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Semi-Automated Conversion of 2D Orthographic Views of Wood Building Components to 3D Information Models

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ABSTRACT

Offsite construction (e.g., wood modular houses) has many advantages over traditional stick-built construction, ranging from schedule/cost reduction to improvement in safety and quality of the built product. Unlike stick-built, offsite construction demands higher levels of design and planning coordination at the early stages of the construction project to avoid cost overruns and/or delays. However, most companies still rely on 2D drawings in the development of shop drawings, which are required for the fabrication of the building components such as walls and roofs. In practice, the process of developing shop drawings is usually based on manually interpreting the 2D drawings and specifications, which is time-consuming, costly, and prone to human errors. A 3D information model can improve the accuracy of this process. To help achieve this, the authors developed a semi-automated method that can process 2D orthographic views of building components and convert them to 3D models, which can be useful for fabrication. The developed 3D information model can be further transformed to building information models (BIMs) to support collaboration amongst users and data exchanges across platforms. The developed method was evaluated in the development of wall components of a student apartment project in Kalamazoo, MI. Experimental results showed that the developed method successfully generated the 3D information model of the wall components. A time comparison with the state-of-the-art practices in developing the wall components was performed. Results showed that the developed method utilized approximately 22% of the time it took the state-of-the-art manual method to generate the 3D models.

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INTRODUCTION

Offsite construction is a new paradigm shift that has the potential to improve productivity in the architectural, engineering, and construction (AEC) industry. Some benefits of offsite construction over traditional construction (e.g., stick built) methods include time saving, quality improvement, and opportunity for greater automation, etc. Unlike traditional construction, offsite construction requires considerably more planning, coordination, and accurate design (Sacks et al. 2018). These challenges can be addressed with the implementation of Building Information Modeling (BIM). BIM enables a digital representation of the building design – 3D model and functional requirements of the building or facility. As a result, BIM provides accurate and reliable information to support offsite construction processes (e.g., fabrication and assembly). However, a large portion of construction companies in the industry still rely on 2D orthographic views in the form of 2D drawings (.pdf format) or CAD for information exchange in their workflows. Comparing to 3D BIM, these types of formats are inefficient, lack functional attributes, and may interrupt the continuity of a digital workflow from design to construction, and ultimately operations of the building. For example, the developments of shop drawings are performed manually through interpretations of 2D drawings and specifications, which are time consuming, cumbersome, and error prone. In addition, this approach is limited in the capability to apply design changes in an automated way, which requires laborious rework to accommodate design changes and could incur additional cost.

The manual creation of 2D orthographic views (i.e., shop drawings) from design models for construction and fabrication involves additional efforts and time spending from stakeholders, especially contractors, and can lead to cost overruns and/or delays in construction projects. On the other hand, the use of 3D models can improve the accuracy and efficiency in the development of construction and fabrication models. Moreover, it can support automation by using 3D models as input for automation technology such as CNC, automated machines, and robotics. Therefore, to address this gap, the authors propose a method that can semi-automatically process 2D orthographic views of building components and convert them to 3D information models. This paper presents the method and algorithms developed to generate 3D models from 2D PDF architectural plans. The 3D output files can be further transformed to BIM to help improve collaboration amongst users and data exchanges across different platforms.

BACKGROUND

Offsite wood construction. Recently, offsite construction has been gaining favor by the AEC industry (Laubier et al. 2019) because of its numerous benefits in terms of protected working conditions (e.g., controlled environments), opportunities in schedule compression (e.g., perform activities in parallel), and opportunities in optimization (e.g., reduction of wastes) over

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conventional onsite construction (e.g., stick-built) (Lawson and Ogden 2010; KPMG 2016; McGraw Hill Construction 2011). These benefits could result in schedule shortening (Ormarsson et al. 2019), quality improvement, safety improvement, and overall cost reduction, amongst others (Tam et al. 2007). Wood construction is one of the most common type of construction for residential structures, and it has been primarily used in residential houses and some commercial buildings, especially in North America and Europe (Lawson et al. 2012). For example, 90% of the residential houses in the United States are wood structures (Nunnally 2007). Historically, wood has performed well in a wide range of climate conditions. Moreover, comparing to most other construction materials (e.g., concrete and steel), wood is more environmental friendly because of its less CO_2 emission (Nässén et al. 2012) and less embodied energy (Glover et al. 2002). Due to the need in the prefabrication process, offsite construction has more rigorous requirements in terms of design and planning (Alwisy et al. 2019) than those of onsite construction. Therefore, the use of 3D model information is critical for the success of modular construction projects. However, current implementations of modular construction process still mainly rely on 2D orthographic views. For example, standard CAD and printed drawings are used in the design and manufacturing stages of timber module prefabrications (Johnsson and Meiling 2009). CAD and 2D drawings are inefficient to directly fulfil the needs of offsite construction automation as the building components are manufactured and assembled both in 3D. The dependence on CAD and 2D drawings in the creation of 3D information models for manufacturing and assembling the building components creates a bottleneck of information transfer between design and construction phases.

3D model generation. In order to take full advantages of the BIM tools available for offsite construction in the AEC industry, the 3D model generation from 2D drawings are needed for providing richer geometric information. One commonly used technique is the generative modeling, which allows the construction of 3D objects representation from 2D views/images (Lin et al. 2018). Many research efforts have focused on the use of generative modeling in developing 3D models such as those by Wu et al. (2016), Brownlee (2019), and Lin et al. (2018). Similar to previous research efforts, the authors utilized generative modeling in developing a method for the semi-automated processing of traditional 2D architectural drawings to generate a corresponding 3D information model.

PROPOSED METHOD

To address the gap in the generation of 3D information models for offsite construction, the authors developed a semi-automated method and algorithms that process 2D architectural building plans and generate a 3D model of building components . The proposed method consists of the following six steps/processes in generating the 3D information models from the 2D architectural plans (Figure 1). *Process I*: PDF – PNG Conversion; *Process II*: PNG – SVG Conversion; *Process III* – SVG File Segmentation; Process IV: SVG File Contouring; *Process V*: SVG to 3D Objects Conversion; and *Process VI*: Texturing.

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Process I: PDF – PNG Conversion. The input files (2D architectural building plans) are typically using Portable Drawings Format (PDF) format. This process converts the PDF input files into the Portable Graphics Format (PNG) file format. PNG file format is a raster graphics file format that supports true colors and is suitable for image compression.

Process II: PNG – SVG Conversion. This process converts the PNG file format from *Process I* into the Scalable Vector Graphics (SVG) file format. The SVG file format is a vector graphics file format and provides flexibility in scaling, that is, it can be scaled up or down without forfeiting quality. This process also helps get rid of irrelevant markings on the PNG file from *Process I*.

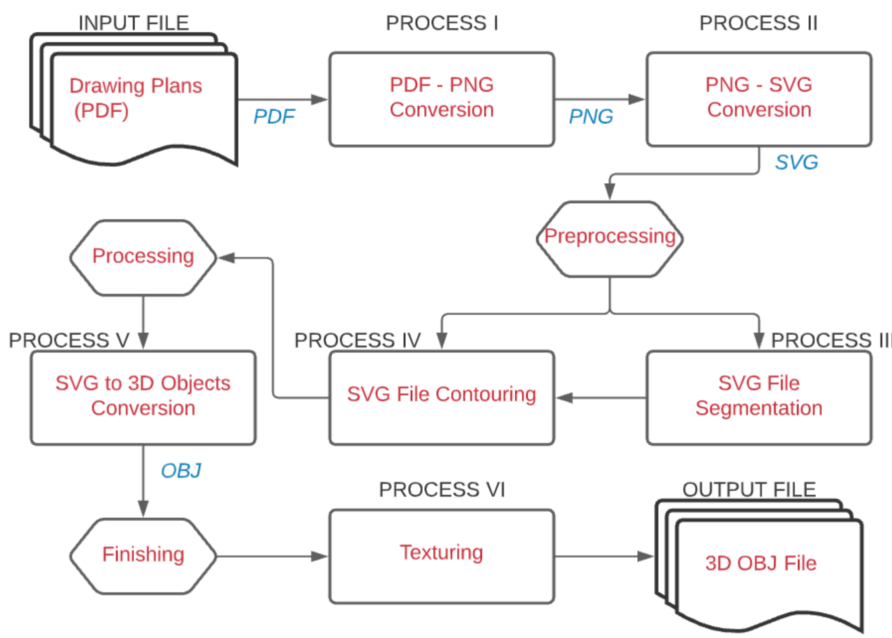

Figure 1. Proposed method.

Process III: SVG File Segmentation. Prior to converting the SVG file format to 3D information models, two preprocessing processes are still needed (SVG File Segmentation and SVG File Contouring). Process III is the first preprocessing process, which splits each building component into segments. Each segment is determined by the design features of the elements of the group to which it belongs; based on the general characteristics of each group, individual structural elements are determined. As an example, for the building wall component, the entire wall component of the building on the architectural plan will be ungrouped and split into several pieces, called segments. Each of the similar elements found on the general plan will be used in building the 3D model of the wall component. The boundary of each segment is selected in accordance with design features and visualization. For example, the boundaries of the nearest corners can be utilized to determine and separate different wall segments.

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Process IV: SVG File Contouring. This is the second preprocessing process on the SVG file format. This process further cleans up the segmented SVG file by eliminating lines that are not required in generating the 3D information model. Distinctive geometric features of each group of elements highlight the necessary attributes of the elements to a certain degree of reliability. Other information, e.g., markups, explanatory texts, etc., will be removed and will not be included in the final formation of the structure. These unnecessary elements can lead to model redundancies if items without constructive use values are preserved and displayed.

Process V: SVG to 3D Objects Conversion. This is the last step in generating the 3D information model. This process converts the individual sections of the components, that is, the contoured segments into a volumetric model of the object. Each individual section consists of typical objects and their collected characteristics (e.g., their size and position). Typical objects will be converted into 3D objects in accordance with the database for typical elements. The selected objects will be compared with the collected characteristics (e.g., their size and position) and displayed on the general plan.

Process VI: Texturing. After the 3D information model has been generated, a type of "finishes" is applied to each generated section of the component.

EXPERIMENT

To test the validity of the proposed method, it was evaluated on a student apartment building in Kalamazoo, MI. For the experiment, hardcopy architectural plans were obtained and used in generating the 3D information models for the wall components of the student apartment building. To generate the needed 3D information model, the architectural plans were processed using the proposed method. The details of the experiment are explained below.

Process I: PDF – PNG Conversion. In this process, the sheet containing the floor plan to be processed was manually selected from the provided batch of architectural plans (Figure 2). After the selection of the sheet, the sheet was then imported into the system. Process I converted the imported architectural plan sheet to a PNG file. To achieve this, the proposed method utilized an Optical Character Recognition (OCR) software to scan the PDF building plan and convert the scanned page to a PNG file format. More specifically, the authors utilized a python utility tool called pdf2image.

Process II: PNG – SVG Conversion. The converted PNG file from *Process I* contained information that were unnecessary for the generation of the 3D information model and therefore to be removed. There were three main sub-processes in generating the SVG file: (1) the first sub-process was the utilization of the "opencv" library in python to process the PNG image into red-green-blue-alpha (RGBA) color model; (2) The second sub-process was the creation of a gray-scaled mask to mask the unimportant features in the image file; (3) The third sub-process was the utilization of a configured tracing map to reduce the objects by removing irrelevant objects below

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a certain threshold, and then further exported the image file to a vector graphics file format. An architectural drawing plan, as shown in Figure 2, contained several markings such as symbols and dimensions; some of which were irrelevant to the generation of the 3D information model. The third sub-process ensured that irrelevant marks/symbols were eliminated.

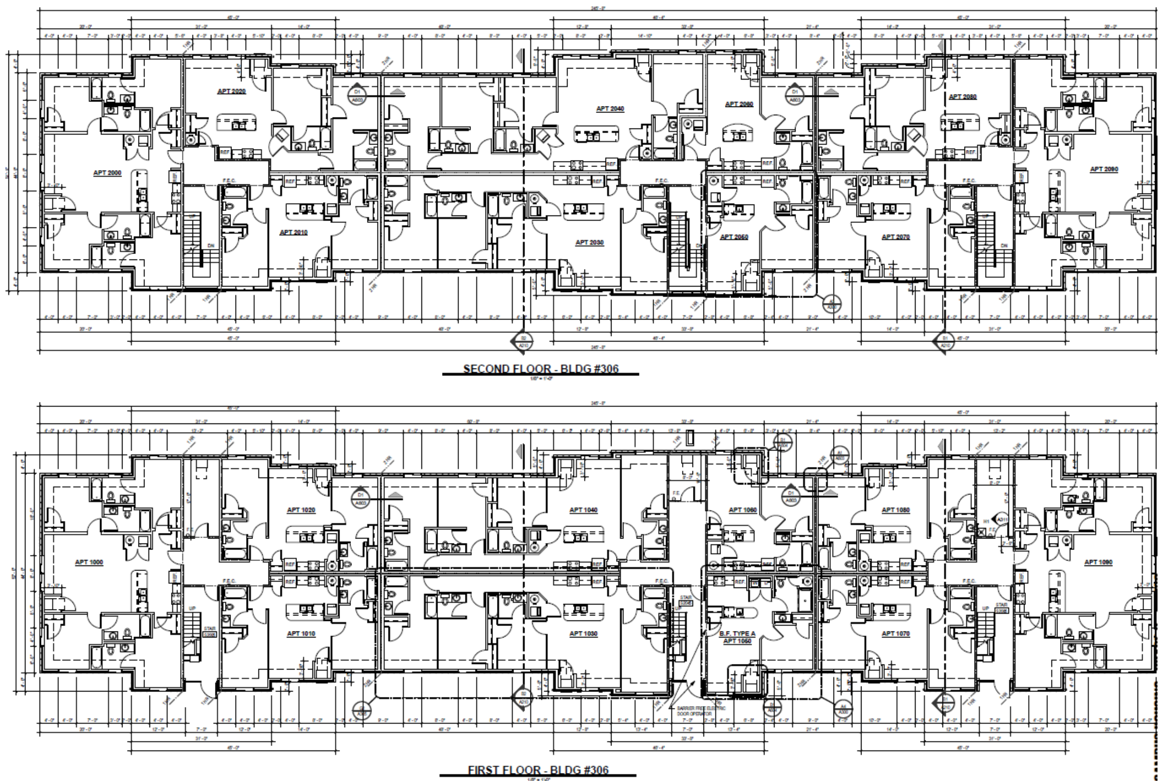

Figure 2. 2D architectural plan sheet.

Process III: SVG File Segmentation. In this process, the SVG file format generated from *Process II* was segmented. Segmentation was the process of extracting regions of importance from a graphical document image. To achieve this, symbol spotting methods were utilized. Each symbol to be recognized was inputted as a query to recognize, and then the system located similar symbols in the architectural plan. As an example, if our query symbol was the graphic element for wall component, we labeled a wall and used geometric feature descriptors to match and locate similar symbols on the architectural plan (Figure 3). Further in Figure 3, four symbols were highlighted: (1) the red highlight represents a window component symbol; (2) the yellow highlight represents a door component symbol; (3) the blue highlight represents a stair component symbol; and (4) the green highlight represents a wall component symbol.

Process IV: SVG File Contouring. In this process, the segmented SVG file format was optimized. Optimization was necessary to remove any false polygons, lines, or symbols that might have been located in the architectural plan from *Process III.*

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Process V: SVG to 3D Objects Conversion. In this process, individual segments of the wall (flat contoured segments) were converted into a volumetric model using an Application Programming Interface (API). More specifically, the blender python API was utilized. Typically, a mesh consists of vertices, edges, and faces; hence, in this process, the vertices, edges, and faces were created to depict the 3D objects. For this experiment, the authors manually extracted the height of each wall component from the elevation plan view sheet as this was an important attribute in defining the vertices.

Process VI: Texturing. After the generation of the 3D objects in *Process V*, the final step was the application of "finishes" to the wall component. For this experiment, the authors utilized the brick "finishes" texture to the wall components (Figure 4). This was achieved using the built-in material data-block in the blender python API. For this experiment, the authors manually extracted the material "finishes" of wall component from the elevation plan view sheet.

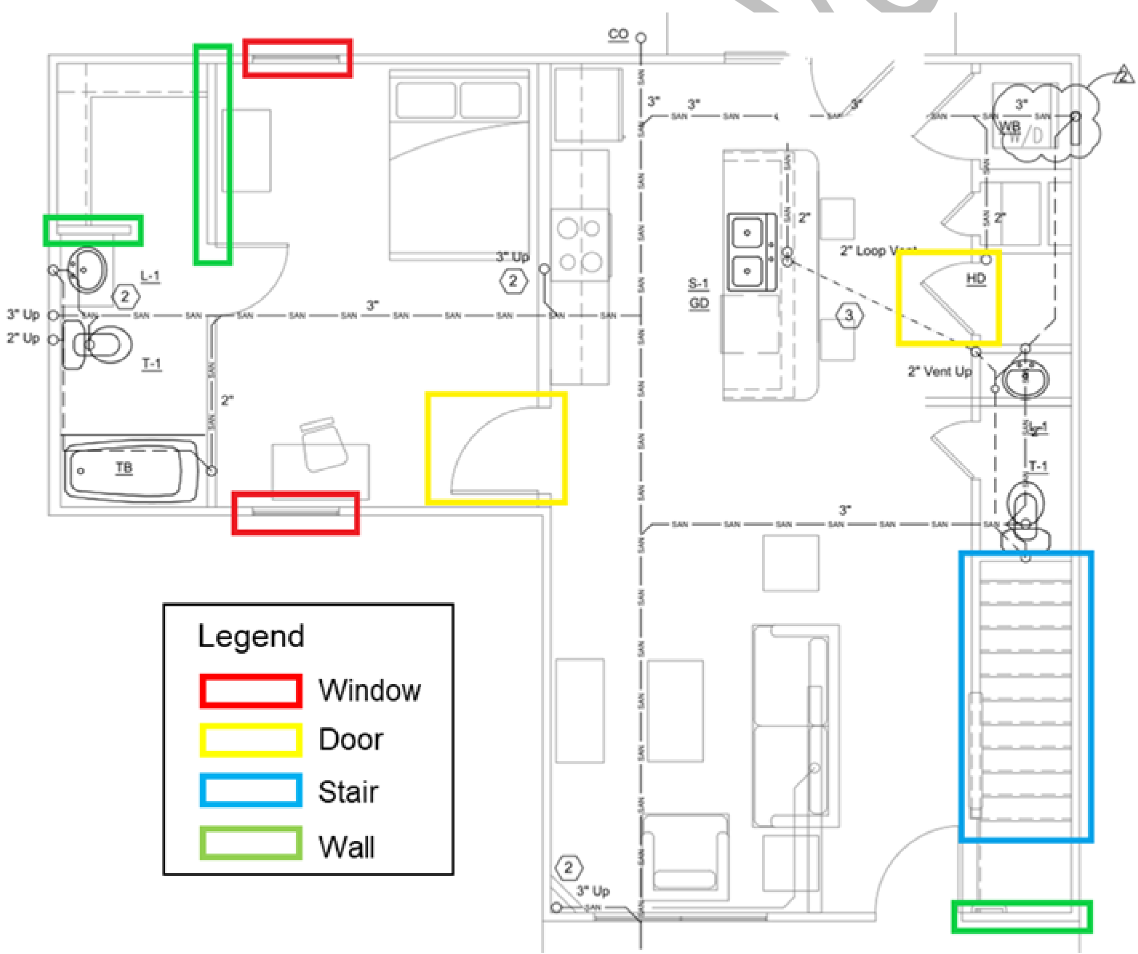

Figure 3. Examples of query symbols.

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RESULTS AND ANALYSIS

Figure 4 shows the textured 3D information model of the wall components of the student apartment building. Figure 5 shows a comparison of the 2D architectural plans with the 3D information model of the wall components generated using the proposed method. The results in both figures show that the proposed system can successfully generate 3D information models from 2D architectural plans. Furthermore, a comparison was made with the state-of-the-art practices in generating 3D information models from 2D architectural drawings, that is, the manual development of these 3D information models from scratch. The time it took to develop the wall components using both methods were recorded. The manual development of the 3D information model using Autodesk Revit took 92 minutes whereas the development of the 3D information model using the proposed method took 21 minutes. The proposed method utilized approximately 22.8% of the time it took the manual 3D information model development.

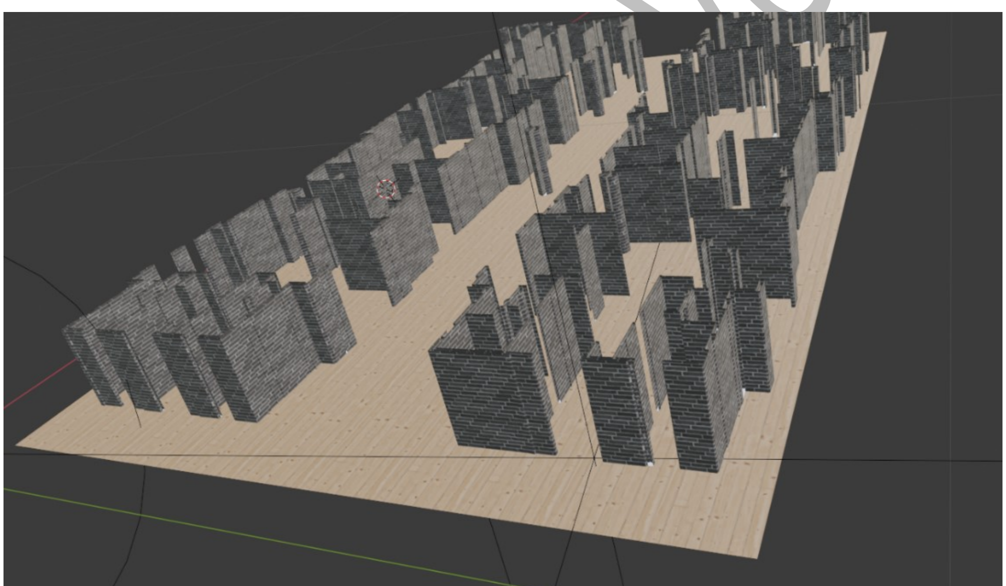

Figure 4. Brick textured finishes of the wall component.

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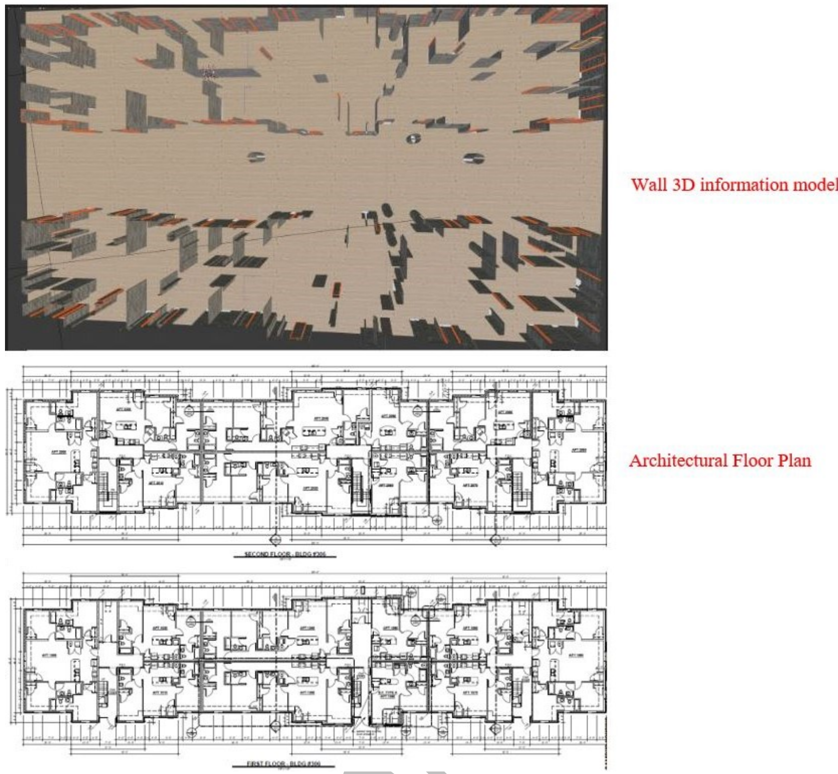

Figure 5. Plan view of the wall 3D information model and the architectural floor plan.

CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

The authors proposed a semi-automated method to process 2D architectural plans and generate 3D information models. The method was tested on a student apartment building in Kalamazoo, MI. The results indicate that the proposed method is effective in generating 3D information models, and more efficient comparing to the manual generation of the same 3D information models.

Three limitations are acknowledged. First, the proposed method was only tested in generating the wall components. Other components and elements that make up a building, e.g., the floor component, the stair component, and the window system, etc. were not tested within the scope of this paper. In future work, the proposed method will be used to expand the conversion algorithms to cover other building components and structures in order to test the robustness of the method. Secondly, the wall height and finishes were manually extracted from the elevation plan view. In future work, the method and algorithms are to be expanded to automatically extract those information or (in the case of fail to extract) provide users with an option to enter these values. Lastly, the selection of 2D architectural floor plan sheet was a manual process. In future work, the method is to be refined to automate the process of selecting the 2D architectural floor plan sheet from a batch of architectural 2D drawings as well, through OCR or computer vision.

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