Development of a Parametric Modeling Method for Masonry Wall Systems to Support Robotic Construction

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ABSTRACT

The construction industry has undergone a technological shift. Technology advancements have made robots a topic of discussion in construction. One challenge to overcome is how the robot receives information from designed BIM models. This study describes the methods employed for parametric modeling and generating model content of wall systems in Autodesk Revit added with a Dynamo script. Coordinates are determined for components based on model geometry and dimensions. Once generated, components are placed with the required material based on wall parameters. This research develops a method to add components based on wall materials from a traditionally modeled BIM extracting information such as location, object identifier (ID), type, and orientation which is formatted to transfer to the robot based on the needs of the robotic system as a list of tasks in a comma-separated values (.CSV) file. This study details the development process and early implementation of the Dynamo script.

INTRODUCTION

Building Information Models (BIM) is an essential source of information for construction projects, and as new technology emerges, BIM is a key platform for leveraging facility design data. As the need for the data contained in these models increases, information exchanges will become more diverse, resulting in the integration of emerging third-party applications with BIM authoring software (Karimi et al., 2021). In addition, BIM models currently have an insufficient level of development (LOD) to provide the necessary foundation for robotic construction (Ren & Zhang, 2021). Wall systems are a common example, where the LOD is represented as a simplistic wall texture in two dimensions on a parametric wall object. Project specifications provide insight into the requirements, which craft workers supplement to incorporate the construction means and methods based on experience. Despite the availability of this knowledge and information, the design BIM does not typically represent it. Parametric modeling provides a potential solution for adding supplemental model information by increasing the LOD. Parametric modeling specific to model development or optimization, like Dynamo and Rhino, leverage content libraries to generate new model content, such as placing individual components that make up the wall structure. These programs allow for the modification of model geometry quickly by updating dimensional values within the parametric modeling software (Fu, 2018). Essentially, parametric modeling programs allow minimal user input for supplemental models by doing the heavy lifting when creating geometry and content (Summit, 2014). Using Dynamo, a parametric modeling algorithm, increases the LOD wall systems. Parametric modeling generates the additional model content quickly and allows for rapid change of model parameters. The process is tested using Autodesk Revit based on model

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parameters, such as system geometry and materials, to integrate supplemental information sources, including material content libraries and technical specifications. Two steps formulate the basis of the study's methodology: 1) Supplementing model information and 2) Extracting and re-using model information. Existing studies investigated similar processes; however, the distinguishing feature is the need to provide the detailed information required to inform robotic construction. Therefore, the research presented in this study presents a method to extract information from the BIM to enable the robotic construction of masonry wall systems and demonstrates that parametric modeling is an essential tool for improving construction projects' efficiency and effectiveness.

PROCESS OVERVIEW

The BIM model contains information essential to the construction process; however, the information in a BIM model may not support the LOD required to support construction robots (McClymonds et al., 2022). Third-party applications can utilize parametric modeling methods to extract or supplement model information about the construction process (Follini et al., 2021). Parametric modeling is a software tool that can represent wall structures in a BIM to reflect wall elements' size, shape, and analytical properties. However, ensuring that the input data used to develop the parametric model is fit for other purposes or analyses is essential, as this impacts the model's reliability and effectiveness. An example of a parametric modeling method that detailed model LOD was completed by (Banfi, 2016); however, it did not focus on robotics. Therefore, methods from previous examples are adapted for this research. The process developed in figure one shows the process taken for parametric modeling. It summarizes the appropriate LOD process for parametric modeling. The process begins by determining the system's initial LOD and supplementing it with additional information. In the case of this research, it generates model content to increase the LOD for construction purposes.

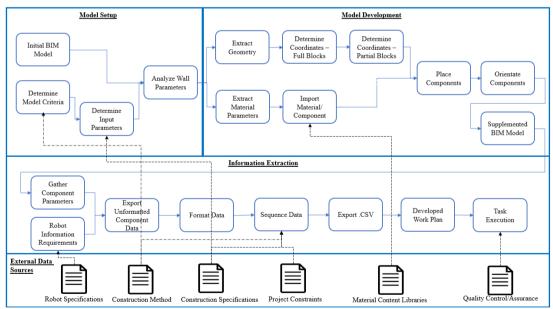


Figure 1: Proposed Parametric Modeling Process for BIM to Robotic Construction Integration Overview

PHASE 1: MODEL SETUP

The first phase of the process is model setup. This phase begins the parametric modeling process by compiling information from the model and external data sources. Identification of

the construction task and corresponding information requirements for the robot occurs and defines the conceptual requirements for the parametric modeling process.

Step 1 Determine Wall System Scope and Obtain Model: First, the systems from the BIM are identified to assess the existing model information. Masonry wall systems are used as an example in this study. The existing information in the model is then compared to the requirements for robotic construction; therefore, establishing the basis for the supplemental information for the BIM model and additional supporting documentation for the different wall elements, such as project specifications, is also critical.

Step 2 Determine Model Criteria: Specific criteria must be established based on the system and the end goal for the parametric modeling information generation. First, the relevant elements and data must be extracted from the model. For the development, a target LOD of 400 was set, which contains information on the installation of the component, such as individual masonry units with location-based data based upon BIMFourm (Bedrick et al., 2020). Within Autodesk Revit, wall material information is extractable; however, the information about wall materials is insufficient for robotic construction. Default naming schemas are generic, providing limited information on material type that is intended to be supplemented with notes in the construction drawings or specification information. An example is naming a concrete masonry unit wall 8" x 8" x 16" concrete masonry units (CMU), which provides specific details on the sizing and type of material required. Based on the naming convention on standards published for masonry construction (Shaffer, 2019.; NCMA, 2017.). However, depending on the material, different standards are applicable. The parameter identification and naming for the parametric modeling should exhibit sufficient specificity for the script, as the script reads the wall material information and imports the necessary component libraries.

Step 3 Determine Input Parameters: Additional factors in the wall construction impact the parametric modeling process. These factors are determined by analyzing the construction methods and project specifications. For masonry construction, blocks are not always set in identical patterns or configurations. Therefore, these factors must be considered input parameters. The input parameters are values set before running the parametric modeling process that can change the overall construction of the walls. Examples include material type, spacing, coursing type, bond type, mortar thickness, and other specifications. To accommodate this, sliders were input into the Dynamo script that allowed for changes in mortar gap and bond type which modified how block coordinates are determined in the later phases. For example, the bond type slider changed a value (0-1) related to an offset of blocks between each row, and if the value was 0, it related to a stack bond (no offset between blocks) or a running bond if the value was set to 0.5 (blocks are offset half a block on alternating courses). While these values are specific to masonry, similar methods can be explored and input for other systems in future iterations.

Step 4 Analyze Wall Parameters: This step begins developing the model and uses the information gathered thus far, establishing the basis for the required supplemental information. This step links the next phase, model development, and provides the basis for developing the information. Figure 2 shows the model that will be used for this research, such as the dimensions of the wall (Length, Width, and Height), material dimensions (Length, Width, and Height), type of bond pattern (running), joint mortar thickness (0 inches – dry setting blocks).

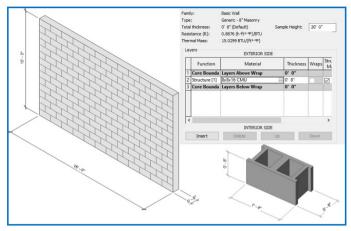


Figure 2: Simple Masonry Wall System, Wall Parameters, and Material

PHASE 2: MODEL DEVELOPMENT

Model development supplements model geometry based on data extracted from the wall materials, allowing components to be imported from the material content library. To extract the information required for robotic construction, the location of each component must be identified to inform the robot of its final location (Xu et al., 2021). Based on the wall system geometry, the process locates the starting position for each CMU's material parameters and specifications. This process generates coordinates (X, Y, Z Points) on the local Revit Coordinate system for each CMU based on the blocks' geometry and the wall's reference line. Once determined, CMUs are parametrically generated and can be placed in their design position. The result of this phase is the creation of individual elements that compose each wall. Figure 3 summarizes the extraction of model geometry for the masonry wall, with the steps involved being described in the following sections. The current abilities of the Dynamo script only allow for the generation of masonry components; however, future iterations will allow for diversity in wall materials.

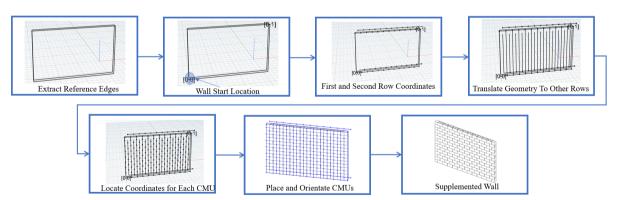


Figure 3: Process of Extracting Geometry to Generate Individual Components

Step 1 Extract Geometry and Material Parameters: The first step of model development is to use the model parameters and geometry gathered in the model setup and apply them to generate supplemental model content. The geometric information includes dimensions, orientation, start location, openings, and references to edges of the wall that directly impact the placement of Revit Families. Wall material parameters are read, allowing wall materials to be understood and used in later steps of the process. The critical geometric and materials parameters used in the method are wall reference lines (the path wall was modeled on), wall orientation (directional vectors), wall materials, and wall start/endpoints.

Step 2 Import from Material Content Libraries: The parametric modeling script imports full-sized components from the material content library, which contain (Revit) families that can be generated in the model. The families are parametric, allowing for variation in model geometry and adaptation for the input parameters. For example, a masonry unit must be cut for a doorway or other opening. Therefore, content libraries must be completed for the multitude of construction materials to ensure the success of parametric material. However, due to complexities in some construction materials, it is beneficial to generate some components with Dynamo, such as partial-sized CMUs or other not standardized-sized materials (Sharif et al., 2015). Therefore, the material content library is developed based on standardized materials. Work has been started on defining material content libraries; however, more content creation is needed due to the vast array of construction systems, materials, and components (B. Kim & Chin, 2016; Sharif & Gentry, 2015). Project specifications for the materials supplement the material content library with information on tolerances, quality control/ assurance, and other critical details.

Step 2 Determine Block Locations: Previous studies have used local coordinate systems for the locations of elements; therefore, a similar approach is taken here to determine the location of wall elements (Xu et al., 2021). The origin point is extracted from the starting location of the wall materials subjected to the parametric modeling process, in this case, the CMUs. The center of the wall and component The origin point of the family was also set to allow the coordinates to be offset for additional blocks by a factor of one block length plus the value set for the mortar thickness. The origin point of the wall element must also be determined as it directly impacts the location it gets placed in the BIM model. For simplicity, the CMU location(s) are defined relative to the origin of the BIM model per the BIM authoring software (Revit). Figure 4 shows the origin points for the project site, wall, and CMU.

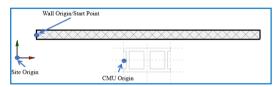


Figure 4: Origin points for Masonry Wall

The CMU wall includes the thickness of mortar, size of blocks, course type, and wall openings. Once the location of all full-sized elements is determined, locations for partial-sized elements are determined along with the size of the block required for that area which will be crucial for walls with openings. Based on the origin point of the wall, locations for the model elements are determined by utilizing the dimensions of the materials and industry-standard requirement data to define the location of wall elements. Other studies have shown benefits in generating partial-sized components rather than modifying the full-sized component to fit in the location or additional non-standardized sizes or designs (Sharif et al., 2015). This method uses this method because partial-sized CMUs are less frequent than full-sized CMUs reducing the overall complexity of placing blocks in the following steps. Therefore, the method used here would generate a CMU identified by creating a solid mass in the locations identified with points defining the gap for mortar from the previous CMU to the edge of the wall horizontally. To locate the coordinates of the blocks vertically, an array is utilized for odd and even rows that locate the points on the higher courses based on the points determined in the first and second courses.

Step 3 Place Components and Orientate: Once all coordinates are determined, the required element is generated as a component. The parametric model component is automatically sized

for that specific instance in areas with partially sized blocks. For the masonry model, partial blocks are placed at each side of the wall system. A vector extracted from the wall's direction orients each masonry unit. If the elements were not appropriately rotated, the elements could extend passed the limits of the wall. Figure 5 shows the wall with the elements placed in the model utilizing Dynamo.

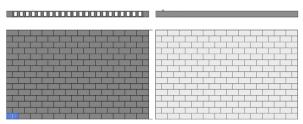


Figure 5: Comparison between a parametrically modeled wall (left) and a traditionally modeled masonry wall (right) in Autodesk Revit

PHASE 3: INFORMATION EXTRACTION

Information extraction aims to support exchanging information based on the need to install wall system components properly, ultimately using a robot. This information is supplemented with sequencing data from traditional construction and trade practices. The end format for this information is a .CSV file containing local coordinates (X, Y, Z), orientation, and component-related information (McClymonds et al., 2022). A similar approach for adding a linear construction method was taken with simplistic wall models made of concrete masonry units (CMUs) (Stephans et al., 2022). This process focuses on the requirements of a Husky A200 robot operating on the robot operating system (ROS) melodic.

Step 1 Gather Data and Information Requirements: Information extracted from the model for each element includes coordinates, orientation, component identification (ID), and component type (McClymonds et al., 2022; Stephans et al., 2022). Revit assigns each element a specific number or its component ID #. The component type defines the enumerated value of the element in place. For a masonry wall, this would be an 8x8x16 CMU that provides information to the robot about the specific material for a given set of coordinates. Two sets of coordinates are extracted from the model. One set of coordinates is provided in metric units for the robot, while the other is provided in the imperial system to allow a co-worker or operator to verify the element's location and ensure quality. Table 1 shows a subset of the information extracted from the masonry model based on the local coordinate system.

Table 1. A Subset of the Information Extracted From The BIM Model

ID#	Type	X	Y	Z	Rotation	X	Y	Z
5597620	8x8x16	2.044m	0.803m	0m	180°	7'-4 1/2"	2'-3 5/8"	0'-0"
5597619	8x8x16	1.638m	0.803m	0m	180°	6'-0 1/2"	2'-3 5/8"	0'-0"
5597617	8x8x16	0.825m	0.803m	0m	180°	3'-4 1/2"	2'-3 5/8"	0'-0"
5597618	8x8x16	1.23m	0.803m	0m	180°	4'-8 1/2"	2' -3 5/8"	0'-0"
5597621	8x8x16	2.451m	0.803m	0m	180°	8'-8 1/2"	2'-3 5/8"	0'-0"

Step 2 Sequencing Tasks: A sequence of work is applied to the data extracted above to inform a robot of the location and order for each component. Information to develop the work sequences is based on traditional construction methods of masonry wall systems. Traditional schedules lack the detail for the block-by-block sequencing process, resulting in challenges in implementing it into Dynamo. Therefore, a manual approach has been taken to provide a linear construction method for the robot. Additional research is required to fully integrate sequencing information into the parametric modeling method. Research is beginning to integrate construction planning and sequencing into robotic construction (Follini et al., 2020). Table two provides a subset of sequenced data exported as a .CSV file.

Table 2. A Subset of the Sequenced Tasks for Robotic Task Execution

Seq	ID#	Type	X	Y	Z	Rotation	X	Y	Z
1	5597616	8x8x16	0.419m	0.803m	0m	180°	2'-0	2'-3	0'-0"
							1/2"	5/8"	
2	5597617	8x8x16	0.825m	0.803m	0m	180°	3'-4	2'-3	0'-0"
							1/2"	5/8"	
3	5597618	8x8x16	1.231m	0.803 m	0m	180°	4'-8	2'-3	0'-0"
							1/2"	5/8"	
4	5597619	8x8x16	1.638m	0.803m	0m	180°	6'-0	2'-3	0'-0"
							1/2"	5/8"	
5	5597620	8x8x16	2.044m	0.803m	0m	180°	7'-4	2'-3	0'- 0"
							1/2"	5/8"	

Step 3 Robotic Task Execution: The parametric model process presented here aims to provide the required information to support robotic task execution. The sequenced information is provided to the robot, which develops tasks based on that sequence to conduct work following the robotic task execution process depicted in an earlier study (McClymonds et al., 2023). The parametric modeling process intends to bridge the gap in the information exchange by providing information from a BIM model to a robot. Future research will send the information formatted to the robot; however, this application currently extends beyond the scope of this study.

CONCLUSION

In conclusion, this study developed a method for increasing the LOD of a traditionally modeled BIM to support the future information needs of construction robots with parametric modeling. Dynamo was used to create a script that analyzed and extracted model information related to a masonry wall structure and then generated individual wall components based on the geometric factors that influenced it. Here a simple masonry wall had the LOD increased with the method developed successfully, placing each block per its parameters. However, the use of BIM and parametric modeling is not without its challenges and limitations. The uncertainties or variability based on variations in design practice, naming, and standard of care in the input data used to develop a parametric model directly affect the accuracy of the supplemented model. Additionally, the complexity and computational demands of parametric modeling can make it challenging to use in some situations, particularly for larger or more complex projects. Despite these challenges, BIM and parametric modeling are likely to grow in popularity in construction, as these tools offer numerous benefits in accuracy, efficiency, and collaboration. By leveraging the full potential of BIM and parametric modeling, it is possible to improve the design, construction, and performance of building wall systems.

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REFERENCES

- Banfi, F. (2016). Building Information Modelling A Novel Parametric Modeling Approach Based on 3D Surveys of Historic Architecture. In M. Ioannides, E. Fink, A. Moropoulou, M. Hagedorn-Saupe, A. Fresa, G. Liestøl, V. Rajcic, & P. Grussenmeyer (Eds.), *Digital Heritage. Progress in Cultural Heritage:*Documentation, Preservation, and Protection (pp. 116–127). Springer International Publishing. https://doi.org/10.1007/978-3-319-48496-9 10
- Bedrick, J., Ikerd, W., & Reinhardt. (2020). *Level of Development Specification BIM Forum*. https://bimforum.org/resource/level-of-development-specification/
- Follini, C., Terzer, M., Marcher, C., Giusti, A., & Matt, D. T. (2020). Combining the Robot Operating System with Building Information Modeling for Robotic Applications in Construction Logistics. In S. Zeghloul, M. A. Laribi, & J. S. Sandoval Arevalo (Eds.), *Advances in Service and Industrial Robotics* (pp. 245–253). Springer International Publishing. https://doi.org/10.1007/978-3-030-48989-2_27
- Kim, B., & Chin, S. (2016). Parametric Library Components for BIM-based Curtain Wall Design Automation Module. *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, 33, 1–6. https://www.proquest.com/docview/1823081919/abstract/4918451B7C114B2CPO/1
- McClymonds, A., Asadi, S., Wagner, A., & Leicht, R. M. (2022). *Information Exchange for Supporting BIM to Robotic Construction*. 839–848. https://doi.org/10.1061/9780784483961.088
- McClymonds, A., Leicht, R., & Asadi, S. (2023). System Architecture for Supporting BIM to Robotic Construction Integration. In S. Walbridge, M. Nik-Bakht, K. T. W. Ng, M. Shome, M. S. Alam, A. el Damatty, & G. Lovegrove (Eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021* (pp. 225–236). Springer Nature. https://doi.org/10.1007/978-981-19-0968-9 18
- NCMA. (2023). TYPICAL SIZES AND SHAPES OF CONCRETE MASONRY UNITS. NCMA. https://ncma.org/resource/typical-sizes-and-shapes-of-concrete-masonry-units/
- Ren, R., & Zhang, J. (2021). A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions. *Advances in Civil Engineering*, 2021, e8824613. https://doi.org/10.1155/2021/8824613
- Shaffer, D. (2019). Dimensioning and Estimating Brick Masonry.
- Sharif, S., & Gentry, R. (n.d.). BIM for Masonry: Development of BIM Plugins for the Masonry Unit Database. 10.
- Sharif, S., Gentry, R., Eastman, C., & Elder, J. (2015). *Masonry Unit Database Development for BIM-Masonry*.
- Stephans, T., McClymonds, A., Leicht, R., & Wagner, A. R. (2022). Automated material selection based on detected construction progress: 39th International Symposium on Automation and Robotics in Construction, ISARC 2022. *Proceedings of the 39th International Symposium on Automation and Robotics in Construction, ISARC 2022*, 406–413.

Xu, C., Liu, J., Li, S., Wu, Z., & Chen, Y. F. (2021). Optimal brick layout of masonry walls based on intelligent evolutionary algorithm and building information modeling. *Automation in Construction*, *129*, 103824. https://doi.org/10.1016/j.autcon.2021.103824