Exploring the Challenges of Implementing Parametric Modeling to Support Robotic Construction

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Abstract. Building Information Modeling (BIM) is a critical data source for constructing new structures depicting the inner workings of the systems and components in detail. However, current modeling practices are based on traditional construction methods, resulting in insufficient details within the BIM model to support robotic construction for many building systems. The model's level of development (LOD) needs to be increased to facilitate the changes in data requirements. One method that allows for increased LOD is computational modeling; however, many factors can influence the process. Therefore, this study investigates challenges for implementation to increase the LOD for building to enable robotic construction. Dynamo is used as the computational modeling software in conjunction with Autodesk Revit to accomplish this. A process was created to place various components, such as concrete masonry units (CMUs), in their final design location and extract information utilizing these platforms for masonry construction. However, challenges were met during this process, including material naming conventions, tolerance/specification inputs, wall openings/lintels, and component/material libraries. The challenges presented during the implementation of the Dynamo mirror what the literature shows for supporting technological infrastructure BIM and mobile robot construction. To accomplish this research, an extensive literature review was completed, along with documentation of challenges during the development and implementation of the script.

Keywords: Parametric Modeling, Level of Development, BIM, Dynamo, Robotic construction, Technological infrastructure

1 Introduction

The construction industry faces unprecedented challenges associated with labor shortages and productivity [1]–[3]. To overcome these issues, the industry has undergone a digital transformation commonly referred to as Industry 4.0, combining automation and digitization factors [4]. For the construction industry, this involves integrating existing technology with automation, such as 3D printing, big data, virtual reality, internet of things (IoT), and robotics [5]. However, this movement has critical precursors associated with digitization, such as the widespread adoption of building information modeling (BIM). The construction industry is also starting to adopt robotics, and BIM models are leveraged as sources of information. Robotics is fundamental in the modernization of the construction industry, much like the effects of BIM [2].

BIM is the digital representation of model characteristics of a building that serves as a knowledgeable resource for project information throughout the facility's life cycle [6]. To further automation in construction, leveraging the information contained within the BIM model for use by robotics has been a recent trend for researchers [7], [8]. While BIM models contain critical data related to the project’s design, some systems are not modeled to the level of development (LOD) that supports robotic fabrication resulting in modeling requiring supplemental information to be generated [7], [9], [10]. Therefore, the following questions were formulated:

Q1: What methods are viable for supplementing and extracting information in the BIM model to support robotic construction?

Q2: What are the challenges and limitations associated with implementing the method?

Multiple methods for increasing the LOD of the model exist to achieve information interoperability; by utilizing computational modeling applications [11]. However, this research investigates parametric and computational modeling to achieve information interoperability between the BIM model and the robotic platform as a viable solution for increasing the LOD of building systems. It is defined as changing the model to generate model content or automating repetitive tasks by modifying different values [12]. BIMFourm established criteria for LOD and published guidelines [13]. Based on this, a LOD of 400 provides data on the installation and manufacturing of elements but is dependent on the use [14]. By leveraging Python scripts, Dynamo can increase the LOD of a system from level 100 to 400, fill in sheets/drawings, place families and components, and import/export models [15]. This study uses computational modeling to increase the LOD of building systems within the BIM model to generate model content to understand the process potential and associated limitations with supporting transfer to construction robotics. The expected contributions of this study are 1) to provide insight into the challenges associated with computational modeling to increase the LOD and 2) to establish the framework for computational modeling for integration of ground-based construction robotics.

2 Methodology

A systematic approach was taken to identify potential challenges and present viable solutions for implementing computational modeling for interoperability between BIM and robots. The first step of the literature review process was defining the questions stated above and establishing the scope of the research to aid in the development of keywords for the following steps. The questions are Q1. What methods are viable for supplementing and extracting information in the BIM model to support robotic fabrication? and Q2. What are the challenges and limitations associated with implementing the method? Step two involved conducting an initial literature review and identifying relevant work. This section explores the current methods for extracting information from a BIM model to a robot documenting the challenges and limitations faced by previous studies. The keywords used in the search include parametric, modeling, systems, robotics, LOD, building information modeling, BIM, Dynamo, data, and construction. Step three involved the review of abstracts to determine their relevance to this research. If determined viable, the study is recorded and documented below. Step four conducts the complete review of the existing studies and records the findings. Upon reviewing all relevant studies, the challenges, limitations, gaps, and results are summarized in the literature review section. Step five verifies the challenges in practice by developing a process based on similar methods to the previous studies and determining the challenges with its implementation. Step six presents the findings and discusses potential solutions for the challenges defined by this study and the implementation. For this study, 39 resources were reviewed, including journal publications, conference publications, manufacturer specifications, and established standards/guidelines related to parametric modeling, BIM, and robotics.

3 Scope of Research

This research serves as the initial step in utilizing a computational design-based parametric modeling process for increasing the LOD of BIM modeling to facilitate robotic construction. First, due to the vastness of robotics capabilities, a focus is placed on ground-based mobile robotics capable of completing construction activities. This research considers the robotic operating system (ROS) and its limitations, specifically with the Clearpath A200 Husky robot, but is intended for robots with similar capabilities.

Dynamo and Autodesk Revit are used in this study. Both Dynamo and Revit are parametric modeling software; however, modeling is completed differently within each software. Revit is based on modeling preconceived objects placed by a user, while other software like Dynamo allows for complete access to model data, allowing for freedom in creating elements that automate the process through computational modeling [16]. In the design industry, buildings are typically designed in programs like Autodesk Revit, but to facilitate robotic construction, typically, methods will not work. Therefore, programs like Dynamo must be explored to automate the generation of model content based on parameters contained in the model and project specifications and extracted data formatted for a robot. Autodesk Revit and Dynamo were explicitly chosen because of the ease of integration between them and their availability to students and researchers, allowing for continued research. Additional studies are being conducted to document the development and implementation of the computational modeling script referenced by this study. This study aims to build the foundation for the computational modeling process for increasing model LOD for supporting robotic construction.

4 Existing Challenges from Literature

Numerous studies have focused on generating model content utilizing computational modeling, finding that BIM models require supplemental information and external data sources, such as schedules, topological data, project specifications, and material content libraries [17]–[21]. However, process variations, such as utilizing different programs, reveal a lack of standardization dependent on the use case.

Information interoperability has been noted as a prime example of a barrier, especially when exchanging data or model preparation for robotic construction [22]. This challenge can be attributed to the paradigm shift presented by integrating digitization and automation into the construction industry [23]. Additional interoperability issues are also presented when considering the requirements of different software and applications [24]

Integrating data sources is challenging and has been the focus of discussion. Material content libraries have been developed to identify requirements and schema [25], [26]. These libraries are necessary for the computational modeling process, and details of component parameters, but the data contained within is variable based on the use case [27]. Additional data sources are also required to create tasks for the robot and must be incorporated, which include project specifications, scheduling information, and site constraints tasks [9]. This information is combined with information extracted from the BIM to create an executable task for the robot [28]. However, a barrier to integrating this information is presented. Therefore, based on previous studies and working with Dynamo to generate model content and parameters, the following challenges have been identified: Challenge one: model geometry and LOD; Challenge two: external data sources and material content libraries; and Challenge three: information interoperability and standardization. These challenges are explored in detail in the following paragraphs.

Challenge One - Model Geometry and LOD: Model geometry refers to the building system's shape, structure, and interactions within the BIM. However, the LOD of building systems is not equal to traditional modeling practices. BIMFourm describes the different LOD ranges from 100 (the element is represented with a generic representation) to 500 (the element is a field-verified representation) [13], [29]. A high LOD model, around 400, is essential for successful robotic construction as it provides the necessary information for task execution [14]. According to the standard, wall systems are developed to 200, which shows a generic representation of materials and wall thickness, while 400 provides information about individual masonry units or other wall components. While having the appropriate LOD is critical, it is paramount to understand the complex geometry and its interaction with adjoining systems which aid in identifying openings, lintels, and mechanical, electrical, and plumbing systems. It also aids in the identification of locations of components that require fabrication prior to installation, for example, concrete masonry units (CMUs) that require cuts or a location in drywall left open to install an outlet.

Challenge Two - External Data Sources and Material Content Libraries: Incorporating external data sources and the methods employed is a critical challenge underlying the implementation. The first data source encountered by the process is the material content library. A material content library refers to the digital database of product and material information providing a centralized repository of detailed information such as product specifications, manufacturer data, and other relevant information, which enable the re-use of a predefined model, so a designer does not have to create a generic component [30]. Computational and parametric modeling processes leverage content within these repositories to generate designs reducing repetitive tasks and automating the process. Currently, there are two main methods for constructing material content libraries 1) libraries defined by dimensions and constraints with descriptive information in the format of Revit Family and 2) those using languages that can describe parameters and algorithms such as the Geometric Description Language (GDL) [31]. To fully understand the material content libraries' requirements, a building system review is undertaken to determine the necessary components for construction. The requirements will vary vastly based on system components. For example, a metal curtain wall has around 19 different components, which include: anchors, fasteners, mullions, glass, and gaskets [31], while a masonry content library contains models for various masonry shapes. However, even with the expansion of material content libraries, complex geometry results in some units being represented as custom-made units, specifically in areas requiring cuts or with nontypical masonry attributes [32].

Additional to incorporating the material content library, other external data sources must be integrated to support BIM and construction robotics interoperability. Examples of additional external data sources include; topological/GPS data, weather data, robot capabilities, logistical information, specifications, assembly data, and sequencing information about the specific task [9]. Incorporating each data source presents its specific constraints and challenges, and integrating construction task information is a well-established problem for construction robots. Some studies investigate creating a BIM model and construction schedule, edited based on the contractor's knowledge and exported as an industry foundation class (IFC) file; yet, this format may need to be converted to support the desired robotic platform. Finally, the robot task planner system generates an executable task [20]. However, the construction task method must be understood and incorporated for this process to succeed.

Challenge Three - Information Interoperability and Standardization: The lack of interoperability in the construction industry is inefficient and presents a considerable challenge for integrating new technologies, such as robotics [33]. For a robot to execute a task, it needs to know the location, orientation, and type of material being placed; with some systems, information is not readily available in the BIM model. However, interoperability challenges do not singularly extend from the BIM model but also an abundance of robotic systems, sensors, and hardware [33]. Research has been conducted to determine requirements associated with interoperability in the industry, finding that a computer-controllable workflow model, a detailed BIM model, and a streamlined method for generating tasks are required for automating the construction industry, correlating with the concerns discussed in challenges one and two [34].

Standardization is a presents a challenge, such as no set standards or formats exist for computational modeling processes and are dependent on use case. Organizations have established and maintained standards for BIM, such as buildingSmart, which developed the open standard for IFC and is one of the more widely embraced 3D object file types [35]. Other 3D object files also exist, including but not limited to FBX, OBJ, and 3Ds, to name a few. BuildingSmart also has standardization efforts focused on the International Framework of Deliveries (IFD) [36] and the Information Delivery Manual (IDM) [37]. However, numerous standards exist for BIM and have been highlighted in existing literature [35]. These standards refer to BIM, not to integrating BIM and Robots. However, IFC schemas and standards are anticipated to contribute to the standardization efforts for construction robotics [38]. These standards must also comply with the requirements associated with robotics. The framework associated with robotics is the robot operating system (ROS), which allows for the implementation of commonly used algorithms that enable robotic functions [19],[39]. However, one of the significant challenges is the lack of task planning systems and the standards surrounding them [20], [40].

5 Developed Computational Modeling Process and Challenges

This section describes the process implemented in the study providing insights into where the challenges discussed apply in the application. This section describes the methods and processes employed for computational modeling to increase the LOD of a model developed in Revit by creating individual components and extracting model information for a specific task. There are three phases: model setup, development, and information extraction. Phase one aims to gather the entire model and determine the wall systems that will undergo computational modeling based on the system's LOD. A level 400, which contains details about installation and manufacturing, may be required for a specific system [14]. Phase two aims to supplement model geometry based on data extracted from wall parameters, allowing information related to wall types and materials to be known and utilized. Phase three aims to format the information based on the information requirements to install wall system components properly. This information is supplemented with sequencing data provided by analysis of traditional construction methods and in-field rules of thumb. The development process of the computational modeling script extends beyond the scope of this study, but understanding the process provides excellent insight into the challenges associated with implementation. The script was developed in Dynamo and Autodesk Revit and was designed specifically for wall systems construction from masonry; however, the concepts and methods are adaptable for other systems. This section details encounter challenges during the implementation for generating CMUs based on the geometry and layout of a wall in a Revit model. The following sections are loosely based on where the challenge would present itself in the system architecture developed by McClymonds et al. (2023) [9].

In implementing the Dynamo script, determining a method for increasing the LOD of the model while respecting model geometry was the first step, which requires a detailed understanding of the construction task to generate components based on design requirements. For a CMU wall system, the specific start location for the construction is input, along with tolerances and project specifications. Incorporating all required tolerances into the model process increases the overall complexity and computational time associated with generating the CMUs. For this research, a few configurations were tested to determine the computational time of a simple masonry wall of varying sizes constructed in a straight line shown in Table one. Only full-sized 8” × 8” × 16” CMUs are included in this assessment.

Table 1. Computational Time for Generating CMUs of Straight Walls

Wall Size (Length x Height)	Blocks Generated	Computational Time (seconds)
8’ × 8’	78	3
16’ × 16’	300	6
24’ × 24’	666	10
32’ × 32’	1176	18
48’ × 48’	1176	41

The wall sizes were chosen to allow the maximum number of full-sized CMUs to be generated during the process. Noticeably the computational time drastically increased with the wall size of the project.

The implementation identified potential requirements for a model loaded from the material content library. The Revit family, loaded from the material content library, origin point must be identified and inputted for the CMU to be placed correctly. The result of increasing the model LOD is shown in Figure 1, where 276 CMUs were placed in the correct location. Due to an error in the script, an additional 24 blocks were placed, which accounts for the differential from Table 1. The wall is 16’ × 16’ and constructed from 8” × 8” × 16” CMUs.

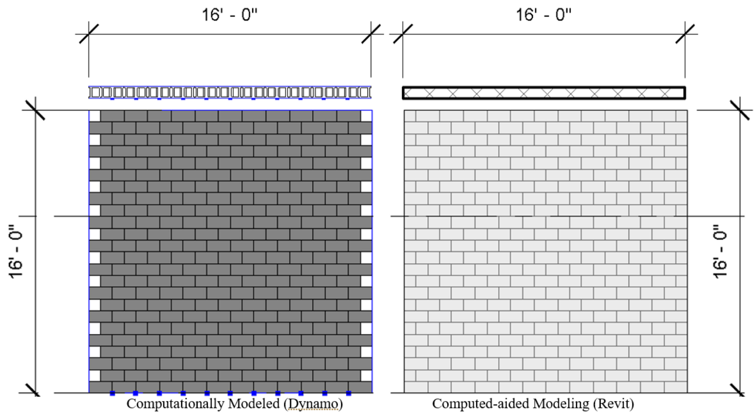

Fig. 2. Increasing the LOD of a Wall constructed out of 8” × 8” × 16” CMUs in both plan and elevation view.

The process used here must be generalized to overcome these challenges, allowing the method to be adapted to other building systems. Additionally, an in-depth analysis of the construction and installation is conducted to ensure all system inputs are understood and incorporated into the process.

Integrating the material content library and external data sources proved challenging in development and implementation. First, the format of the material content library is critical for importing families and components. The material properties from the wall are extracted with the script, which imports the correct material and families from the directory location associated with the material based on a standardized naming convention. Revit families were developed for CMUs to be imported, and wall materials were named based on the size of the CMUs used in the construction. Additionally, a standard method for developing families is required to ensure placement of wall components is accurate for construction. For the CMUs, the origin point of the block was a critical factor in placing the CMUs as it dictated its placement and rotation while implementing the script. Full-sized CMUs were placed, and location information was extracted. Partial CMUs were generated based on the remainder of the space after the placement of the full-sized CMUs. Each partial unit had a name defined based on the standard naming convention to inform the robot which block type was required for a specific location. This method was employed for all units varying in size from the standardized-sized material or designs used in the wall construction. The benefits of this have been demonstrated in earlier studies [32].

Challenges exist with integrating other external data sources, such as sequencing. This study used a linear approach for block placement and was manually applied. Automating the process presents challenges. First, the process would have to encompass the entirety of the construction process of the wall, meaning that rules of thumb and workers' experiences must be integrated to create the construction sequence. Second, a linear approach for placing CMUs was undertaken by starting at a corner or edge of the model geometry and placing components next to each other until completion of a course, then progressing to the following. A similar process was taken for sequencing construction tasks for small-scale masonry wall systems by Stephens et al. (2022) [28]. Due to the lack of standardization, this method was employed for inputting construction task information for the ROS system. Future work will include further analysis and implementation of strategies to better understand this challenge's scope and develop solutions.

Further interoperability issues stem when combing these concepts with the computational modeling process. First, the data exported must be tailored to the robotic system. It must contain all required detail to complete the task; for this research, a detailed .CSV file with the following information was generated: component identification (ID), component type, location, and orientation. This information was exported in both metric and imperial units. The metric system was provided for easier integration with ROS; the imperial system in feet in inches was provided for on-site personnel based on the system requirements of the Husky A200.

6 Conclusion

This study investigated the challenges associated with computational modeling in Dynamo to support the implementation of robotic fabrication in the construction industry. To accomplish this goal, two research questions were formulated:

Q1: What methods are viable for supplementing and extracting information in the BIM model to support robotic fabrication?

Q2: What are the challenges and limitations associated with implementing the method?

For question one, computational modeling was investigated for supplementing modeling information by generating wall system components in a parametric model. In this study, a script developed in Dynamo generated CMUs based on wall geometry from a model developed in Autodesk Revit. Challenges were initially identified by literature, and then using the gained knowledge; the script was implemented on a simple masonry wall where the generated content had information extracted and formatted for a robot, specifically a Husky A200. This study's three challenges are model geometry and LOD, external data sources and material content libraries, and information interoperability and standardization.

Future work includes advancing the computational process to allow easy integration of additional data sources and provide use cases outside masonry wall systems. Additionally, work must address the challenges and increase standardization in the construction industry's methods and processes for implementing automation and digitization.

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