An Automatic Scheduling Approach: Building Information Modeling-Based On-site Scheduling for Panelized Construction

Hexu LIU1, Zhen LEI2, Hong Xian LI3, Mohamed AL-HUSSEIN4

1 Hole School of Construction Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada T6G 2W2; PH (780) 492-0370; email: hexu@ualberta.ca
2 Hole School of Construction Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada T6G 2W2; PH (780) 492-0370; email: zlei@ualberta.ca
3 Hole School of Construction Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada T6G 2W2; PH (780) 729-8196; email: ho8@ualberta.ca
4 Hole School of Construction Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada T6G 2W2; PH (780) 492-0599; FAX (780) 492-0249; email: malhussein@ualberta.ca

ABSTRACT

Panelized/modular construction is increasingly adopted within the industry as a primary construction method, with in-plant fabrication and on-site assembly as two of the main processes. Each of these two processes involves a different emphasis regarding productivity improvement: for in-plant fabrication, manufacturing process management is the main focus, while, for on-site assembly, scheduling and management of assembly operations are of particular interest. This paper proposes a generic approach by which to generate the on-site schedule automatically based on a building information model (BIM), considering the structural supporting and topological relationships among building elements, as well as knowledge of steel panel construction. The BIM model is developed in an Autodesk Revit environment, based on which precedence relationships of elements are derived automatically, and is utilized to perform the on-site schedule through the Autodesk Revit Application Programming Interface (API). The generated schedule results are exported into Microsoft Project for further analysis, such as resource leveling. A case example is provided to demonstrate and validate the methodology. This paper explores the implementation of BIM, with the scheduling of panelized construction as the focus. This research lays the foundation for further implementation of BIM using Autodesk Revit.

INTRODUCTION

In Canada, mid-rise multi-family residential buildings can be constructed using steel-structured panels which are prefabricated in factories and subsequently shipped to the site for installation in a process referred to as panelized construction. This process, compared with the conventional on-site construction method, minimizes the waste involved in the construction process and enhances efficiency. The success of such projects relies on accurate and reasonable scheduling for the production, shipping, and installation of the panels, where delays in panel delivery or
overproduction in factories can result in project delays and inventory costs. In current practice, schedules are planned manually based on practitioners’ experience and intuition. There are many existing methods for planning scheduling for construction projects (de Vries et al. 2007; Chua et al. 2011; Chua et al. 2013); however, these methods are not suitable for planning panel schedules for panelized construction projects, due to the large number of elements (panels) involved. An automated system is therefore required in order to plan schedules for panelized construction projects.

Building information modeling (BIM), a visualization-based information modeling method, is widely utilized in construction in a variety of applications, such as (1) automated BIM drafting and design for modular construction (Alwisy et al. 2012); (2) building energy analysis based on BIM (Barnes and Castro-Lacouture 2009; Cho et al. 2010); (3) use of BIM for collision detection in order to mitigate safety risks in construction projects (Zhang and Hu 2011; Cheng and Teizer 2013; Zhang et al. 2013); and (4) cost estimation based on BIM models (Cheung et al. 2012). In terms of project scheduling, a few attempts have been made in academia targeting BIM-based project scheduling, such as a prototype developed by Kim et al. (2013) for automating construction scheduling by parsing an Industry Foundation Classes (IFC) BIM model. However, their work did not illustrate how sequence reasoning rules generate the logistics for the schedule. In industry, there are some excellent BIM/4D tools such as Tekla Structure and Autodesk Navisworks. Most of them are developed for the purpose of project visualization, and they do not provide the scheduling feature for construction management. On the other hand, some well-developed commercial scheduling tools, such as MS Project and Primavera P6, also exist in the market which are instrumental in project management. Nevertheless, any scheduling utilizing these existing programs requires massive manual involvement during the planning phase, and cannot make full use of existing enriched information in BIM for the automated generation of construction schedules. Planners thus are still challenged to handle scheduling automatically for construction projects based on BIM, and an exploration of BIM-based scheduling for panelized construction projects in particular is missing from the literature.

Based on previous studies, this research aims to implement and manipulate information from the BIM model. The research objective is to propose a generic approach by which to generate schedules automatically from the BIM model based on the structural supporting and topological relationships among building elements and knowledge of the construction process for residential building which uses the Light Gauge Steel (LGS) system.

CONSTRUCTION SEQUENCE OF RESIDENTIAL BUILDING USING LGS

Light Gauge Steel (LGS) provides a cost-effective building solution due to the fact that most of the building elements in this system, such as the walls and bathrooms, are prefabricated in the factory and then delivered to the site for on-site assembly. Compared with other construction systems or methods, the on-site work involved in LGS construction mainly involves assembly of building elements, such as wall panels and floor joists. In practice, the LGS system has unique requirements in terms of on-site assembly. At present, in LGS construction, structural bearing walls are pre-assembled in the manufactory factory and installed on site as wall panels, while, in
the case of non-bearing walls, the steel building materials are delivered to the construction site and the walls are fabricated in place in a conventional manner. The floor, made up of steel joists, is constructed in the same fashion as the non-bearing walls. It is assembled on site from pieces of steel joists, rather than being installed as a pre-fabricated floor. It should also be noted that the washroom is pre-fabricated as a module in the factory and shipped to the site for on-site installation. The washroom module usually consists of four walls, a floor, and a ceiling, (which serves as the floor for the level above); all other components in the washroom, such as the tub, are also installed prior to shipment to the site. Additionally, since the washroom is a stand-alone module which does not require an additional temporary bracing system, on-site assembly work for wall panels at the same level commences with installation of the washroom module. The next elements to be installed are the wall panels, which are connected to the washroom module. Following the walls adjacent to the washroom module, other wall panels are installed sequentially. Figure 1 illustrates one feasible construction sequence of an apartment unit in a hypothetical panelized building which is adopted as a case example. It should be noted that “CS” refers to the construction sequence and “Bearing”/“Non-Bearing” indicates the wall panel structure function. In the figure, some wall panels have the same construction sequence number, since technically they can be assembled concurrently provided that there are sufficient construction resources (e.g., equipment and labor) on the construction site. Construction of the steel joists for the floor is divided into zones corresponding to the different apartment units in the residential building, i.e., assembly of floor joists is performed apartment-by-apartment.

![Figure 1. Construction sequence of a hypothetical structure](image)

**PROPOSED METHODOLOGY**

In this research, in order to determine the on-site erection sequence and schedule the on-site assembly process effectively, Autodesk BIM Solution-Revit is adopted to model the LGS residential building, and is extended to perform the on-site
scheduling. An extension for Revit is developed for construction sequence reasoning and automatic scheduling. Figure 2 illustrates the architecture of the proposed automatic schedule system based on Revit. The automatic system comprises the following three components: (1) Microsoft (MS) Access, where project resources information and the resource requirements and productivity of each process are stored; (2) Autodesk Revit, which is used to design the building project; and (3) MS Project, which is employed in order to display the generated schedule and perform resource leveling analysis. The three components are connected through an Autodesk Revit application programming interface (API) in C# language. More specifically, Revit API is utilized to extract and manipulate the information of building elements in order to analyze the precedence relationship, to read available resource information of projects, resource requirement and productivity information of each activity from MS Access, and to export the generated schedule into MS Project.

The methodological flowchart of the proposed schedule system is demonstrated in Figure 3. The inputs in the research methodology include: (1) available resources for the project; and (2) the resource requirements and productivity of each activity, which determine the activity duration for each process and will also be utilized for resource leveling afterward. The first step of the main process is to parse the information of building elements and then to infer the supporting relationship and topological relationships among building elements based on the 3D BIM model. Precedence relationships are further generated according to the aforementioned relationships among elements in the BIM model and to panelized construction knowledge (sequence reasoning rules). The activity duration for each process is calculated based on the productivities stored in MS Access. Based on the precedence relationship and the duration, on-site operation is scheduled. The outputs from the system are the schedule results, which are imported into MS Project in order to facilitate communication among project stakeholders, as well as construction resource leveling. In the proposed system, the core components are the construction sequence reasoning module and the activity duration calculator. Detailed illustrations of the automatic system are discussed below.
BIM-BASED CONSTRUCTION SEQUENCE REASONING

Theoretically, the construction sequence depends mainly on the structural behavior of the temporary structure during construction and the adopted construction method. Previous researchers have attempted to derive the construction sequence based only on topological relationships, and have developed several topological deduction algorithms based on 3D geometric information from 3D CAD models. With the development of BIM, however, it is possible to generate the construction sequence more efficiently and practically. Compared with traditional 3D-based project modeling, which only includes geometric information of buildings and cannot bear any semantic information or knowledge about construction, BIM offers enriched information (content) for each element, thereby laying the foundation for many kinds of analysis. Figure 4 shows the overall flowchart of the construction sequence reasoning algorithm, while detailed explanations of the algorithm components are provided in the following section.

Supporting relationship of structural elements

Residential buildings using LGS, which are the main focus of this research, from the structural perspective are composed of walls, floors, and foundations. In order to derive construction sequences, the supporting relationships among structural elements must first be determined. With respect to the floor, two different systems are commonly adopted in current practice, as shown in Figure 5. On the right side of the figure, the floor joists are resting on top of the wall panels, whereas the floor system on the left side of the figure is connected to the interior side of the wall panel. As a result, the direct supporting building elements for wall panels on the above floor will
be different for the two floor systems. For the case of the system on the right side of the figure, the wall of the upper level is supported directly by the floor system, whereas for the case on the left side of the figure the wall panel on the upper level is supported by the wall panel on the lower floor. Although the direct supporting elements are different, in both cases the erection work of the wall panels on the above floor cannot begin until the floor is assembled. In coping with this challenge, Revit provides a cost-effective way to find the supporting information of building elements through an analytical model, a simplified 3D representation of the full engineering description of a structural physical model which is created automatically when the 3D physical model is created. The supporting information of each structural element can be easily extracted by means of the Revit API function, “element.GetAnalyticalModelSupports()”. Regardless of the type of floor system, both the wall panel and floor are collected by Revit API as supporting elements for the above wall panel. Also, supporting information among other structural elements, such as the foundation slab and wall foundation, can be easily extracted by the above mentioned function. Furthermore, the supporting elements are recorded as the predecessors of the building elements being supported.

**Figure 1. Flowchart of predecessor relationship detection**
Connection relationships among walls

After the predecessors of building elements are derived from the structural perspective, topological relationships are used to ascertain the construction sequence on the same floor in order to take into account the special construction sequence mentioned in the previous section. Topological relationships, it should be noted, encompass all the spatial relationships among building elements, including connection, adjacency, intersection, and containment (Nguyen et al. 2005), but the present research investigates only the connection relationships among walls on the same floor.

In terms of connection relationships among walls, Revit API provides some functions, such as get_ElementsAtJoin(indexofWallEnd), which detect walls joined end-to-end. In addition, Revit always forces the elements to automatically join to their neighbors where appropriate; therefore, this function can be used to detect the connections. However, the calculated results cannot be used in the construction sequence reasoning directly when more than two walls join at one point, as shown in Figure 6, so further modification is required. For the case presented in Figure 6, wall panel 3 and wall panel 2 join together and share one edge; however, they do not connect by sharing one face and thus will never have a direct predecessor relationship. This paper proposes an algorithm by which to infer the connection relationships among walls based on the Revit function, get_ElementsAtJoin(indexofWallEnd). Figure 4 shows the flowchart for calculation of the connection relationships among walls in the dashed-line box.

ACTIVITY DURATION CALCULATION

It should be noted at this juncture that the schedule generated by this research is for the building element level, rather than for the detailed construction activity level. With respect to activity duration, in this research the durations are calculated based on
the quantities from the BIM model and the productivities stored in the project
database. For instance, the duration for one foundation is the volume of concrete
divided by the concrete crew’s productivity. The available resource information is
also stored in the database. All stored information is extracted and imported into Revit
using Revit API. In Revit, the available resources from the database are allocated to
the building element based on the semantic information in the BIM model. For
example, the building foundation is made of concrete, and according to the material
information, the foundation is to be constructed by a concrete crew. Then the concrete
crew is assigned to the foundation activities using Revit API. Later, the generated
schedule, including the resource information, is exported to MS Project through XML,
and resource leveling can be executed to manage the on-site resources.

CASE EXAMPLE
The schedule system embedded into Revit is tested in a residential building as
shown in Figure 7. The building is composed of two storeys, each having four
apartment units and one staircase. Each apartment unit has two washrooms where the
assembly work commences. In addition, there are 182 panels, including sixty non-
bearing walls and 122 bearing walls. The building is sitting on twenty-nine concrete
footings.

![Figure 4. 3D view and plan view of a two-storey residential building](image)

To test the proposed schedule system, the building model is first built in Revit
2014, and the on-site schedule is automatically generated by clicking the “schedule”
command as shown in Figure 8. Meanwhile, the schedule exported into MS Project is
further refined by conducting “Level Resource” in order to avoid the resource over-
allocation. In the case study, a standard workweek which runs Monday to Friday with
each day starting at 8:00 a.m. and ending at 5:00 p.m. is used for each resource. After
leveling, the generated schedule with respect to resource allocation is more reasonable.
For instance, the maximum “% Work Allocated” for the “Frame Crew” is reduced
from around 700% to 100% by using the “Level Resource” feature, with the final
project duration being 52 days. One pertinent consideration is that leveling order for
the resource over-allocation is set on an activity priority basis in MS project, whereas
within the proposed system the priority is assigned to each activity randomly. As shown in Figure 9, which displays part of a generated schedule, assembly of bathrooms 542361 and 542362 follows the completion of supporting floor 458112 and triggers the assembly of the connected wall panels. The schedule logistic replicates the sequences discussed in the previous section as expected.

CONCLUSION AND FUTURE WORK

BIM is increasingly utilized within the construction industry. This research develops a scheduling system based on Autodesk Revit which makes use of the designed BIM model to automatically generate scheduling of on-site operations. The automated system includes two main components: (1) the construction sequence reasoning component, which derives the construction sequence of building elements; and (2) the activity duration calculator, which conducts duration calculations based on the quantities in the BIM model and the resource productivities stored in the project database. Furthermore, the automatically generated schedule in Revit can be exported to MS Project in order to facilitate communication among project stakeholders and support project management on site. Additionally, in MS Project, the project manager can further conduct resource allocation and leveling. Ultimately, the automated scheduling system developed in this research will assist project managers to effectively plan on-site assembly work and reduce the human error in scheduling for panelized construction. However, since productivities of resources have been obtained based on project managers’ experience, further time studies on construction processes and prediction of durations based on historic data should be conducted in order to improve the performance of the system. Also, automated generation of schedules at the activity level should be investigated.
ACKNOWLEDGEMENTS

The financial support of the Natural Resources and Engineering Council of Canada (NSERC) is gratefully acknowledged. The authors are also sincerely grateful to Fortis LGS Ltd, Edmonton, Canada for their assistance, and to Jonathan Tomalty for technical editing.

REFERENCES


