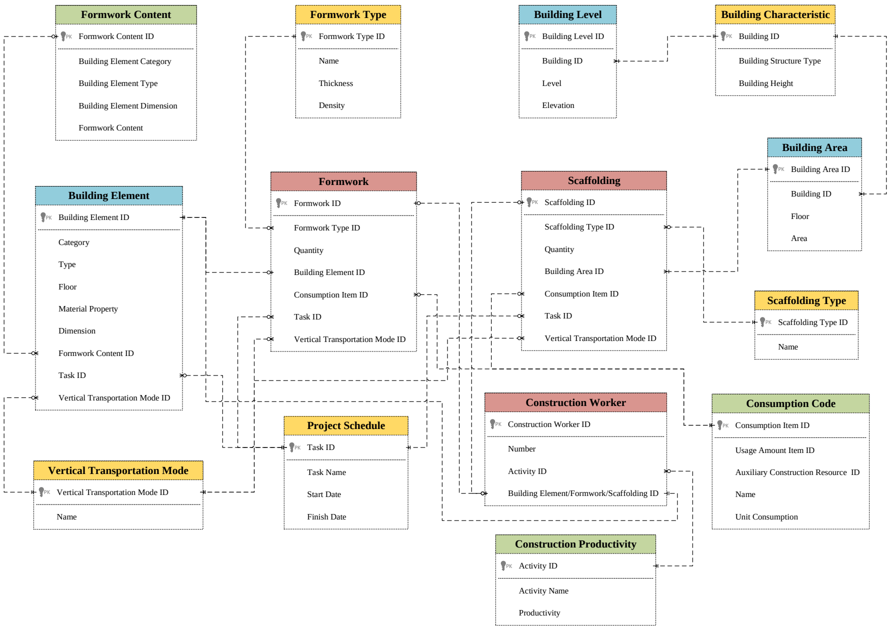

Figure 9. Database model diagram of the prototype tool

Figure 10 through Figure 14 show the vertical transportation demands for different types of vertical transportation systems. The horizontal, longitudinal and vertical axes represent the trip date, location and transportation volume, respectively. They provide valuable information for the project team. For example, this information shows that the maximum transportation weight of 765,871.43 kg for tower cranes occurs on May 24, 2015 and it is transported to floor 1 (Figure 10); the maximum transportation weight for construction elevators is 411,943.68 kg (139,232 kg to floor 4 and 272,711.68 kg to floor 19) on October 18, 2015 (Figure 11); the maximum transportation volume for construction elevators is 385.61 m³ to floor 8 on August 22, 2015 (Figure 12); the maximum transportation volume to be transported using concrete pumps is 615.57 m³ to floor 24 on October 22, 2015 (Figure 13); 238 construction workers (the maximum number) take construction elevators to floor 2, 3, 8, 16 and 21 on October 5, 2015 (Figure 14). With the information generated, the maximum transportation demands for different types of materials can also be obtained. For example, the maximum transportation weight for rebar is 142,613.59 kg (May 24, 2015/floor 1) and the maximum transportation weight of formwork is 176,658.9 kg (August 2, 2015/floor 10).

In addition to the obvious maximum transportation demands, the different trends can also be analyzed from the results. For example, different phases can be defined by the project manager based on the requirements for different transportation modes. When looking at the number of construction workers using construction elevators per day (Figure 15), from May 24 to August 20, 2015, the number of construction workers gradually rises to 149, this period could be defined as Phase 1. From August 21 to December 28, 2015, the number of construction workers starts to exceed 150, with the peaks over 200, this period could be defined as Phase 2. From December 29, 2015, the number quickly drops below 100, after that, the utilization remains stable, this period could be defined as Phase 3. The number and type of construction elevators to be used can be adjusted for each phase.

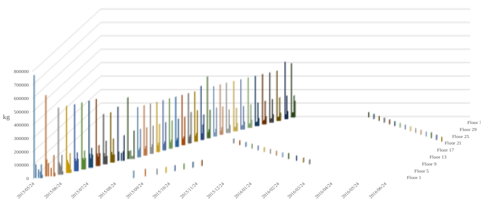

Figure 10. Output showing the vertical transportation demands (kg) to be transported by tower cranes

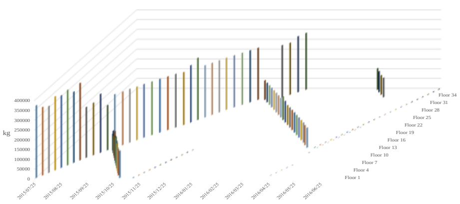

Figure 11. Output showing the vertical transportation demands (kg) to be transported by construction elevators

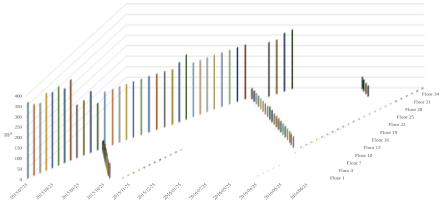

Figure 12. Output showing the vertical transportation demands (m³) to be transported by construction elevators

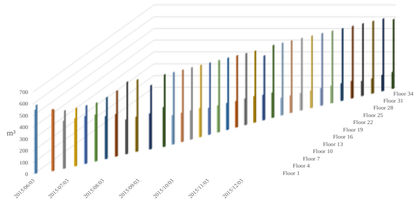

Figure 13. Output showing the vertical transportation demands (m³) to be transported by concrete pumps

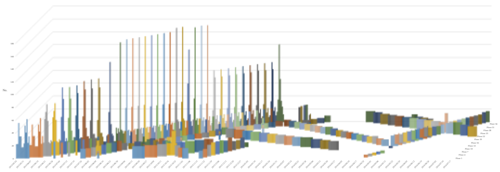

Figure 14. Output showing the vertical transportation demands (No. of workers) to be transported by construction elevators

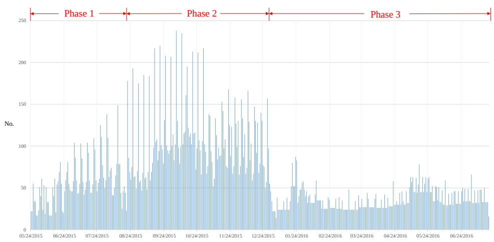

Figure 15. Output showing the number of workers to be transported by construction elevators per day

4 Discussion

This study is beneficial to the information collection of vertical transportation resources, and it makes three main improvements to the existing literature. First, the information of temporary construction materials is automatically generated without creating them directly in the BIM model (i.e., the design information model), as well as that of construction workers, which greatly enhance the efficiency of the collection process. Second, the proposal of the naming structure for tasks in the project schedule breaks the information barriers between BIM model and project schedule, making no additional manual operation is required for their interoperability so that reducing the unnecessary duplication of work and the loss of information. Third, the demands on multiple vertical transportation modes (i.e., tower crane, construction elevator and concrete pump) are generated simultaneously, not just one mode, allowing the project team to easily plan and manage the overall vertical transportation systems for achieving the global optimal solution. At the same time, the framework provides a dynamic aspect, generated results can be easily adjusted to account for changes.

This framework provides a promising solution to automate the generation process of vertical transportation demands during the construction of high-rise buildings, however, there are limitations yet to be addressed. First, it is common to use some floors as temporary storage spaces in the construction of high-rise buildings, hence, it is necessary to account for the transportation of resources between floors. Second, the framework does not consider the issue of transporting construction waste produced during construction down due to the amount of construction waste is not negligible in high-rise building construction. Third, it is normal to use permanent elevators when construction elevators have to be removed before finishing building enclosure work, which would reduce the demands on construction elevators, so the permanent elevator should be included as a vertical transportation mode. Ongoing research is carried out by the authors for addressing these limitations to make the framework more practical and valuable.

5 Conclusion

The boom in the construction of high-rise buildings creates some new challenges, such as the planning and management of vertical transportation systems. It also indirectly puts forward new requirements for the speed and accuracy of the vertical transportation demand collection. This paper proposes a BIM-based framework to automatically generate the vertical transportation demands, integrating the construction codes and project construction documents. The framework has been validated through an example project consisting of a 36-story high-rise building using a developed prototype tool. From the application of the proposed framework, the construction materials and workers needed by different types of vertical transportation systems were obtained quickly and effortlessly, greatly reducing the collection time. The generated three-dimensional graphs clearly show the quantity, location, and date of different vertical transportation demands, they can be utilized by the project team during the planning and management of vertical transportation systems (e.g., determine vertical transportation period time). The current framework is at an early stage, it is expected to make the estimation on vertical transportation demands faster and more accurate by expanding and extending this basic framework. Ongoing work is conducted to address the limitations mentioned above.

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