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BIM-based Simulation of Construction Robotics in the Assembly Process of Wood Frames

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Abstract

One main challenge in the development/implementation of construction robotics is the need of accurate and explicit information as input for the robots to reliably perform the designated tasks. Building information modeling (BIM) can fill this gap by providing information to the construction phase that utilizes automated fabrication. However, current BIM authoring tools and construction workflows do not directly support robotic simulation and are not designed to be compatible with robotic technologies. Thus, the authors developed a simulation-based methodology to evaluate the automated assembly of wood frames. Results showed that the robotic assembly process was successfully simulated/analyzed on three test cases. Compared to manually creating such robotic simulations, the proposed approach was on average 39 times faster and is expected to dramatically reduce errors from design to build. The proposed approach opens a new door for practitioners to analyze a building design related to the use of robotics for its construction.

1 Introduction

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Construction, a labor-driven industry, is experiencing a concerning labor shortage [1,2] amid the accelerated aging of the construction workforce [3]. This labor shortage is negatively affecting the productivity in the construction sector [4]. Moreover, construction is a dangerous industry, with nearly half of the deadliest job tasks in America [5]. Automation in construction, especially with robotics, has the potential to relieve some of the strain imposed by the labor shortage and increase productivity [6]. The presence of robots in construction is becoming prominent [7]. According to [8], the number of robots in the construction industry is expected to exceed seven thousand by 2025. Robots excel at performing repetitive tasks with precise motions in controlled environments such as those in offsite construction facilities. In addition, robots save workers from dangerous, repetitive, and labor-intensive tasks, which in turn allows them to focus on more high level and more meaningful tasks. Therefore, adopting robotic automation by the Architecture, Engineering, and Construction (AEC) industry can bring numerous benefits in terms of productivity, quality, and safety, which is aligned with the goal of restoring and improving the urban infrastructure, one of the grand challenges of the 21st century [9].

Unfortunately, the benefits of robotics are not yet fully realized due to its slow adoption by the construction sector. Some limiting factors of the slow adoption rate of robotics in construction include high implementation cost, fragmented nature of the industry, incompatibility with current workflows, immaturity of construction robotic technology, among others [10,11]. One way to help better understand the benefits as well as the challenges of construction robotics is through virtual design and construction (VDC). VDC allows the testing and visualization of processes before the actual construction takes place. For example, 4D simulation and energy simulation have been used for schedule and energy consumption analyses, respectively. In construction robotics, simulation can be used to analyze, test, and visualize construction processes executed by a particular robotic system. One of the challenges in the development and implementation of robotics simulation is the need of expert knowledge from the fields of both robotics and construction, because of the multidisciplinary involvement from various stakeholders, including general contractors, robot developers, and researchers. Furthermore, robots require accurate and explicit information to reliably perform the designated tasks [12]. For instance, frames of reference and dimensions of objects are essential information to determine how the robots interact with the objects and its environment. These challenges demand thorough planning and coordination, and absolute accuracy in the design information is required for successful analyses.

Building Information Modeling (BIM) is emerging as the new standard for the design, planning, construction, and operation of the built environment. BIM is a "modeling technology and associated set of processes to produce, communicate, and analyze building models" [13].

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Collaboration among stakeholders in the modeling and analysis processes at different life cycle phases of a facility is the primary goal of BIM in the AEC industry. BIM has been used in different analyses of a construction project such as cost estimation, schedule simulation, and building energy consumption, among others. However, current construction workflows are incompatible with automation technologies (e.g., robotics) [10], BIM authoring tools do not have the capabilities to perform robotic automation planning [14], and methods for planning and simulating construction robots are lacking [12]. The limited interoperability between design and construction tools requires manual transfer and integration of data between design and construction phases, which is time consuming, tedious, and prone to errors. This limitation contributes to the substantial cost ($15.8 billion per year) that the AEC industry incurs due to the difficulty of interoperability [15].

Despite its limitations, BIM is a promising digital representation of physical and functional characteristics of a facility that can directly drive the transition from design phase to automated fabrication. To address this interoperability gap, the authors propose a new methodology for automated extraction and analysis of BIM design parameters to generate a robotic fabrication plan for an offsite construction automation system. The methodology leverages BIM design models as input data and integrates a simulation-based approach to emulate the robotic automation of wood frame assembly. The methodology involves developing a set of algorithms for robotic systems to automatically perform the framing and fastening operations based on the extracted and analyzed input data from BIM.

2 Proposed simulation-based approach to robotic construction analysis and BIM data integration

2.1 BIM-based approach

BIM design models are reliable digital representations of building designs and a "shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle" [16]. As such, it provides a 3D model with its physical and functional information that can support the analysis of construction processes such as those in the assembly of wood frames. The proposed approach extracts critical data from the BIM design models of a candidate structure as input for a simulation to assess the feasibility of automated construction of the candidate structure by a particular automated construction system. This direct linkage of design models to fabrication reduces the likelihood of errors in the transition from representation to actualization and increases the speed and accuracy of the bidding process.

BIM-based data include building element type (e.g., beam or column), element dimensions (e.g., length, width, height), and element location (e.g., cartesian points with respect to the global coordinates of the BIM design model). The data are extracted and derived using a logic-based method (i.e., logic representation and reasoning) to analyze building design information. For further details on this logic representation and reasoning work, the reader is referred to [17]. In this paper, the open standard Industrial Foundation Classes (IFC) was selected because of its openness and transparency [18], which makes it the most promising direction in solving the interoperability issues in the AEC domain due to inherent limitations when using proprietary data exchange formats [19].

2.2 Robotic system approach

In this paper, a robotic system analysis approach is employed rather than focusing only on individual components (e.g., a particular robot, or end effector, or fixture). A robot by itself provides the illustration of generalized motion, but only when it is complemented with other components such as sensors, end effectors, fixtures, software, and many other domain-specific necessities, can the holistic interaction of the different components within the system be fully evaluated with regard to opportunities for automation. Therefore, the robotic system analysis approach is a comprehensive solution to the automation of the construction process. As a result, it is expected to achieve higher accuracy than the analysis of its individual components.

2.3 Simulation approach

The proposed approach is based on computer simulation, which can be used to design, understand, predict, evaluate and verify the states of a system [20]. A simulation-based approach allows the generation and evaluation of different configurations and scenarios of a target robotic construction system and allows for the comparison of different robotic construction systems for bid analysis. By allowing the testing of different alternatives, each simulation scenario provides valuable new knowledge about the dynamic behavior of a system [21] and therefore the range of structures it can fabricate. Moreover, the simulation-based approach is a rapid and cost-effective alternative to the testing of the actual physical robotic systems, used during the preconstruction phase and can lead to more accurate bidding and more efficient construction automation. For example, potential issues can be identified during the simulation of the construction operations and subsequently addressed, either in the configuration of the system or in the design of the structure, before the implementation of the actual physical system. The focus of this paper is on

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the integration of BIM data to generate the required information for the emulation of spatiotemporal behavior of a robotic system for wood construction.

3 Background

3.1 Wood construction using robotics

Many efforts have been undertaken in the area of robotic research for construction in general. The beginning of these efforts date back to the early 1980s, in which the focus was on single-purpose robots [22]. Initially, the focus was on concrete and steel buildings with applications such as finishing of concrete floor slabs, positioning of steel members in steel erection, and fireproofing of structural steel members [23]. Currently, many research efforts can be found in the implementation of robotics for wood construction [24,25,26,27]. For instance, the Gramazio Kohler Research group at ETH Zurich is known by the implementation of robotics in full scale architectural structures through digital fabrication.

In [26], a robotic system called Robotic Timber Construction (RTC) was proposed, which employs a design-to-fabrication digital workflow for the assembly of non-standard timber structures. RTC consists of three main components: 1) Design Processes, 2) Material and Constructive Systems, and 3) Integrated Robotic Fabrication. In the Design Processes, RTC used an assembly driven approach that adapts to different functional requirements (e.g., structural integrity and construction tolerances in real time), considering criteria such as material and construction. This component was developed in Python and embedded in Rhinoceros-3D (CAD tool). In Material and Constructive Systems, a connection typology (at non-orthogonal angles) and gluing technique were used for the self-supported elements instead of the more traditional orthogonal placement of the elements and connections, respectively. Finally, in the Integrated Robotic Fabrication component, the prefabrication and assembly steps were integrated in a single workflow: (1) grip, (2) cut at the ends, (3) perforate, and (4) move to final position. This allowed a continuous and automated workflow from design to construction. The robotic system of the RTC consisted of a custom six-axis overhead gantry robot having a workplace of 48×6.1×1.9 m (capable of handling timber components between 0.50 m to 10 m in length) and was tested in the construction of the Sequential Roof.

Moreover, [27] proposed a robotic system for the prefabrication of functional volumetric timber components on a 1:1 scale. Their method provided continuity in the digital process at the assembly stage, which minimizes information loss and precision issues. The robotic system consisted of many integrated components including scanning devices, two industrial robots with pneumatic grippers (ABB IRB 4600-40/2.55) and mounted on a 5 m linear axis carriage, a CNC saw (with servo motors for three controllable axes), and a worktable (6 m x 2.2 m) with aluminum rails for fixing wood structures. The software used include Rhino (in C# script), Karamba, and ABB Robotstudio (in Python script) for the fabrication geometry, structural calculation, and robot controller, respectively. In terms of implementation, the robotic cell was capable of creating spatial, structural, functional, and highly customized timber frame volumetric modules from unprocessed raw timber material as well as timber beams and panels with variable dimensions [27].

Furthermore, motivated by digital design and robotic fabrication in architectural applications, [28] proposed an automated method in the production of a full-scale timber structure using robots, to minimize material waste and cost. The tested timber structure consisted of 18 framing elements placed horizontally, forming a uniquely shaped structural system. The ABB IRB2600-20/1.65 industrial robot was used for the cutting and assembly of timber elements. Similarly, [24] presented a process to produce a spatial timber structure using the KR 150 L110-2 KUKA robot for the robotic fabrication and assembly of the optimized space-frame structure.

These research efforts have contributed to the advancement of robotic research in wood construction and can push offsite construction to a higher degree of automation in the prefabrication and preassembly processes. However, these implementations were on non-conventional projects (i.e., free-form structures and other special topology configurations of wood construction), which are usually one-off projects and are far less common compared to current standard practices such as frame construction. In addition, the representation of the building models in their workflows/systems was based on proprietary CAD platforms (e.g., Rhinoceros in [26] and [27]) or not reported ([24] and [25]). The dependency on multiple proprietary CAD/BIM platforms instead of open BIM (e.g., IFC), limits the feasibility of a truly seamless workflow in the implementation of automation in offsite construction and is a key differentiator of our work.

3.2 BIM-based workflow for offsite construction

BIM has become more prevalent in the AEC industry, and it is currently playing a major role in construction workflows [29]. BIM data serves as a single and centralized source of information for all building related processes [30]. As such, it provides reliable data for the different analyses required during the lifecycle of a construction project. In the context of offsite construction, BIM has been used for design, manufacturability verification, assembly optimization, and structural health monitoring purposes. For instance, in [31], a VBA-based CAD system was created that takes information from BIM to automate the design and drafting processes of wood panels. In [32], a system to check the manufacturability of wood frame assemblies was implemented. In addition, in [33], a system to increase the efficiency and reduce the waste in the assembly process of offsite construction was developed. Moreover, in [34], a BIM-based data management system was applied for structural health monitoring of modular buildings. However, despite these research efforts, the integration of the current BIM-based workflow with robotic technology is still lacking.

3.3 Simulation of robotic systems for construction applications

Uncertainties and risks are common in construction [35], and they often lead to delays and/or economic losses in construction projects when they are overlooked or have not been properly taken into consideration in advance. Virtual design and construction (VDC) provide an effective way to identify and test potential solutions to minimize risks in construction projects. VDC is the process of testing construction operations in a virtual environment before the actual construction process takes place [13]. VDC can be performed through simulations. In a broad sense, simulation is an approximation of a mathematical model to analyze a system [36]. Simulations can be used to analyze, visualize, and explore construction operations in a safe and virtual environment. Examples of basic simulation methods include discrete-event simulation, agent-based modeling, and system dynamics.

The use of simulation is essential in robotics research and development [37]. Robotic simulators are important tools that allow the testing of control algorithms to determine their efficiency, safety, and robustness [38], and allow emulating operational behaviors of a physical robotic system. In the construction domain, [14] explored the potential of integrating BIM, Computer Aided Design (CAD), and the Robotic Operating System (ROS) using simulation and visualization tools such as Gazebo [39], MoveIt [40], GraspIt [41], and Rviz [42]. The KINOVA JACO robot, a human-assistive robotic arm was selected to simulate the installation of timber panels and the assistance of elderly people for the BERTIM (a building renovation project) and LISA-HABITEC (a domotics project) programs, respectively. In [43], a software package in development, namely Robot Studio for Builders (RS4B), is being created to link BIM design models with robot controls. This software package contains four components: 1) BIM Exporter: this component reads, divides, classifies, extracts, and stores the information from a BIM design model, 2) Assembly Planner: this component imports components and regulations, generates the framing and temporary supporting layouts, as well as the assembly sequence, 3) Robot Simulator: this component creates the motion of the robot using animation-based robotic programming, solves the forward and inverse kinematics, warns about collisions and singularity, and generates the codes for real robots,

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and 4) Motion Planner: this component optimizes the robotic movements of the assembly process. Moreover, [12] created a BIM prototype for general-purpose robots' task planning in interior wall painting. Their task planning approach integrates ROS with BIM and construction schedules. Our projects share many goals, but their software will not be completed for several years and the authors of [43] note that a missing component is design policy for robotic manufacturing that includes "consideration of robotic manufacturing to fit the capacity of robots for increasing both efficiency and productivity…" This is exactly what our project is designed to do by assessing the suitability of a specific wood frame design for construction on a target robotic construction system. Therefore, the projects are complementary.

4 Proposed simulation-based methodology

The proposed methodology aims to generate simulations of robotic systems based on building design information, to support the analysis of offsite construction automation. The building designs, in the form of IFC-based BIM instance models, are used as input to the simulation. The simulated construction process involves the assembly of wood frames by a robotic system. The assembly process consists of a set of framing and connection operations on wood elements. The proposed simulation methodology is divided into six phases (Fig. 1): 1) BIM Design Data Input, 2) Robotic System Model Selection, 3) Simulation Environment Setup, 4) Construction Operations and Control System Definition, 5) Simulation Generation and Execution, and 6) Evaluation. Details of each phase are provided in the following subsections.

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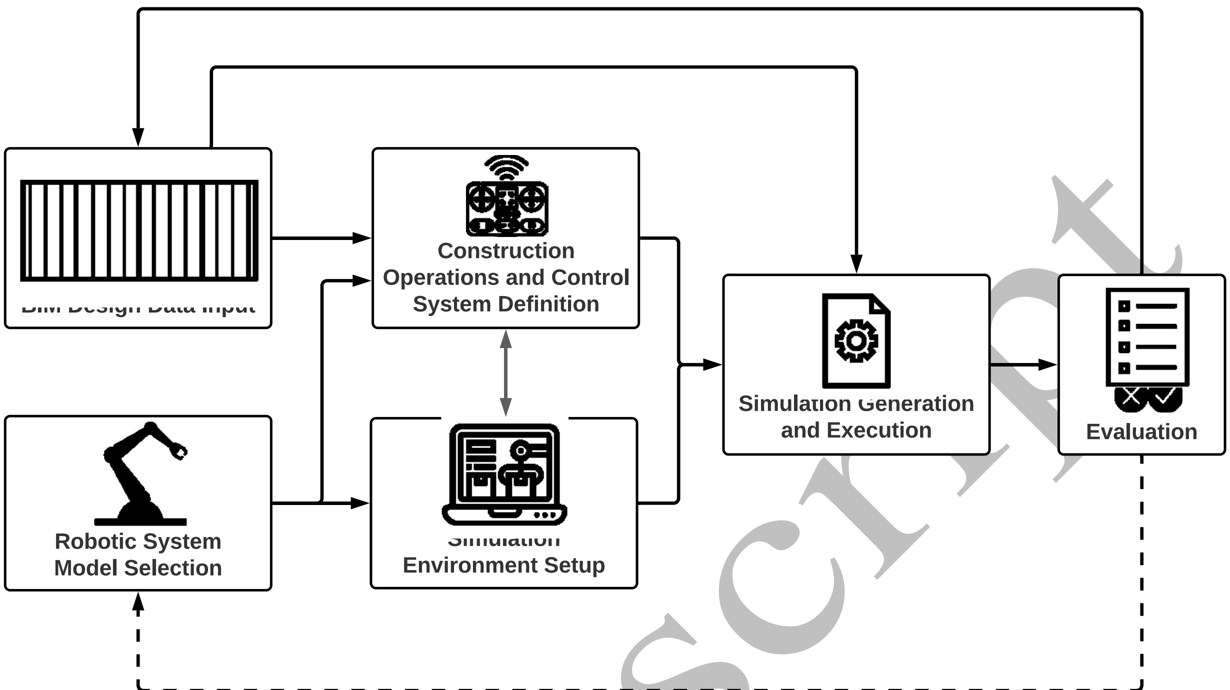

Fig. 1. Proposed methodology.

4.1 BIM design data input

The initial input for the proposed methodology consists of building design data derived from BIM instance models. The IFC-based BIM data includes the order of the building elements (e.g., bottom plate->studs->top plate), dimensions and weights of the building elements, and location (position and orientation of the elements relative to the BIM design model coordinate system) that are extracted and derived from IFC models. The extraction and inference make use of a logic-based approach and provide input to the simulation. The BIM data input used for the simulation environment and for the robot controller are shown in Table 1 and Table 2, respectively. As mentioned in Section 2.1 (*BIM-based Approach*), the details of the information extraction and analysis methods and algorithms of IFC models using logic representation and reasoning are described in [17].

Table 1. BIM input data for the simulation environment.

Input data	Description

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Density of element	The density of the elements was assigned to the element during the matching of the elements from BIM input to the simulation world.
Sequence of construction	The sequence of the construction was determined using a soft sequencing requirement (i.e., any feasible sequence without optimization consideration). The elements are instantiated in the simulation environment according to the determined order.
Dimension	The dimension was mapped to the simulation objects.
Position and orientation	This element is the position in the simulation environment and the orientation of the cross section.

Table 2. BIM input data for the robot controller.

Input data	Description
Name	The name of the element provides a unique identifier and the type of elements (e.g., beam23, column45).
Local placement	The local placement location is the centroid of one of the extreme end’s cross-section of the element relative to the global coordinate system of the BIM design model.
Main axis	The main axis refers to the orientation of the longitudinal axis of the element relative to the local coordinate system of the element’s cross section. For a regular element, it corresponds to the extrusion of the element when using solid sweeping 3D representation. In IFC, it is the direction of the z-axis in the coordinate system of the element’s cross section.
Dimension	Dimensions include the width, depth, and height of a stud element.

4.2 Robotic system model selection

The second phase of the proposed methodology is the selection of the robotic system. The process consists of selecting the components of the robotic system to support the assembly process of wood frames. In this paper, the components of a robotic system refer mainly to the physical components of a robotic cell such as robot, end-effectors, fixtures, material handling devices, and sensors. A brief description for each component is provided in Table 3. The selection of the components is based on its specifications and functions in the assembly process and can be divided

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into two steps: 1) define the specifications for the components of the robotic system, and 2) select the components of the robotic system.

Table 3. Description of robotic system components.

Robotic system component	Definition	Description
Robot	According to the ISO (International Organization for Standardization) 8373, a robot is an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks" [44].	Performs the framing and nailing operations in the frame assembly. For example, industrial arms.
End-effector	A "tool to enable robots to interact with environments" [45].	Tools attached at the end of the robot's arm for gripping, fastening elements, etc. Examples include grippers, nailing gun, or other tools.
Material handling device	A device used to move materials between specific points on a fixed path.	Transport and feed materials to the robot. Examples include conveyor, which can be single or a system of conveyors.
Fixture	A fixture is any tools that support the assembly process.	Examples include tables, floors, and other tools.
Sensor	A "device that receives a stimulus and responds with an electrical signal" [46].	Allows the perception of the environment and the measurement of parameters of the robotic system (e.g., joint angles). Examples include displacement, rotation, and touch sensors.

4.2.1 *Define the specifications for the components of the robotic system*

The first step is to narrow down the number of alternatives for the selection of the robotic system components based on the constraints, specifications, or performance criteria for each of the components in the framing and nailing processes. Examples of specifications for a robotic system component include the load capacity and the reach of the robot which are indicative of how heavy and how far a robot can carry and reach, respectively. Another example could be the speed of the conveyors. Once the specifications are defined, the selection of the specific components of a robotic system can be performed. It should be noted that we assume sufficiently flexible automated

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fixturing is provided to immobilize the wood frame components wherever they are placed by the robot.

4.2.2 *Select the components of the robotic system*

After the definition of the specifications and functions for each component of the robotic system, the next step is to select the specific components. The selection of the components can be from existing commercially available components or conceptualized components (e.g., new robotic design) that meets the automation requirements/specifications of the assembly process.

4.3 Simulation environment setup

Following the selection of the robotic system components, the next phase is the setup for the simulation. This phase consists of four steps: 1) create the models of the construction materials, 2) create/import the models of the robotic system components, 3) aggregate the models of the robotic system components into assemblies, and 4) define the layout of the robotic system.

4.3.1 *Create the models of the construction materials*

The construction materials of interest for wood construction are the 2x4 and 2x6 studs because they are commonly used as vertical framing members in wall structures [47]. In the simulation environment, the respective 3D models of the wood studs for the simulation of the assembly process are created. The models of the studs serve as templates in the mapping process (in subsequent steps) from the BIM data to the stud models of the simulation. During the mapping process, the lengths and density of the stud models are adjusted accordingly based on the BIM data input.

4.3.2 *Create/import the models of the robotic system components*

This step creates or imports the 3D models of the selected robotic system components in the simulation. The 3D models can be created using the built-in modeling tool of the robotic simulator or in any 3D modeling software and then imported to the simulation environment. Following that, parameters of the created/imported models such as bounding box, physics, anchor points and movement ranges of the joints need to be verified and adjusted if needed for its correct function in the simulation.

4.3.3 *Aggregate the models of the robotic system components into assemblies*

Simple 3D models can be aggregated into a single model called assembly to represent or form more complex models. For example, basic 3D objects can be aggregated into assembly to represent

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the different links (i.e., components) of a robot, while the models of the links (i.e., assemblies) can be further aggregated into another assembly to form a multi-degree-of-freedom robot model. Assemblies facilitate the reuse and instantiation of complex objects in the simulation environment. In addition, an assembly provides the flexibility to customize parameters in the simulation environment. Some common modifiable parameters include translation, orientation, and size of the 3D model assembly.

4.3.4 *Define the layout of the robotic system*

The spatial layout of the components within a robotic system affects the workflow of the system. For example, the workspace of the assembly area needs to be defined to avoid potential collisions with other components (e.g., feeding devices). Therefore, it is important to consider the different layout configurations of each individual component in the planning of the assembly process. Some considerations in the definition of the spatial layout include the relative location and orientation of each component of the robotic system within the workspace of the simulation world.

4.4 Construction operations and control system definition

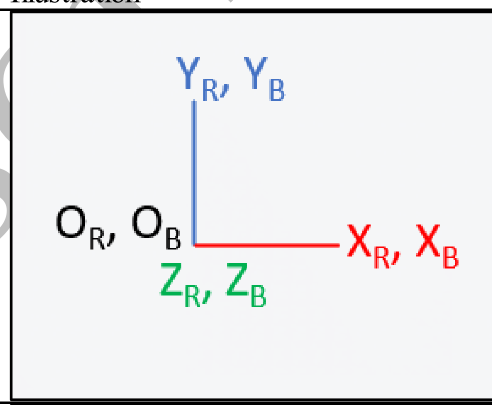
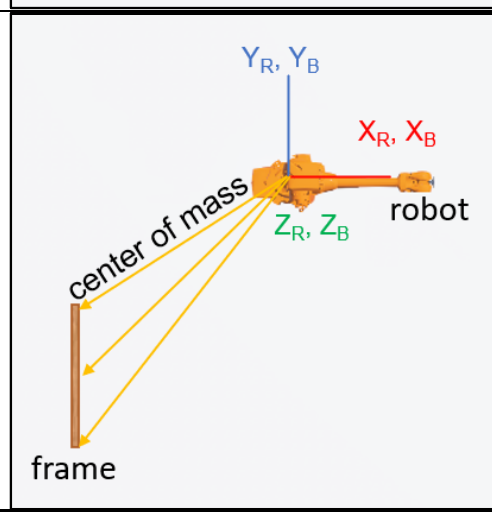
In this phase, the behavior of the robotic system is defined, coded, and integrated in the control system based on the construction operations (i.e., assembly process). The control system defines the behavior of the robotic system to perform the assembly operations, based on the information provided from the BIM data input. The creation of the control system involves six steps: 1) determine the framing target locations for the framing operation, 2) determine the nailing target locations for the nailing operation, 3) define the placement orientation of the frame with respect to the robot, 4) define and create the subroutines for the robot, 5) code the control system and BIM data in the robot controller, and 6) define the behavior for the robotic system components.

4.4.1 *Determine the framing target locations for the framing operation*

The framing target locations refer to the center of mass of the elements relative to the origin of the robot's base. In other words, a framing target location is the cartesian point measured from the robot's coordinate system to the center of mass of the element in the final assembled (constructed) state of the frame. The framing target locations are determined based on the data from the BIM design models, which are provided as BIM data input. This data includes locations of local placement, dimensions, and orientations of the main axis for each of the elements as defined in the BIM data input.

Following that, a series of coordinate transformations are needed. The coordinate transformations for the framing operation are divided into eight sub-steps and involve three Cartesian coordinate systems: 1) global coordinate system of the BIM design model, 2) local coordinate system of the robot, and 3) global coordinate system of the simulation world. To reduce the complexity of the transformation process, the origin of the local coordinate system of the robot is set to overlap with the origin of the global coordinate system of the simulation world. The sub-steps for the coordinate transformations are presented in Table 4.

Table 4. Sub-steps for determining the framing target locations.

#	Sub-step	Illustration
1	Align the origin of the BIM coordinate system O_B with the origin of the coordinate system of the robot O_R. This simplifies the transformation between the BIM and robot coordinate systems.	
2	Compute the center of mass of the elements. The center of mass is determined based on the length, placement location, and the direction of the main axis of the elements.	

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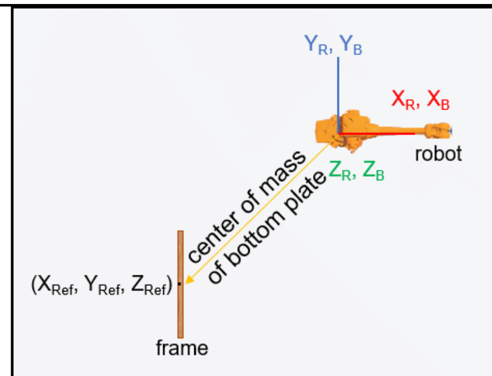
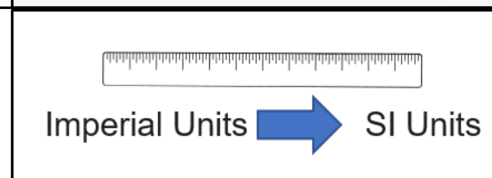
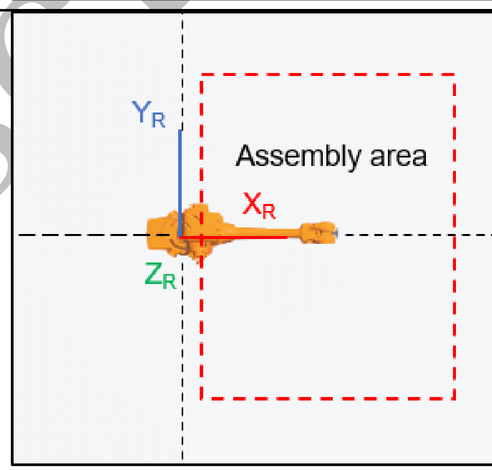
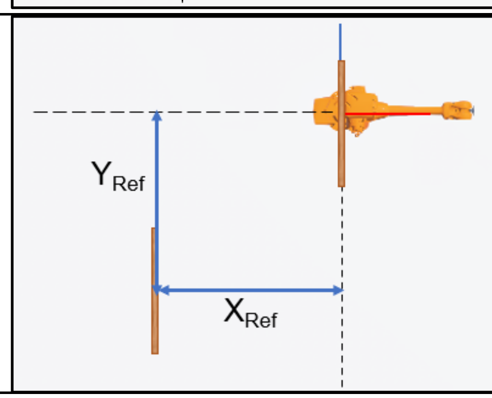
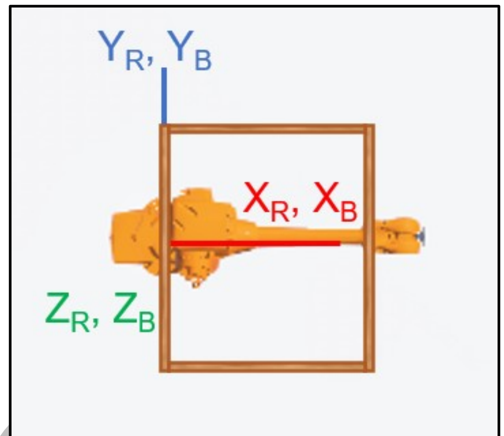
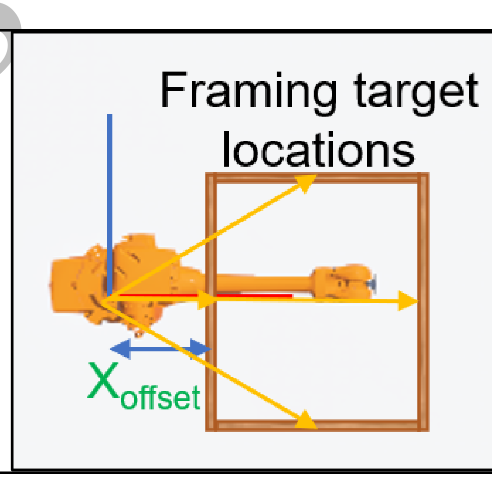
#	Sub-step	Illustration
3	Set the coordinate of the center of mass of the first element as the framing reference point. The framing reference point serves as a positional baseline for all the elements for the framing.	
4	Verify the unit of length used in the two coordinate systems. If they differ, convert all the length values of the BIM design model coordinates to match the unit of length of the simulation environment.	
5	Define the area (quadrants) for the framing operations, relative to the coordinate system of the robot.	
6	Translate all the elements from their original positions in the X-Y plane using the framing reference point as offset.	

#	Sub-step	Illustration
7	Rotate the axis of the BIM coordinate system according to the defined framing area. The number of rotations depends on the orientation of the wall in the BIM design model relative to the robot. For instance, if the original position of a wall in the BIM design model is perpendicular to the robot, two rotations (Z_{90} and Y_{90}) are needed. In another case, if the wall is parallel to the robot, only one rotation of Y_{90} axis is sufficient. The perpendicularity of a building component, in this case a wall, depends on the wall positioning and orientation of the BIM design model. The Y or the X dimensions in the BIM design model coordinate system become the Y of the robot's coordinate system based on if the wall is parallel or perpendicular to the robot. The Z dimension in the BIM design model coordinate system becomes the X in the simulation coordinate system.	
8	Add the offset distances from the origin of the coordinate system of the robot to the computed coordinates of the elements.	

4.4.2 *Determine the nailing target locations for the nailing operation*

In this step, the target locations for the nailing operation are defined. The nailing target locations are the locations where the robot performs the nailing operations to connect the elements in the frame, relative to the coordinate system of the robot. The nailing target locations are determined based on the framing target locations according to Eq. (1), Eq. (2), and Eq. (3) based on the nailing schedule for studs and plates (top and bottom) connections [47]. The two values for N_z in Eq. (3) correspond to the two nailing locations in the z-axis. A representation of the nailing target locations in a frame is shown in Fig. 2.

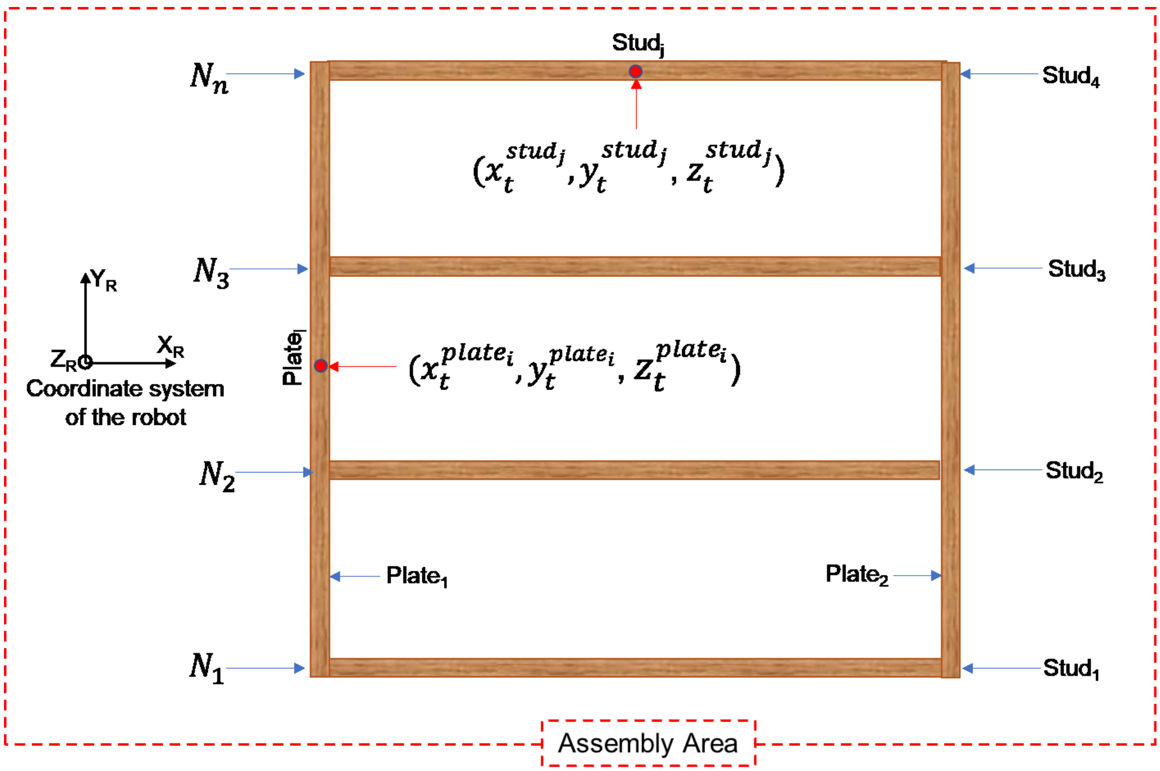


Fig. 2. Definition of the nailing positions.

$$N_x^{ij} = x_t^{plate_i} - thickness^{plate_i}/2 \qquad (1)$$

$$N_y^{ij} = y_t^{stud_j} \qquad (2)$$

$$N_z^{ij} = \begin{cases} z_t^{plate_i} - \dfrac{width^{plate_i}}{6} \\ z_t^{plate_i} + \dfrac{width^{plate_i}}{6} \end{cases} \qquad (3)$$

where N_x^{ij} = x component of the nailing target location between plate i and stud j

N_y^{ij} = y component of the nailing target location between plate i and stud j

N_z^{ij} = z component of the nailing target location between plate i and stud j

$x_t^{plate_i}$ = x component of the center of mass location of plate i

$z_t^{plate_i}$ = z component of the center of mass location of plate i

$y_t^{stud_j}$ = y component of the center of mass location of stud j

$width^{plate_i}$ = width of plate i

$thickness^{plate_i}$ = thickness of plate i

4.4.3 *Define the placement orientation of the frame with respect to the robot*

In this step, the placement orientation for the frame is defined. The orientation of the frame determines the orientation of its elements. The orientation can be perpendicular, parallel, or at an angle with respect to the y-axis of the robot. A parallel orientation means that the length (left-right direction of the frame) of the frame is parallel to the y-axis of the robot (left-right side of the robot), while a perpendicular orientation means that the height (bottom-top direction) is parallel to the y-axis of the robot. Once the orientation of the frame is defined, the longitudinal axis for each element is determined, and this information is included in the controller in order to provide the direction for the placement of the elements in the framing and nailing operations.

4.4.4 *Define and create the subroutines for the robot*

The subroutines for the framing and nailing operations are defined and created to enable the robotic system to perform the operations automatically. The framing and nailing subroutines consist of a list of operations such as pick, move, and open/close grippers. The subroutines take the location of the elements from the feeding device (conveyor tray), the type of element, and the framing and nailing target locations as input. Based on the type of element (i.e., plate, stud) and its order (i.e., construction sequence), the robot performs the corresponding subroutine (i.e., framing, nailing). Each complete cycle of the subroutine corresponds to the framing of an element. Examples of framing operations are shown in Fig. 3. A flowchart for the framing subroutine is shown in Fig. 4.

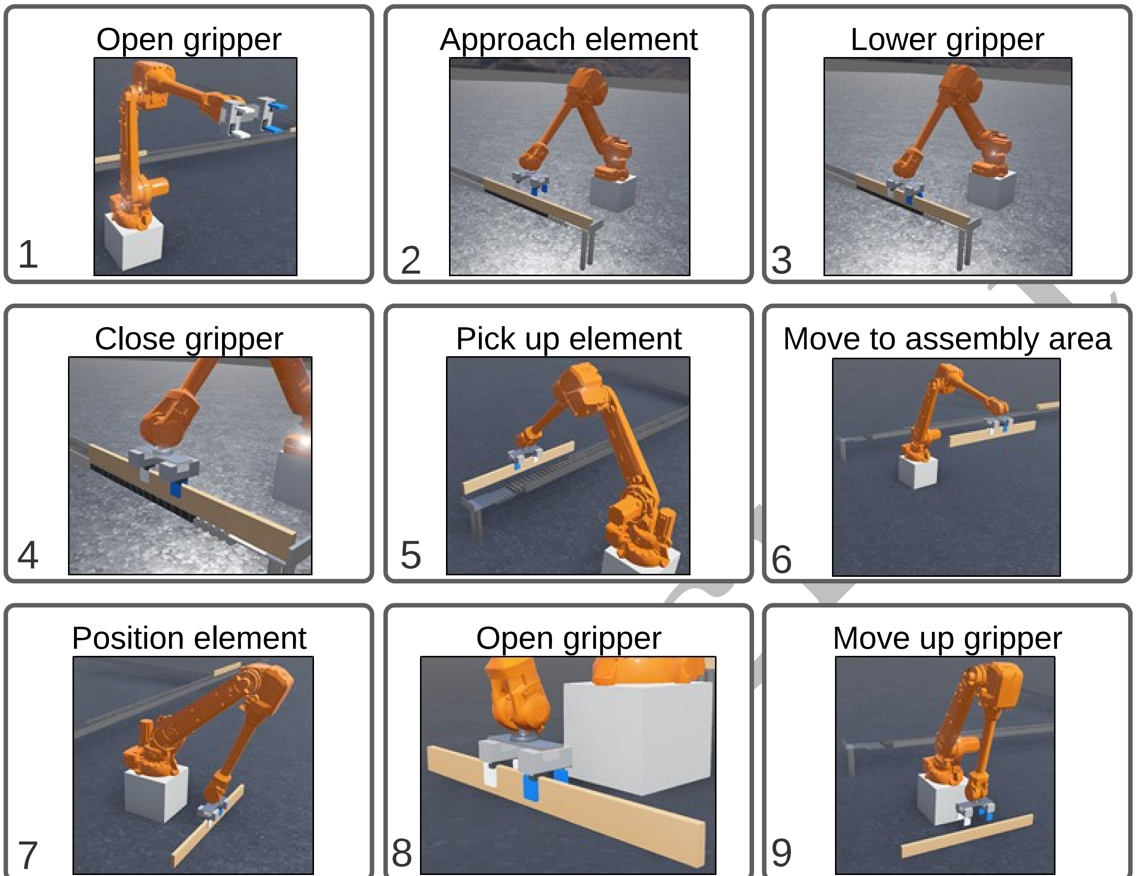


Fig. 3. Framing operations.

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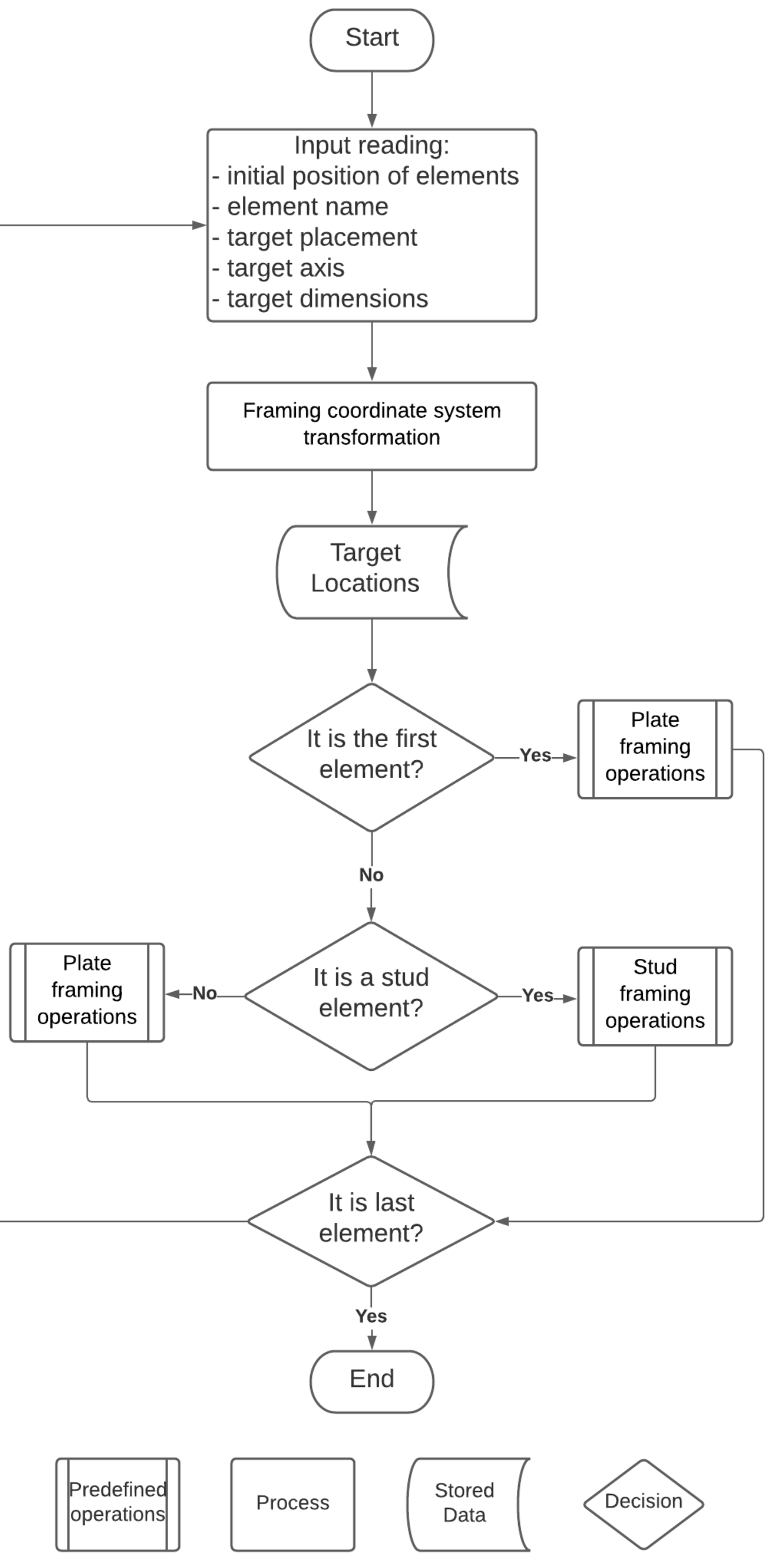

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Fig. 4. Framing subroutines algorithm flowchart.

4.4.5 *Code the control system and BIM data in the robot controller*

Controllers contain the instructions (e.g., subroutines) for the robotic system to perform the assembly process. The control of the robot is determined using inverse kinematics (IK), which takes the cartesian position of the end-effector to compute the joint angle of each link joint. The IK function along with the framing and nailing subroutines can be integrated in the controller or used as a support module to the controller. The latter case is used in this paper to increase the modularity of the algorithm.

In addition, the BIM data are included in the controller and are used to determine the target locations for the framing and nailing operations, which in turn are used in the framing and nailing subroutines for the execution of the assembly process. The BIM data are included in the controller as input, which include the name, local placement, main axis, and dimension of the elements (as specified in Section 4.1 - *BIM design data input*).

4.4.6 *Define the behavior for the robotic system components*

The behavior of the robot is defined in the framing and nailing subroutines. Now, the behavior for the other components of the robotic system is defined for the assembly process. For example, the movement of materials by the handling devices (i.e., conveyors) is set to move at a constant speed instead of a predefined distance. As another example, a touch sensor with an emitter is created at the end of the second conveyor to signal the robot when an element is ready for pick up, while stopping the movement of the conveyors until the current element is picked up by the robot in the framing process. The defined behaviors are then coded and integrated into its respective component controllers when applicable [some behaviors are integrated into the robot's controller (e.g., the open and close functions of the parallel gripper)].

4.5 Simulation generation and execution

In this phase, the simulation file is generated, which include the robotic system components and BIM data from the previous phases. The generation process and execution of the simulation consist of four steps: 1) map the BIM building elements to the construction materials from the simulation, 2) define the initial position and orientation of the construction materials in the simulation environment, 3) generate the simulation file, and 4) execute the simulation file.

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4.5.1 *Map the BIM building elements to the construction materials from the simulation*

In this step, the building elements (e.g., columns and beams) from BIM are automatically mapped to the created construction materials (i.e., studs) in the simulation environment. Information such as dimensions, weight (density), quantities for each stud are mapped to the studs of the simulation.

4.5.2 *Define the initial position and orientation of the construction materials in the simulation environment*

In the simulation environment, the elements are generated according to the sequence of bottom plate->studs->top plate in the first conveyor. Each element is positioned parallel to each other and separated with a constant spacing to avoid misalignment and prevent collision between elements, respectively, during the transfer to the next conveyor. The longitudinal axis of the elements is aligned with the next element on the conveyor in a straight path while the element is standing on one of its narrower side surfaces. This facilitates the grasping operations by the robot and avoids the need of rotating the elements during the assembly operations.

4.5.3 *Generate the simulation file*

In this step, the simulation file that contains the information from the previous phases such as simulation assets (i.e., 3D models of the robotic system components, building elements, controllers, and properties) is dynamically generated and loaded. The generation and loading processes are conducted through programming. The model directory structure of the robotic simulator is followed in these processes.

4.5.4 *Execute the simulation file*

Once the simulation file that contains the assemblies and the embedded controllers for the robotic system is generated, the simulation is ready to be executed. The simulation automatically starts when the simulation file is executed. During the simulation, the robotic system performs the programmed assembly subroutines.

4.6 Evaluation

This phase of the proposed methodology evaluates the performance of the simulation. The evaluation process can be divided into three categories: 1) BIM-simulator integration, 2) assembly process simulation, and 3) collision detection. In the first category, the information generated (e.g., building materials) in the simulation environment are compared against the building elements in

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the BIM design model to verify the accuracy of the mapping and generation processes. Second, the simulation of the assembly process is evaluated to determine the performance of the construction algorithms (e.g., framing and nailing subroutines), which are based on BIM data. This evaluation identifies components of the robotic system that did not perform as intended due to their insufficiency and/or inaccuracy of the BIM data. The visualization of the simulation allows users to inspect specific operations performed by the robotic system. In addition, the spatial and temporal information is used to identify any unexpected behavior of the robotic system components during the construction operations. The third category is the collision detection between the components of the robotic system or with any objects within its workspace, which can cause failure of the assembly operations.

The output of this evaluation determines the adequacy of the BIM data, the generated construction operations, and the selected robotic system components for the assembly process. The evaluation phase forms a feedback loop to the reselection/modification of any components of the robotic system (if needed) and/or the BIM data to improve the current assembly process.

5 Experiment

5.1 Software implementation

The proposed methodology was implemented using Webots, an open-source robotic simulator developed by Cyberbotics Ltd [48]. Webots provides a fast prototyping environment for modeling, programming, and simulation of robots [38]. Unlike other open-source robotic simulators, Webots is compatible across different platforms (Windows, Linux, and macOS). It uses an improved version of the Open Dynamics Engine to simulate physics, and can reproduce the same behavior in consecutive simulation runs using the same control algorithm (reproducibility) [49]. Moreover, it contains a set of pre-configured robots, devices, and 3D objects available out-of-the-box, which users can easily adopt and customize. Furthermore, the graphical interface of Webots allows an easy interaction with the robotic system, objects, and workspace.

Regarding the IK, the solver IKPy (implemented as a Python library) was used to handle the computation of the joint parameters according to the cartesian coordinates of the end effector. IKPy is precise (up to 7 digits after the decimal point), fast (7 to 50 milliseconds, depending on the precision of the model), and it has the option to compute for every existing robot the IK for position or orientation only, or for both combined [50]. Although IKPy was selected, any other kinematic solver could be used (e.g., IKFast [51]). The discussion of the implementation and advantages of different kinematic solvers are out of the scope of this paper.

The generation of the Webots world file as described in the Subsection 4.5.3 (*Generate simulation file*) was implemented in B-Prolog, a logic programming platform. B-Prolog is an implementation of the Prolog programming language and was selected because: 1) it has an inherent reasoner that allows automated inference using unification, backtracking, and rewriting techniques [52], 2) it is compatible with C and Java programming languages, which enables bi-directional interface with procedural and object-oriented programming, respectively, for application development [53], and 3) it provides continuity and direct transfer of data from the BIM design models because the information extraction algorithms were created using B-Prolog. Note that the generation of the Webots world file is not dependent on any programming languages. In other words, the simulation world file could have been generated using any other programming languages such as Python or Java.

5.2 System setup

The minimum computational requirements to adequately run Webots are specified in the Webots User Guide [54]. In this paper, the experimental testing was conducted on a Windows 10 (64-bit) laptop with an Intel® Core™ i7 – 9750H CPU @ 2.60 GHz processor, 16 GB of Random Access Memory (RAM), and a NVIDIA® GeForce® GTX 1650 graphics card, which exceeds the minimum requirements specified for Webots.

5.3 Test cases

Three BIM design models were created and used as test cases in the experimental testing following the proposed methodology. The test cases consist of 1) a square frame of a 3-by-3-foot opening with 2”x4” elements (Fig. 5), 2) a rectangular frame with 2”x6” elements (Fig. 6), and 3) a wood structure that consists of 4 exterior walls (Fig. 7). The height of the wall frames is 8 feet with intermediate studs spaced at every 16 inches on center. The stud size of the frames is 2”x4”. The BIM design models were created in Autodesk Revit (version 2019). The dimensions for each test model are shown in Fig. 5, Fig. 6, Fig. 8, and Fig. 9, respectively.

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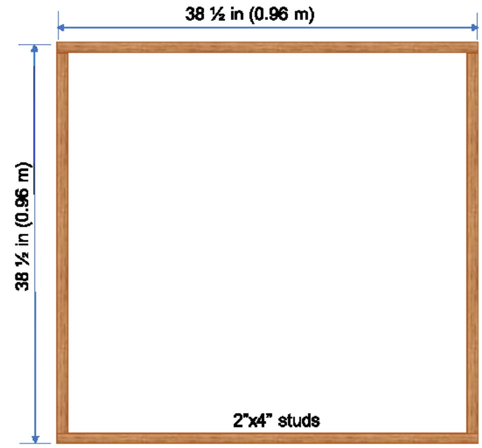

Fig. 5. Square opening frame.

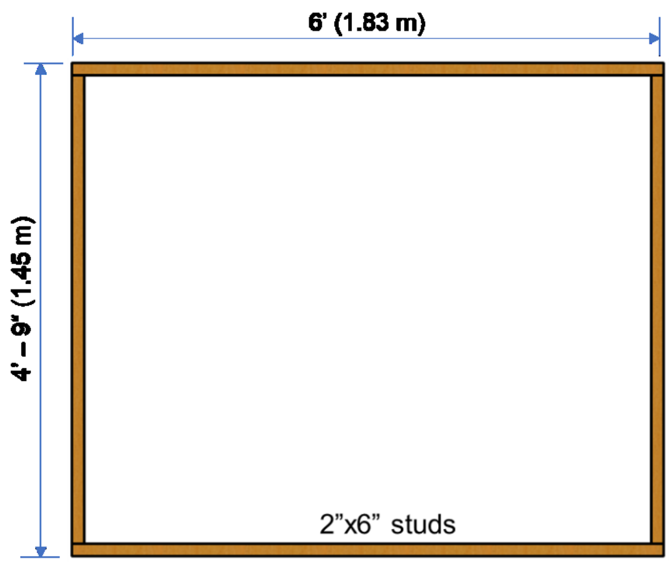

Fig. 6. Rectangular frame.

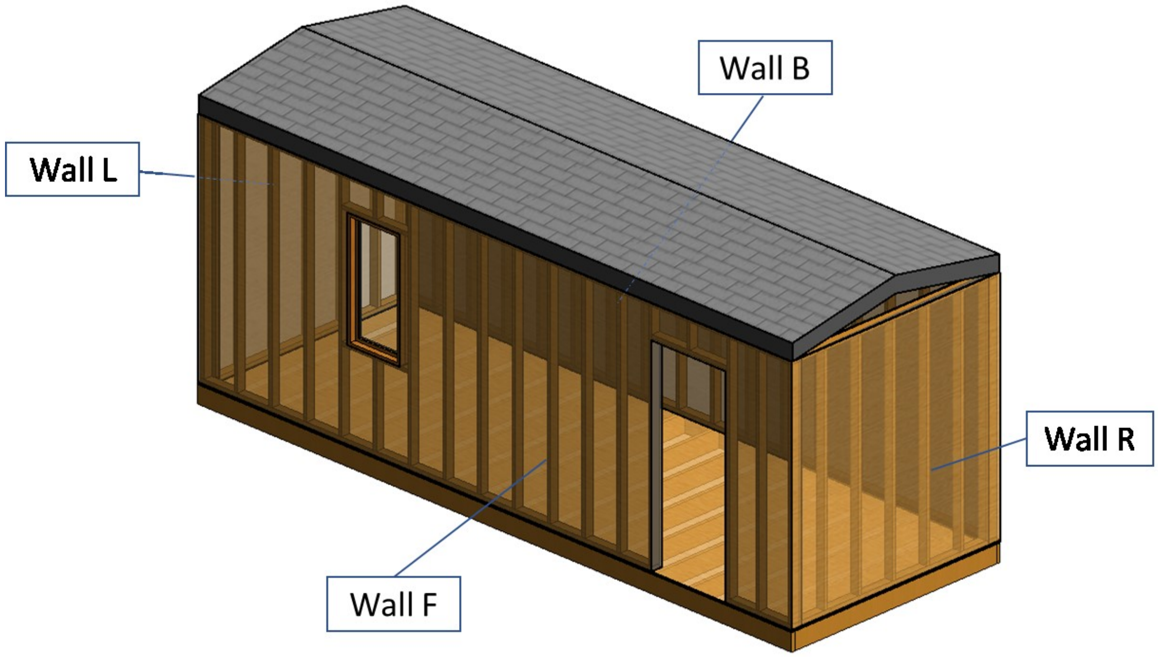

Fig. 7. Wood structure.

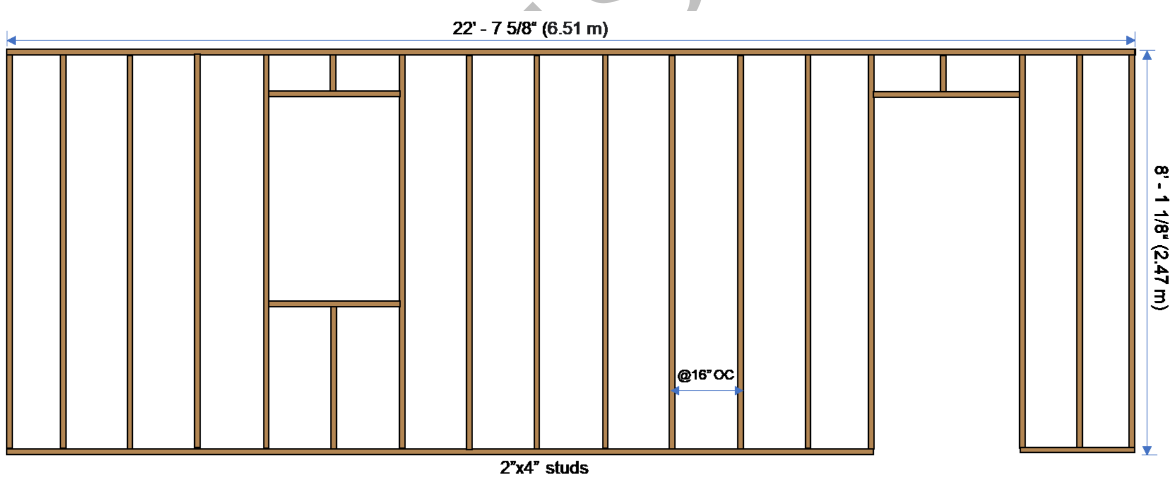

Fig. 8. Overall dimensions of Wall F and Wall B.

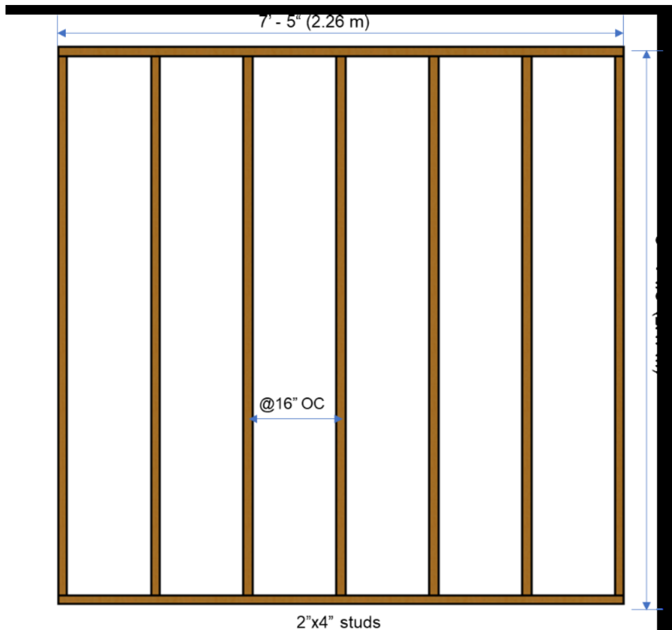

Fig. 9. Overall dimensions of Wall L and Wall R.

5.4 BIM design data input

The BIM data extracted and derived from the three test cases (BIM design models) were used as input in the subsequent phases. The data extraction was performed by decomposing the structure (BIM design models) into individual components (i.e., wall frames) for each wall. Meanwhile for each wall frame, the corresponding studs (represented as IFC columns) and plates (represented as IFC beams) were grouped to the corresponding component (e.g., walls). In addition to the grouping of the elements, the assembly sequence of each element was automatically defined for each wall frame based on its spatial relationship. This extracted and derived information of the components from the BIM design model serve as input to the simulation of wall frames assembly. As previously mentioned, a logic-based method was implemented in B-Prolog to analyze and derive the BIM data.

5.5 Robotic system model selection

The selected components of the robotic system are described below.

Robots: The ABB IRB 4600/40 (Fig. 10a) and KUKA KR 150-2 (Fig. 10b) robots were selected for the simulation because of their reach (2.55 m and 2.70 m, respectively) and payload capacity (40 kg and 150 kg, respectively).

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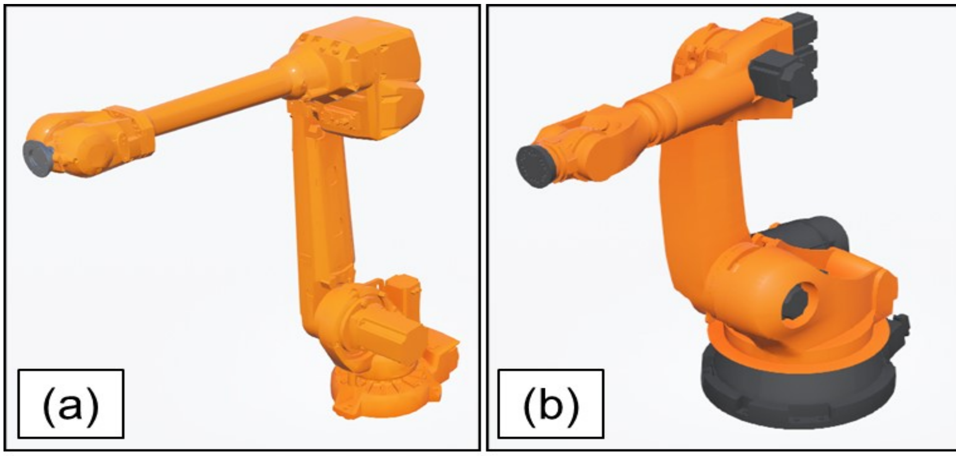

Fig. 10. Robot models: (a) ABB IRB 4600, (b) KUKA KR 150-2.

End-Effectors: For the end-effector, two parallel grippers were used for the stable grasping of the construction materials (i.e., studs) in the framing operations (Fig. 11a). In addition, a nailing gun model was used for the fastening of the wood elements during the nailing operations (Fig. 11b).

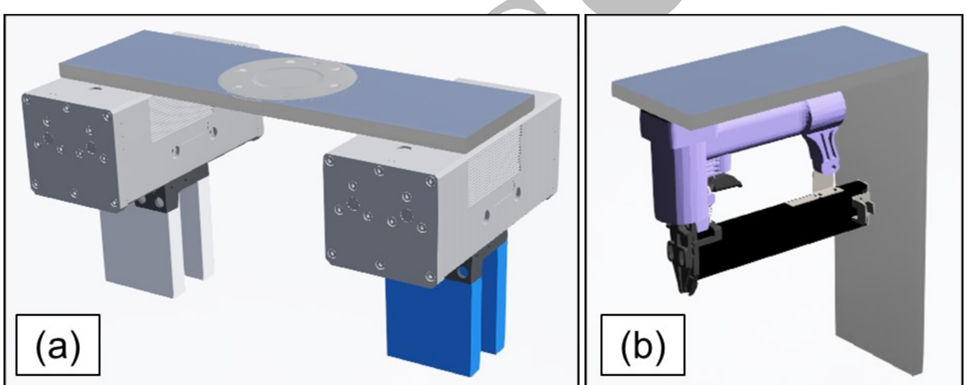

Fig. 11. (a) Two Schunk PEH 30 parallel grippers [55] and (b) Nailing Gun [56].

Material Handling Devices: Two conveyors were created to transport and feed the wood elements (i.e., studs) to the robot for the assembly process (Fig. 12). The first conveyor (Conveyor 1) is used to hold the elements that are instantiated in the simulation world. Conveyor 1 transfers each element (blue arrow) to the second conveyor (Conveyor 2). Then, the element continues to travel (red arrow) until it reaches the end of the Conveyor 2 (far left), where the robot picks up the elements for the framing process. This mechanism allows a constant influx of materials for the assembly process.

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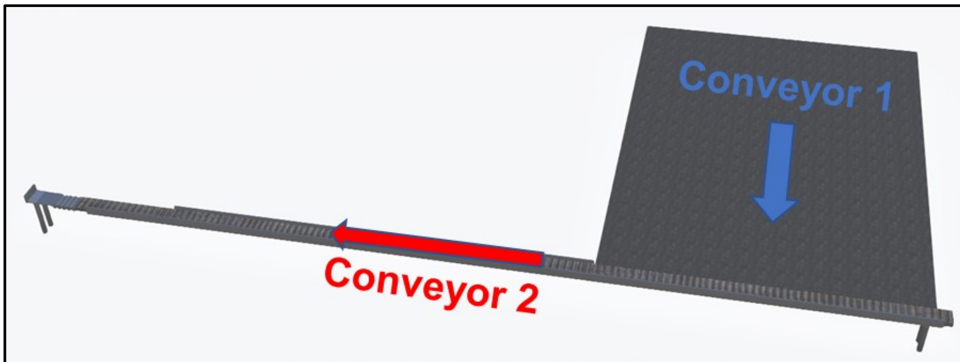

Fig. 12. Conveyor models.

Fixture: For the assembly and nailing process, the factory floor is used as a fixture.

Sensor: the sensors used in this robotic system include rotational and translational sensors, which are embedded in the rotational joint of the robot and in the translational joint of the end-effector's gripper fingers, respectively. In addition, a touch sensor is utilized in the second conveyor to notify the robot through radio frequency signals when an element is available for pick up at the end of the conveyor tray. In the robot, a receiver sensor is used to capture the signal emitted by the touch sensor. Once a signal is received, the robot starts the framing operations according to the framing subroutine.

5.6 Simulation environment setup

The models of the construction materials (i.e., 2x4 and 2x6) were created in the simulation environment. The length for the 2x4 and 2x6 models was one meter, which will be adjusted during the mapping process according to the BIM design models. In addition, each component of the robotic system was created and/or imported in the simulation environment. Following that, the studs and the components of the robotic system were aggregated into assemblies. In Webots, the file format *.proto* is used to represent an assembly, which stores all the information of a 3D asset. Lastly, once the 3D models were added, each component of the robotic system was organized and positioned in the simulation environment (world) as shown in Fig. 13.

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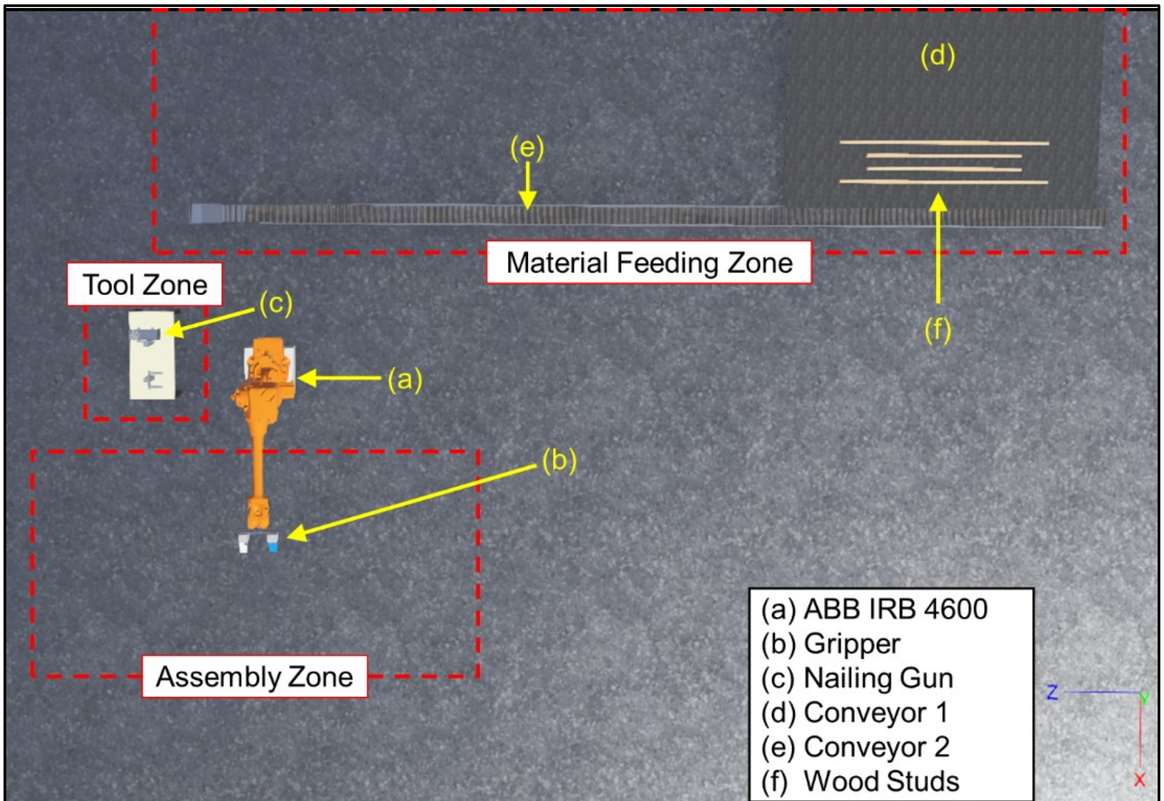

Fig. 13. Spatial layout of the simulation components.

5.7 Construction operations and control system definition

In this phase, knowledge from the construction and robotics domains were applied to support the development of the simulation. Accordingly, the subroutines for the framing and nailing operations were defined and created for the selected robots and coded (in Python) in the controller of the robot. Regarding the type of robot controller, supervisor was selected [57]. A supervisor in Webots is a set of functions that allow the support module (i.e., IK function) to access input information and parameters of the robot during the simulation [57].

In addition to the framing and nailing subroutines, the conveyors were programmed to perform the feeding operations of the construction materials. The speeds of the conveyors were set at a constant value, 0.05 meter per second (m/s) and 2 meter per second (m/s) for conveyor 1 and conveyor 2, respectively. The operation of the conveyor system starts by feeding a construction element. Once the first element reached the end of the second conveyor, it triggers the touch sensor to send a signal to stop the movement of both conveyors and to initiate the construction operations by the robot. The conveyors resume operation after the transported element is picked up by the

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robot. This process continues until the last wood stud element is successfully transported for the framing operations. After the framing operations were completed, the nailing operations were initiated by the nailing subroutines.

5.8 Simulation generation and execution

Webots implements a set of nodes as the core of the model structure in the Webots world files. The set of nodes used are partly derived from the VRML97 standard while other nodes are specific to Webots. By following the syntax of this model structure, Webots world files that contain all the model assets, assemblies, properties, and layout configurations of the robotic system components, were generated using rules developed in B-Prolog. During the simulation generation process, the BIM elements were matched to the stud models of Webots, which were previously created according to the process detailed in Subsection 4.3.1 (*Create the models of the construction materials*). Following that, the matched studs were instantiated in the first conveyor with a spacing between elements set to 150 mm to allow the transfer of the studs from the first to the second conveyor without colliding with adjacent studs (Fig. 14).

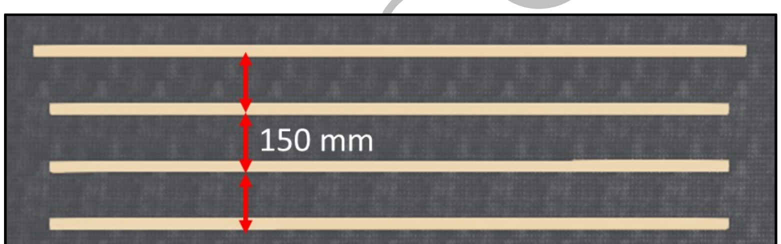

Fig. 14. Initial distribution of construction elements (studs) in the simulation.

Next, the execution of the simulation initiated automatically when the Webots world file was loaded. In the simulation, the robotic system executed the assembly process based on the framing and nailing subroutines and the input information provided by the BIM data. Fig. 15a and Fig. 15b show snapshots of the ABB robot performing the framing and nailing operations, respectively.

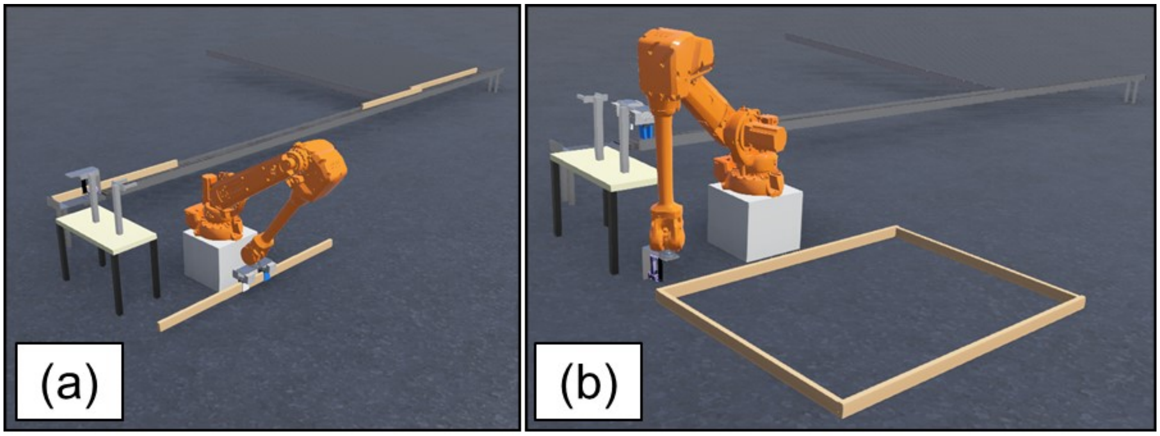

Fig. 15. Assembly operations: (a) framing and (b) nailing.

5.9 Evaluation

The performance of the simulation was evaluated according to the categories defined in the evaluation phase of the proposed methodology. The mapping and generation processes from BIM to Webots were comparatively verified. Following, the simulation of the assembly process was evaluated. During the simulation, the robotic system performed the assembly operations using the developed construction algorithms. After the assembly subroutines were executed, the assembled frames were visually inspected and compared to the BIM design models. For each adjustment made to any of the components of the robotic system, the assembly process was simulated again (following the proposed methodology). This process makes the proposed methodology iterative, which allows for continuous improvement, leading to the desired performance level and outcomes. In addition, collisions were also checked.

5.10 Results and discussion

The purpose of this experiment was to test the proposed methodology using BIM as input for the simulation of robotic systems in the assembly process of wood frames. In the following subsections, the results of BIM integration and robotic system simulation are presented.

5.10.1 *BIM-simulator integration*

The integration of BIM and the robotic simulator Webots to simulate the assembly process of each test models was performed successfully as shown in Fig. 16, Fig. 17, Fig. 18, Fig. 19, and Fig. 20. In [12], the only IFC object used was wall element, which is the object for the robotic painting operation. In this study, for the framing process, stud objects of the wall frames,

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represented as IFC beams and IFC columns, were used. The results showed that the mapped elements in Webots were consistent and equivalent to those from the BIM design model. The automated generation process of the building elements in the simulation (as presented in Subsections 4.4.5 and 4.5) is not only fast and accurate but also avoids the need of manually mapping and creating each lumber objects, which would be time consuming, cumbersome, and error prone.

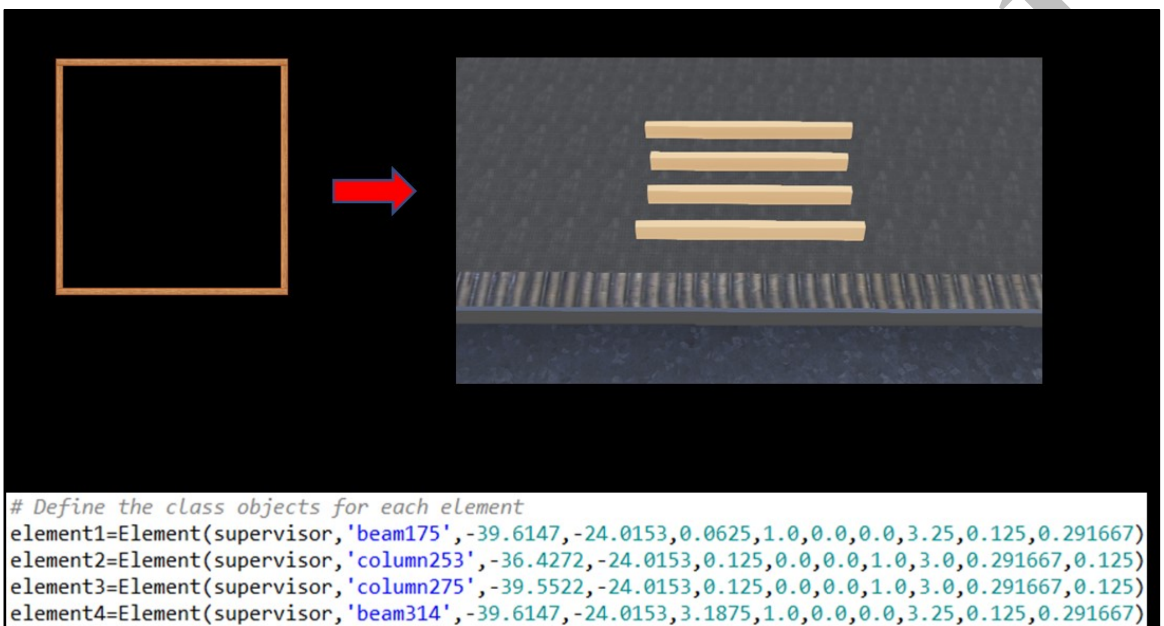

Fig. 16. Integration of test model 1 and robotic simulator.

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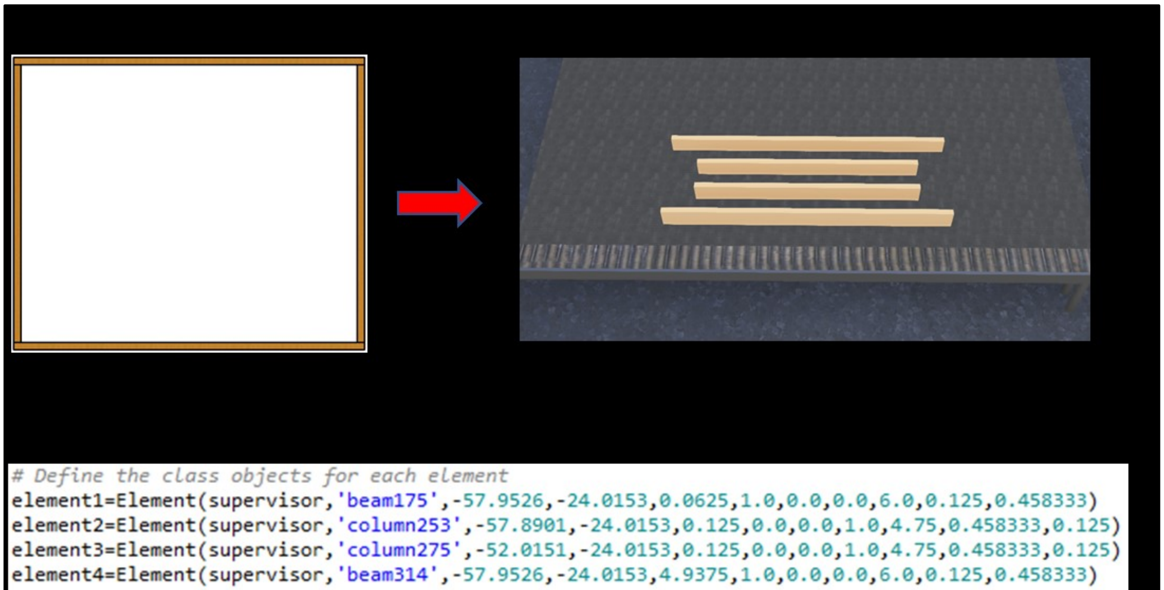

Fig. 17. Integration of test model 2 and robotic simulator.

- Suggested Citation: Wong Chong, O., and Zhang, J., Voyles, R.M., and Min, B. (2022). “A BIM-based approach to simulate construction robotics in the assembly process of wood frames to support offsite construction automation.” *Auto. Constr.*, 137(May 2022), 104194.
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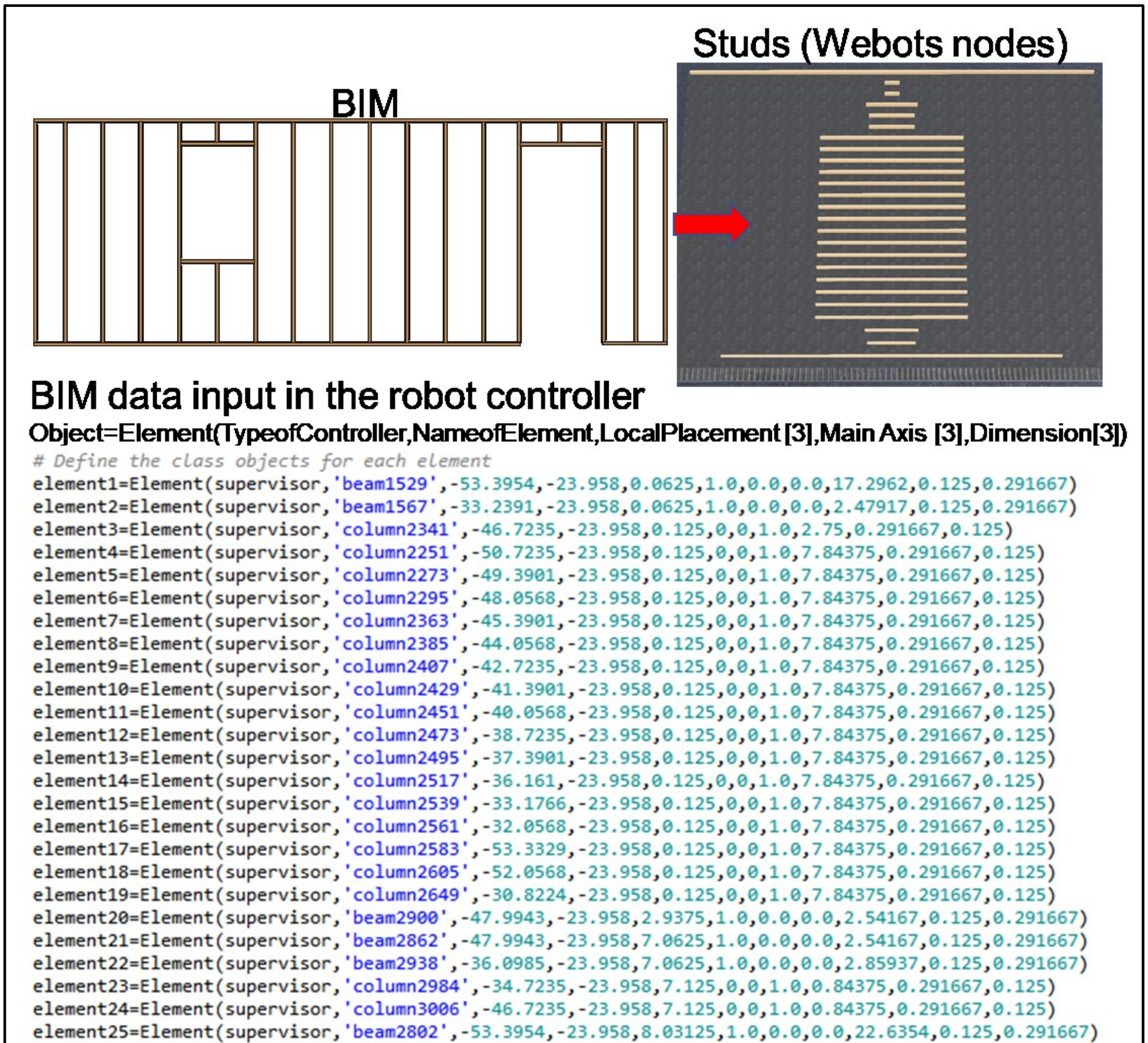

Fig. 18. Integration of test model 3 wall F and robotic simulator

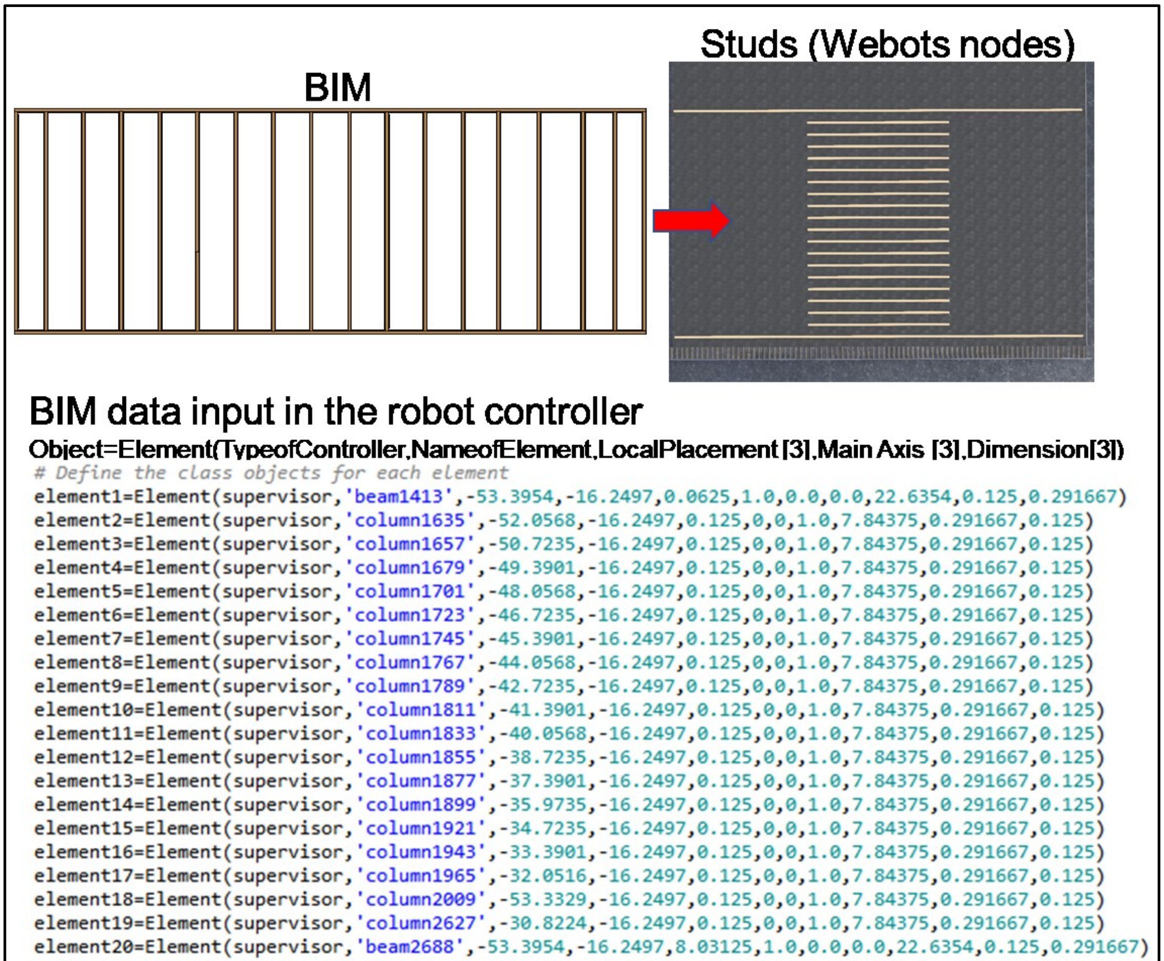

Fig. 19. Integration of test model 3 wall B and robotic simulator

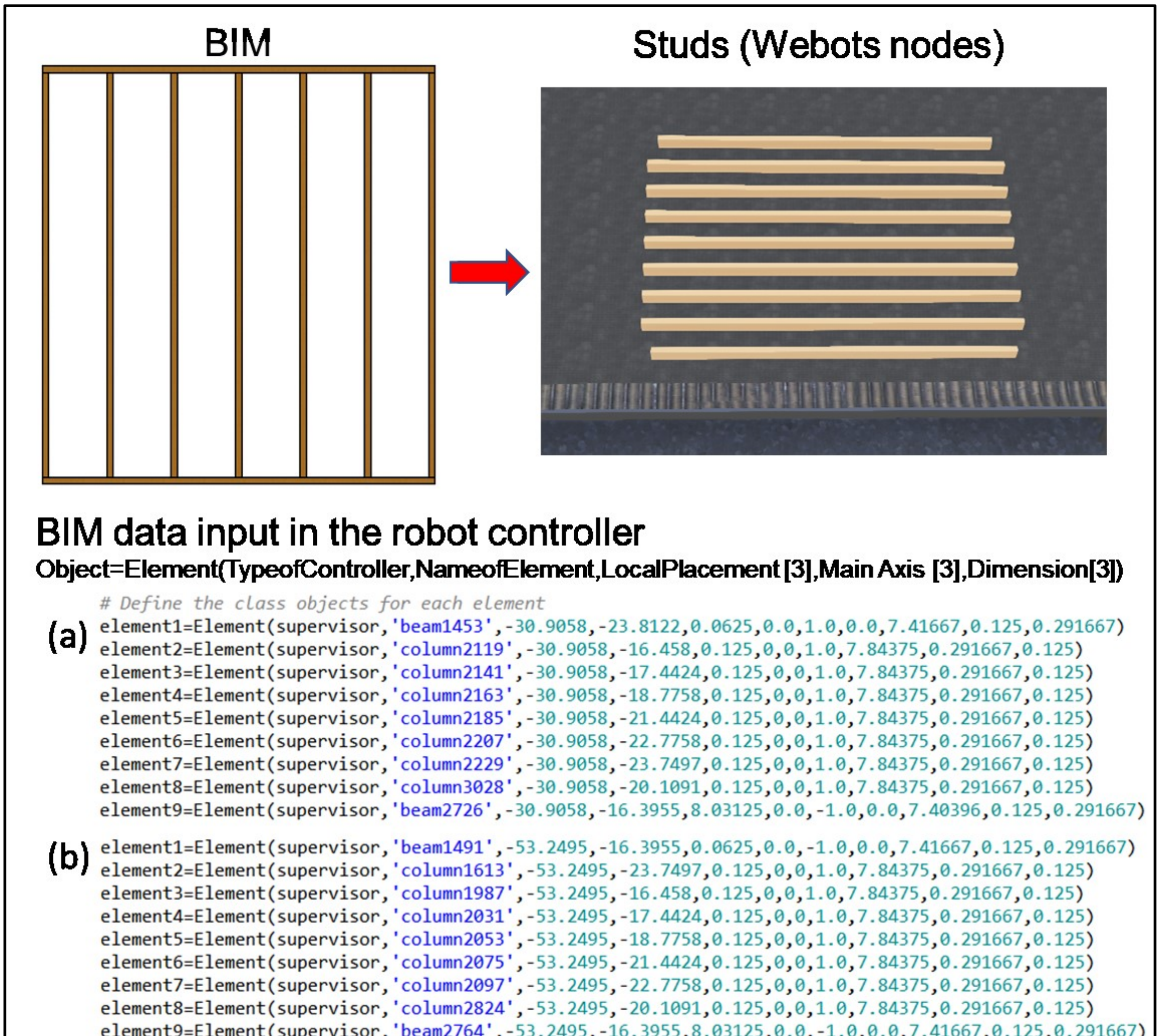

Fig. 20. Integration of test model 3 (a) wall R and (b) wall L and robotic simulator.

5.10.2 *Robotic assembly process*

The developed methodology framework was implemented in the simulation of robotic assembly process of wood frames. The framing and nailing algorithms were successfully implemented using the two selected robots: IRB 4600 and KR 150-2. All the frames were successfully assembled and fastened except for the test model 3 as shown in Fig. 21, Fig. 22, and Fig. 23, respectively. The durations of the simulated framing and nailing processes of the test models were also measured. A summary of the results for the assembly process, including the material feeding process, of the three wood frames is presented in Table 5. For test model 3, the top plate was out of reach of the robot in the framing and fastening operations for Wall L and Wall R as shown in Fig. 23a and Fig.

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23b, respectively. Similarly, the top and bottom plates as well as the five studs on both ends of the frame were out of reach of the robot for Wall F and B as show in Fig. 23c and Fig. 23d, respectively. Therefore, it was labeled as 'Partial' in the framing and nailing processes as shown in Table 5. In addition, the robotic system component corresponding to the failure of the framing and nailing operations, was identified as 'Failed component', which in this case were the robot itself. Note that the duration of the nailing process was not measured due to the premature failure of the nailing operation in the connections between bottom plate and the three internal studs (unable to find the solution of the IK to reach those nailing target locations).

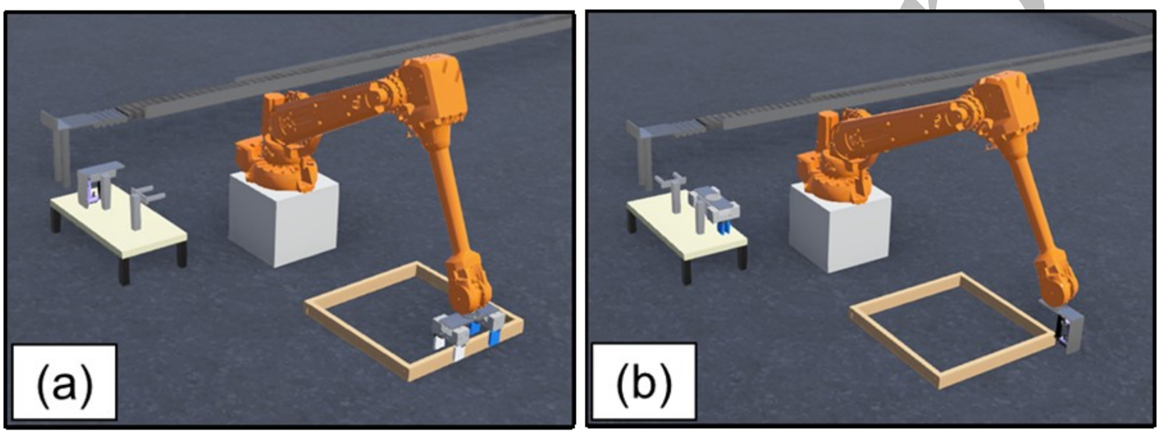

Fig. 21. Simulation result for test model 1: a) framing, and b) nailing.

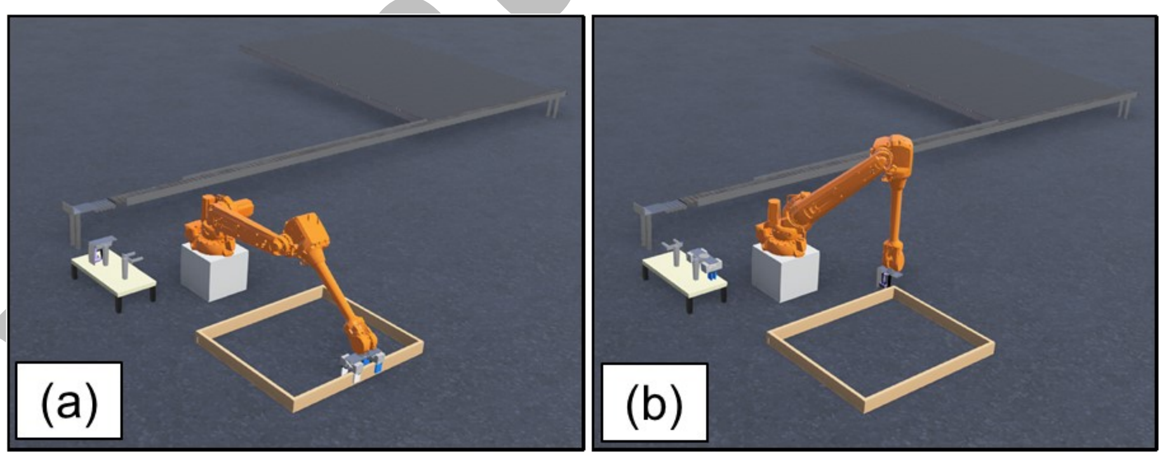

Fig. 22. Simulation result for test model 2: a) framing, and b) nailing.

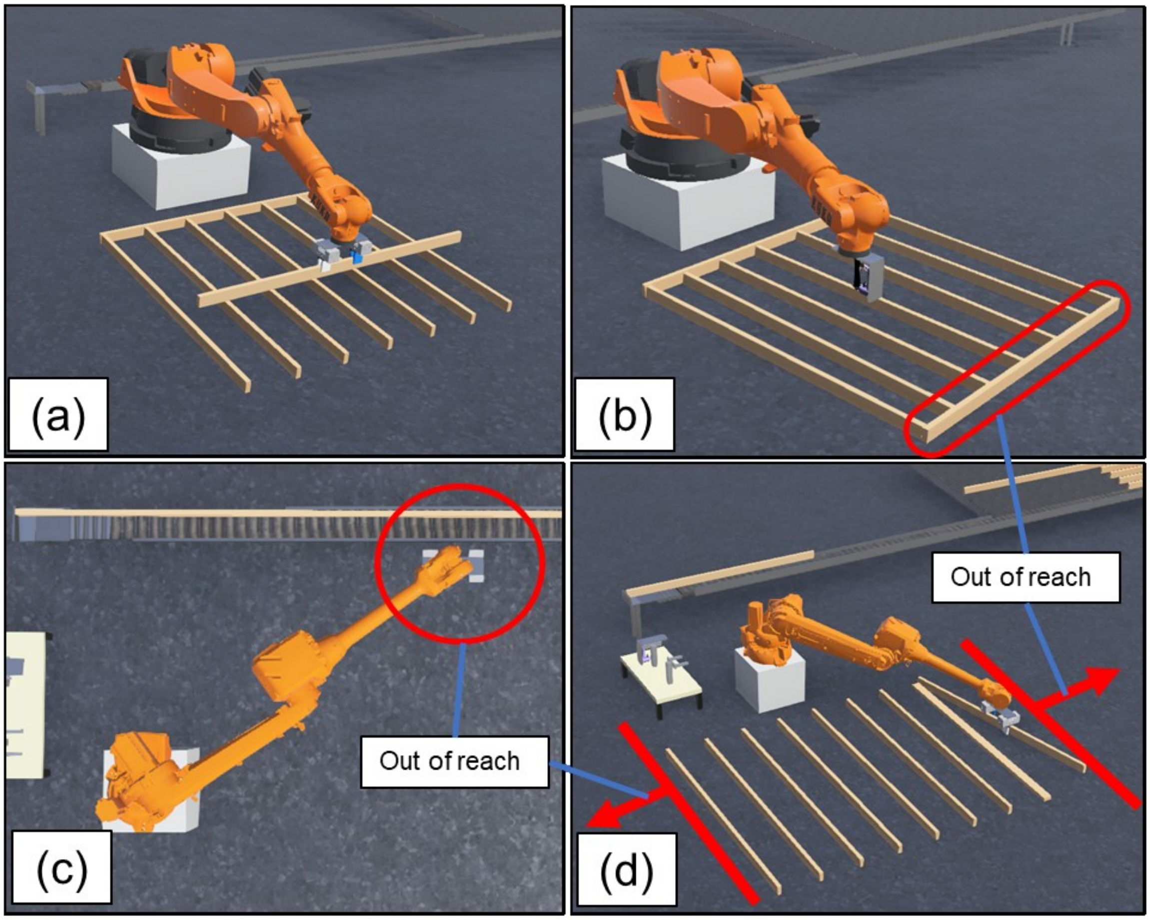

Fig. 23. Simulation result for test model 3: a) framing, b) nailing for Wall L and R; c) and d) framing for Wall F and B.

Table 5. Simulation results of the automated framing and nailing processes for the three test models.

Frame	Material Feeding	Framing	Time (min)	Failed Component	Nailing	Time (min)	Failed Component
1	Completed	Completed	2.22	-	Completed	1.33	-
2	Completed	Completed	2.23	-	Completed	1.52	-
3 L	Completed	Partial	4.53	Robot	Partial	-	Robot
3 R	Completed	Partial	4.50	Robot	Partial	-	Robot
3 F	Completed	Partial	-	Robot	Partial	-	Robot
3 B	Completed	Partial	-	Robot	Partial	-	Robot

Compared to Kim et al. [12] and Meschini et al. [14], where general-purpose robots such as Universal Robots UR10 and Kinova Jaco arm were explored in the simulation of indoor painting and domotics systems, respectively, this work focused on industrial robots (commonly implemented in wood construction), which are more adequate due to the payload demand of the wood elements. In terms of robotic simulators, in [12] and [14], ROS and Gazebo were used, respectively, and in [43], a custom simulator called "Robot Simulator" was in development to facilitate the transition of robotic process in modular construction. In this research, Webots was the selected simulator for the construction operations due to its many features as mentioned in Section 5.1 (*Software implementation*).

Note that robotic automation in construction is an open-ended problem. As such, it is not bound to a unique solution, but rather multiple solutions could exist, in which each has its own implications. For instance, in an offsite construction facility, the selection of a robotic system depends on the constraints and factors such as the size of the manufacturing space and cost of the robotic system components, respectively. Therefore, different configurations of the robotic system components could have been selected in this paper instead of the ones presented.

The impact of the proposed methodology could be significant to facilitate the evaluation of construction robotics and VDC in the AEC domain because it can be used to measure the productivity output of a robotic system and to analyze the behavior of a robotic system in a specific construction process. Also, the control system (algorithms and integration with BIM) from the simulated robots can be directly transferred to actual physical robots to facilitate their implementations, where such applications in the construction domain have been successfully demonstrated in [28,38,58,59].

5.10.3 *Nailing target locations validation*

A test was performed to determine the performance of the nailing target locations as defined in Subsection 4.4.2. The values of the nailing target locations determined using Eq. (1), Eq. (2), and Eq. (3), were verified by manually computing the nailing location values for each element using information from the simulation. The information used for the manually computed values include the position of the centroid and the dimensions of the elements relative to the coordinate system of the robot after the framing process took place. The comparison results for the test models 1 and 2 are presented in Table 6 and Table 7, respectively, where 'Location' refers to the connections points (Fig. 24). For the result of test model 3, the results are shown in Table 8 and Table 9 that correspond to the locations of the frames in Wall L and R, and Wall F and B, respectively, as shown in Fig. 25. The N_x, N_y, and N_z are the nailing target locations determined using the proposed

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method; X, Y, and Z are the nailing locations that were manually computed; and x_{diff}, y_{diff}, and z_{diff} are the relative change (in percentage) of the two approaches. In Table 8, the y_{diff} for the location 4 and 11 was expressed in absolute difference instead of the relative change in percentage because the value of Ny was zero, yielding a relative change of 100%, which could be misleading.

Table 6. Result of the validation for the nailing target location of test model 1.

Location	Proposed Method (m)				Manually Computed Values (m)				Relative Change (%)			
	N_x	N_y	N_z		X	Y	Z		x_{diff}	y_{diff}	z_{diff}	
1	0.881	-0.476	0.029	0.059	0.879	-0.474	0.029	0.059	0.17%	0.42%	0.64%	0.94%
2	0.881	0.476	0.029	0.059	0.879	0.474	0.029	0.059	0.17%	0.40%	0.64%	0.94%
3	1.872	0.476	0.029	0.059	1.870	0.474	0.029	0.059	0.08%	0.40%	0.64%	0.94%
4	1.872	-0.476	0.029	0.059	1.870	-0.474	0.029	0.059	0.08%	0.42%	0.64%	0.94%

Table 7. Result of the validation for the nailing target location of test model 2.

Location	Proposed Method (m)				Manually Computed Values (m)				Relative Change (%)			
	N_x	N_y	N_z		X	Y	Z		x_{diff}	y_{diff}	z_{diff}	
1	0.731	-0.895	0.047	0.093	0.735	-0.896	0.046	0.092	-0.56%	-0.05%	2.22%	0.74%
2	0.731	0.895	0.047	0.093	0.735	0.896	0.046	0.092	-0.56%	-0.08%	2.22%	0.74%
3	2.255	0.895	0.047	0.093	2.259	0.896	0.046	0.092	-0.19%	-0.08%	2.22%	0.74%
4	2.255	-0.895	0.047	0.093	2.259	-0.896	0.046	0.092	-0.19%	-0.05%	2.22%	0.74%

Table 8. Result of the validation for the nailing target location of test model 3 Wall L and R.

Location	Proposed Method (m)				Manually Computed Values (m)				Relative Change (%)			
	N_x	N_y	N_z		X	Y	Z		x_{diff}	y_{diff}	z_{diff}	
1	0.531	-1.111	0.029	0.059	0.530	-1.110	0.029	0.058	0.26%	0.11%	2.29%	1.44%
2	0.531	-0.811	0.029	0.059	0.530	-0.813	0.029	0.058	0.26%	-0.24%	2.46%	1.53%
3	0.531	-0.405	0.029	0.059	0.530	-0.407	0.029	0.058	0.26%	-0.52%	2.46%	1.53%
4	0.531	0.002	0.029	0.059	0.530	0.000	0.029	0.058	0.26%	-0.002*	2.46%	1.53%
5	0.531	0.408	0.029	0.059	0.530	0.404	0.029	0.058	0.26%	0.95%	2.28%	1.44%
6	0.531	0.814	0.029	0.059	0.530	0.810	0.029	0.058	0.26%	0.51%	2.58%	1.59%
7	0.531	1.111	0.029	0.059	0.530	1.110	0.029	0.058	0.26%	0.09%	2.58%	1.59%
8	2.998	1.111	0.029	0.059	3.006	1.212	0.029	0.058	-0.28%	-8.30%	2.58%	1.59%
9	2.998	0.814	0.029	0.059	2.987	0.813	0.029	0.058	0.36%	0.22%	2.58%	1.59%
10	2.998	0.408	0.029	0.059	2.987	0.406	0.029	0.058	0.36%	0.47%	2.58%	1.59%
11	2.998	0.002	0.029	0.059	2.987	0.000	0.029	0.058	0.36%	-0.001*	2.58%	1.59%

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Location	Proposed Method (m)				Manually Computed Values (m)				Relative Change (%)			
	N_x	N_y	N_z		X	Y	Z		x_{diff}	y_{diff}	z_{diff}	
12	2.998	-0.405	0.029	0.059	2.987	-0.406	0.029	0.058	0.36%	-0.28%	2.58%	1.59%
13	2.998	-0.811	0.029	0.059	2.987	-0.813	0.029	0.058	0.36%	-0.16%	2.58%	1.59%
14	2.998	-1.111	0.029	0.059	2.987	-1.212	0.029	0.058	0.36%	-8.31%	2.58%	1.59%

*Absolute difference (m)

Table 9. Result of the validation for the nailing target location of test model 3 Wall F and B.

Location	Proposed Method (m)				Manually Computed Values (m)				Relative Change (%)			
	N_x	N_y	N_z		X	Y	Z		x_{diff}	y_{diff}	z_{diff}	
1	0.531	-3.430	0.029	0.059	0.530	-3.459	0.029	0.058	0.26%	-0.83%	2.58%	1.59%
2	0.531	-3.041	0.029	0.059	0.530	-3.053	0.029	0.058	0.26%	-0.37%	2.58%	1.59%
3	0.531	-2.635	0.029	0.059	0.530	-2.646	0.029	0.058	0.26%	-0.43%	2.58%	1.59%
4	0.531	-2.229	0.029	0.059	0.530	-2.240	0.029	0.058	0.26%	-0.51%	2.58%	1.59%
5	0.531	-1.822	0.029	0.059	0.530	-1.834	0.029	0.058	0.26%	-0.62%	2.58%	1.59%
6	0.531	-1.416	0.029	0.059	0.530	-1.427	0.029	0.058	0.26%	-0.79%	2.46%	1.53%
7	0.531	-1.010	0.029	0.059	0.530	-1.021	0.029	0.057	0.26%	-1.13%	2.58%	4.54%
8	0.531	-0.603	0.029	0.059	0.530	-0.615	0.029	0.058	0.26%	-1.89%	2.46%	1.53%
9	0.531	-0.197	0.029	0.059	0.530	-0.209	0.029	0.058	0.26%	-5.66%	2.46%	1.53%
10	0.531	0.210	0.029	0.059	0.530	0.196	0.029	0.058	0.26%	6.67%	2.46%	1.53%
11	0.531	0.616	0.029	0.059	0.530	0.602	0.029	0.058	0.26%	2.25%	2.46%	1.53%
12	0.531	1.022	0.029	0.059	0.530	1.009	0.029	0.058	0.26%	1.36%	2.58%	1.59%
13	0.531	1.429	0.029	0.059	0.530	1.415	0.029	0.058	0.26%	0.98%	2.58%	1.59%
14	0.531	1.860	0.029	0.059	0.530	1.821	0.029	0.058	0.26%	2.15%	2.58%	1.59%
15	0.531	2.241	0.029	0.059	0.530	2.228	0.029	0.058	0.26%	0.62%	2.58%	1.59%
16	0.531	2.648	0.029	0.059	0.530	2.634	0.029	0.058	0.26%	0.52%	2.58%	1.59%
17	0.531	3.056	0.029	0.059	0.530	3.040	0.029	0.058	0.26%	0.50%	2.58%	1.59%
18	0.531	3.430	0.029	0.059	0.530	3.447	0.029	0.058	0.26%	-0.48%	2.58%	1.59%
19	2.998	-3.430	0.029	0.059	3.006	-3.459	0.029	0.058	-0.28%	-0.83%	2.58%	1.59%
20	2.998	-3.041	0.029	0.059	3.006	-3.053	0.029	0.058	-0.28%	-0.37%	2.58%	1.59%
21	2.998	-2.635	0.029	0.059	3.006	-2.646	0.029	0.058	-0.28%	-0.43%	2.58%	1.59%
22	2.998	-2.229	0.029	0.059	3.006	-2.240	0.029	0.058	-0.28%	-0.51%	2.58%	1.59%
23	2.998	-1.822	0.029	0.059	3.006	-1.834	0.029	0.058	-0.28%	-0.62%	2.58%	1.59%

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Location	Proposed Method (m)				Manually Computed Values (m)				Relative Change (%)			
	N_x	N_y	N_z		X	Y	Z		x_{diff}	y_{diff}	z_{diff}	
24	2.998	-1.416	0.029	0.059	3.006	-1.427	0.029	0.058	-0.28%	-0.79%	2.58%	1.59%
25	2.998	-1.010	0.029	0.059	3.006	-1.021	0.029	0.058	-0.28%	-1.13%	2.58%	1.59%
26	2.998	-0.603	0.029	0.059	3.006	-0.615	0.029	0.058	-0.28%	-1.89%	2.58%	1.59%
27	2.998	-0.197	0.029	0.059	3.006	-0.196	0.029	0.058	-0.28%	0.19%	2.58%	1.59%
28	2.998	0.210	0.029	0.059	3.006	0.209	0.029	0.058	-0.28%	0.44%	2.58%	1.59%
29	2.998	0.616	0.029	0.059	3.006	0.602	0.029	0.058	-0.28%	2.25%	2.58%	1.59%
30	2.998	1.022	0.029	0.059	3.006	1.009	0.029	0.058	-0.28%	1.36%	2.58%	1.59%
31	2.998	1.429	0.029	0.059	3.006	1.415	0.029	0.058	-0.28%	0.98%	2.58%	1.59%
32	2.998	1.860	0.029	0.059	3.006	1.821	0.029	0.058	-0.28%	2.15%	2.58%	1.59%
33	2.998	2.241	0.029	0.059	3.006	2.228	0.029	0.058	-0.28%	0.62%	2.58%	1.59%
34	2.998	2.648	0.029	0.059	3.006	2.634	0.029	0.058	-0.28%	0.52%	2.58%	1.59%
35	2.998	3.056	0.029	0.059	3.006	3.040	0.029	0.058	-0.28%	0.50%	2.58%	1.59%
36	2.998	3.430	0.029	0.059	3.006	3.447	0.029	0.058	-0.28%	-0.48%	2.58%	1.59%

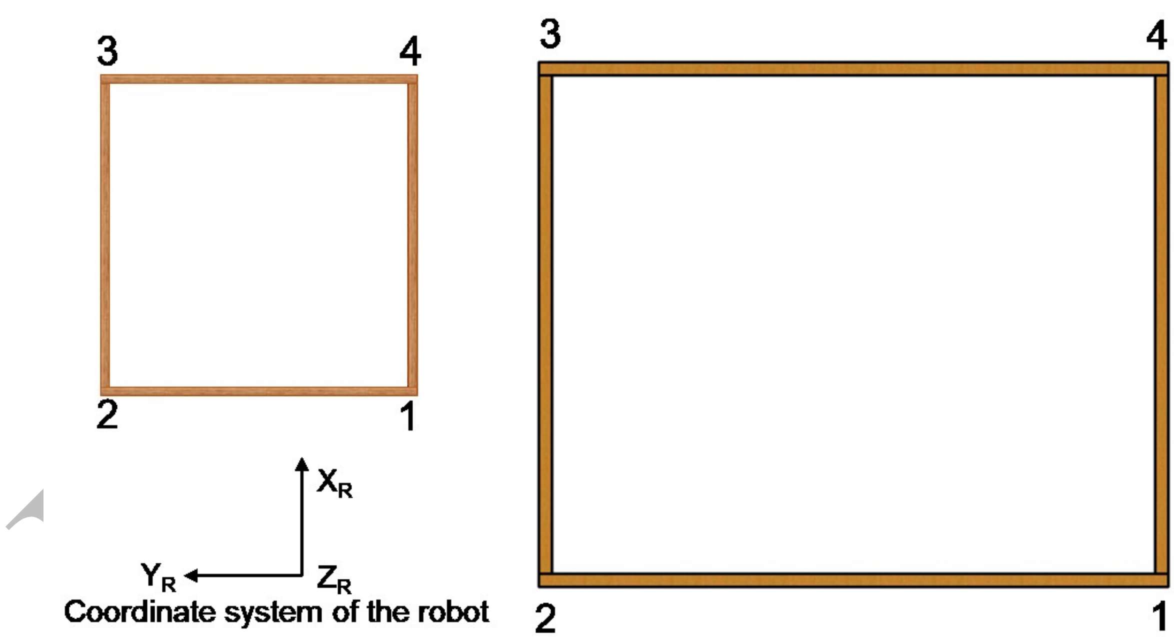

Fig. 24. Locations of the connection points for the nailing operations for test model 1 and 2.

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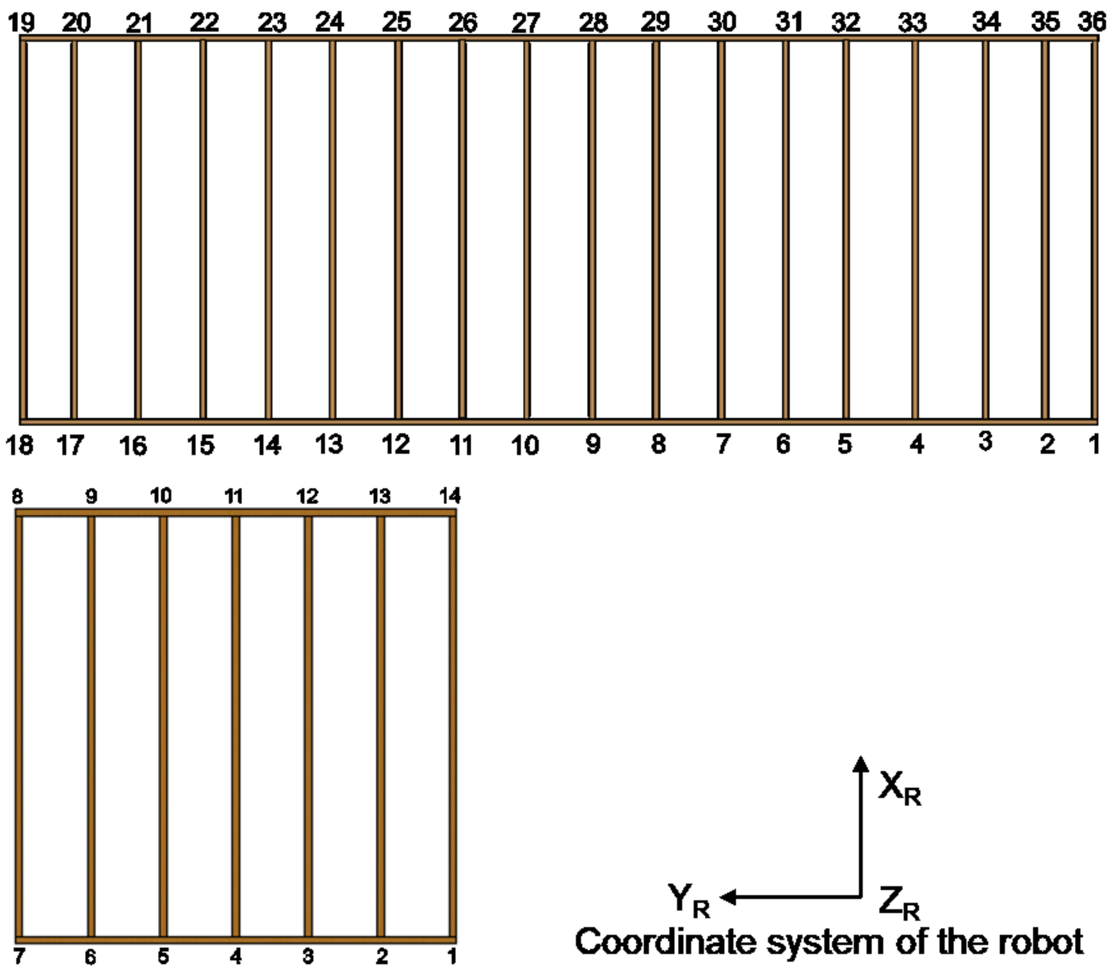

Fig. 25. Locations of the connection points for the nailing operations for test model 3.

5.10.4 *Collision detection*

Similar to clash detection in the building design development (e.g., MEP and structural systems), the simulation of robotic system can be used to detect collisions between different components within the system or any nearby objects, which takes both the spatial and temporal dimensions into consideration. Such collision can interfere with the operations of the robotic system components. During the framing operations, a collision between the robot and the tool table was identified as shown in Fig. 26. The height of the legs of the tool table was adjusted to avoid collisions in subsequent simulations of the assembly process (Fig. 27).

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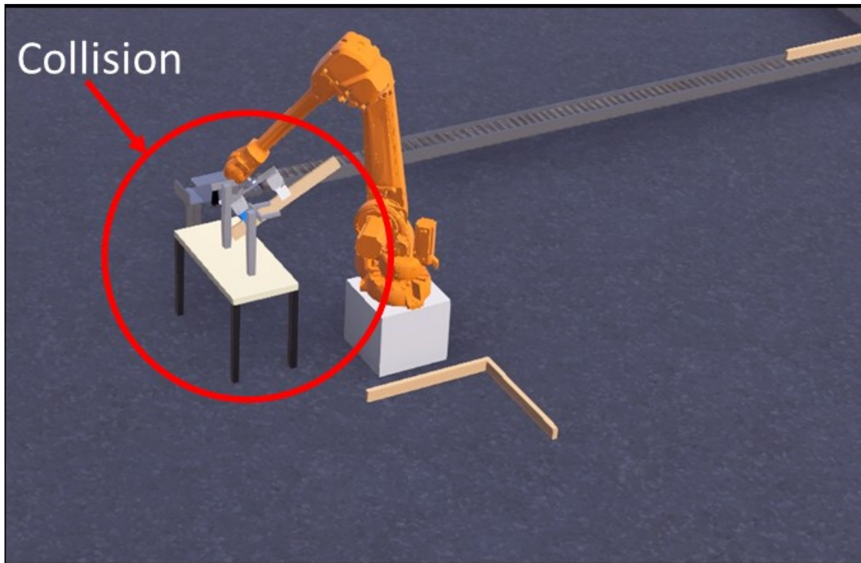

Fig. 26. Collision of the robot and the tool table.

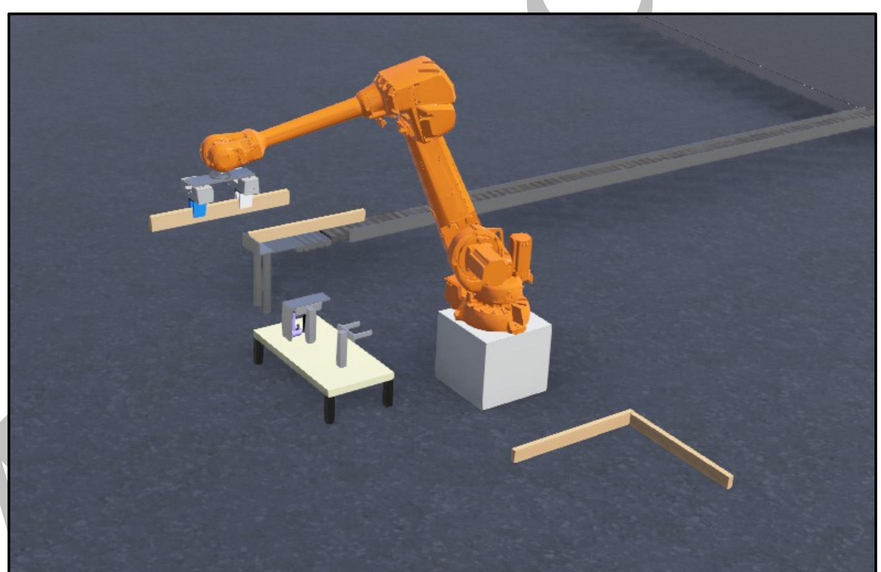

Fig. 27. Adjusted tool table for collision-free robotic operations.

6 Comparison to manual extraction process

The proposed methodology was compared to manual operations in time efficiency. The process of manually extracting the needed information to simulate the assembly process was performed according to the six steps specified in Table 10. The manual process consists of the extraction of the relevant information from the BIM design models. The time performance of the proposed methodology refers to the time taken to generate the simulation file (i.e., Webots world) starting from the BIM authoring tool as described in Section 5.8 (*Simulation generation and execution*).

Table 10. List of steps for the manual extraction process.

#	Tasks
1	Identify all relevant elements (i.e., lumbers) of the frames and their attributes from the BIM design model.
2	Extract the dimensions, main axis, names, and placement locations for all elements.
3	Compute the position of the center of gravity of the elements.
4	Create the elements (Webots objects) in the simulation environment based on the attributes extracted.
5	Position the elements on the conveyor 1 in the simulation environment.
6	Input the data in the controller of the robot for the framing and nailing operations.

6.1 Time performance testing

To compare the proposed methodology against the manual process, the time consumption of both approaches was recorded. The time for the manual process was recorded and presented in Table 11. The time of the manual process was plotted against the number (e.g., studs) of elements present in a frame model (Fig. 28). The trend also shows an increase in the total time consumption when the complexity of the model being tested increases. Specifically, the time for the developed method were 1.68, 2.03, and 4.45 minutes for test models 1, 2, and 3, respectively.

The time comparison results of both approaches on the three test cases are shown in Fig. 29. The results in Fig. 29 indicate that the proposed approach is on average 39 times faster than the manual approach for the three tested cases, 17, 18, and 82 times for test models 1, 2, and 3, respectively. As shown for test model 3 in Fig. 29, the larger and more complex a BIM design model is, the greater the time saving becomes. Another advantage of the proposed approach is that it can generate simulation files automatically, which therefore reduces the errors when there are changes in the building design.

Table 11. Time performance of the manual process.

Task	Time in minutes					
	Test Case 1	Test Case 2	Test Case 3F	Test Case 3B	Test Case 3L	Test Case 3R
Extract dimensions	3.3	4.7	20.7	14.9	10.3	8.3
Extract main axis	1.6	3.1	11.8	7.4	10.7	6.3
Extract names	1.0	0.9	8.3	5.6	4.1	4.6
Extract placement locations	14.8	15.7	53.5	38.1	31.1	31.2
Creation of the elements	4.8	7.7	16.1	7.9	11.1	10.3
Input information	3.6	4.6	20.6	13.1	8.0	9.7
Total	29.1	36.7	131.0	87.0	75.4	70.4

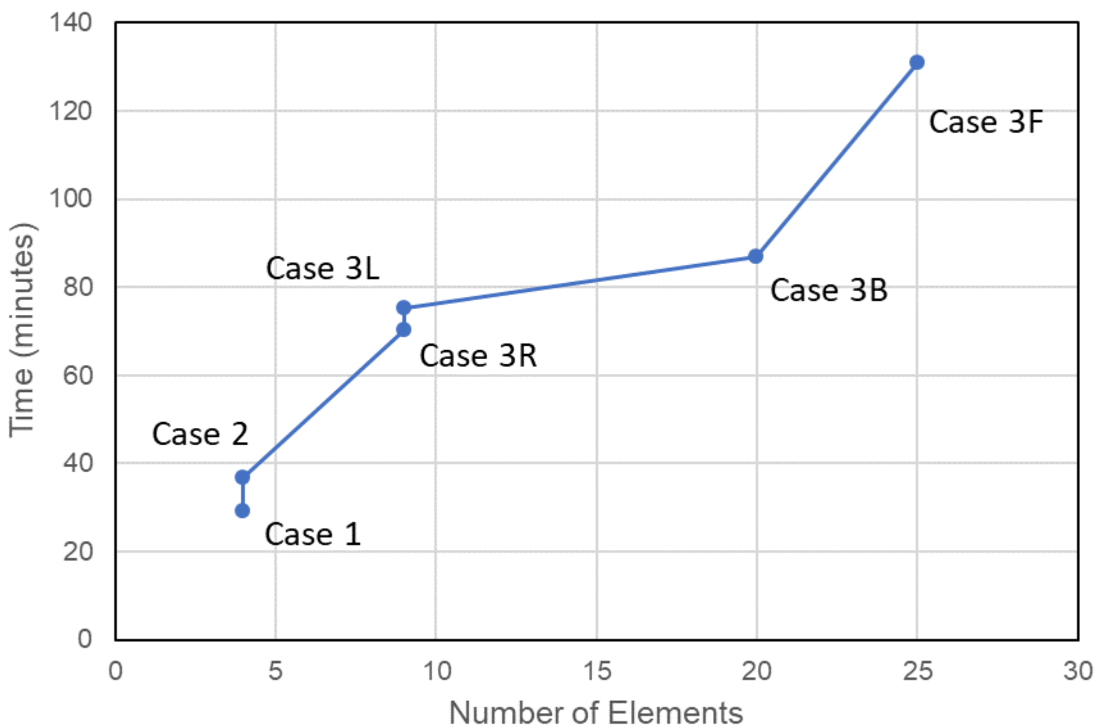

Fig. 28. Plot of the time used in the manual approach compared with the number of elements in a frame for the test models.

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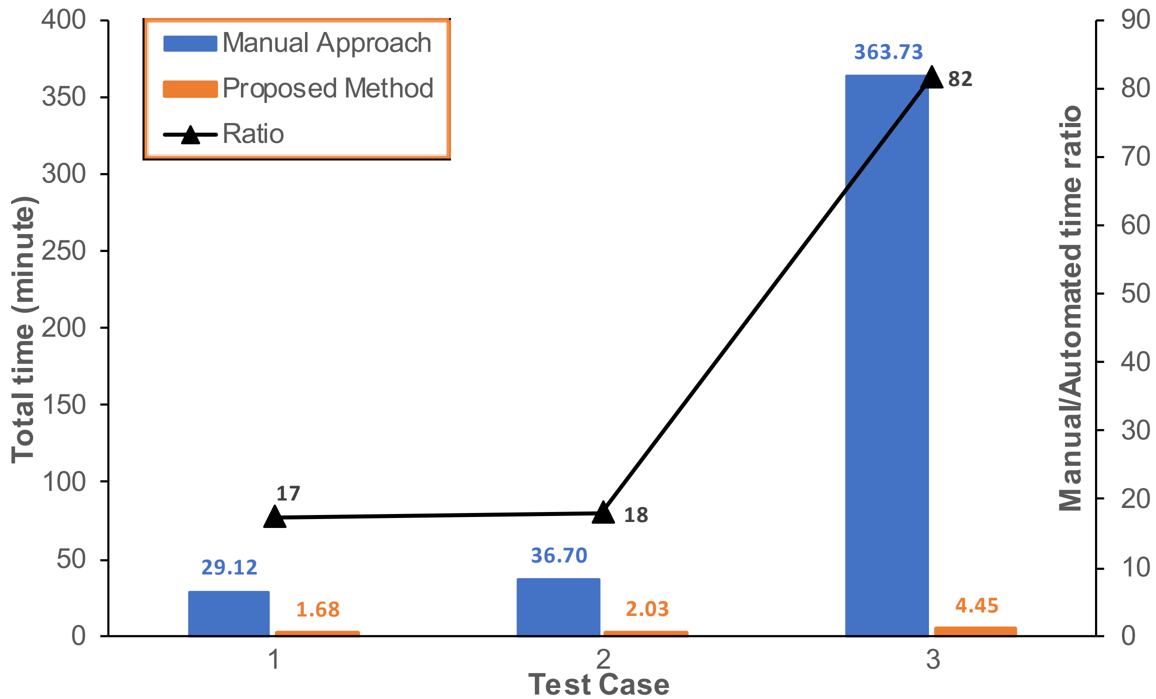

Fig. 29. Time comparison of the manual approach and the proposed methodology.

7 Contributions to the body of knowledge

The proposed methodology contributes to the body of knowledge in four main ways. First, the proposed methodology provides an integration framework to bridge the gap between building design and construction phases through a BIM-robotics workflow for a greater collaboration and coordination compared to current practice (i.e., working in siloes) in offsite construction. Second, the proposed methodology includes practical knowledge from the robotic and construction domains and implementation details of robotic systems to support a wider adoption of construction robotics in the AEC domain. Third, the proposed methodology provides a tool to generate required information automatically from BIM as input for robotic system operational analysis to support wood frame assembly automation in offsite construction. Moreover, the simulation-based approach using robotic simulation allows the analysis of industrial arm (i.e., manipulator-type robots) in the framing and fastening operations during the preconstruction phase to facilitate the planning and analysis of automation strategies. In addition, it serves as a blueprint for researchers and practitioners to adopt and reuse for analyzing other types of robotic systems and/or construction workflows. Fourth, the use of IFC-based BIM in the integration with an open-source

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robotic simulator (e.g., Webots), promotes and contributes to solving the interoperability of information exchange in the AEC industry.

8 Conclusion, limitations, and future work

In this paper, the authors presented a methodology to automatically generate simulations of robotic automation for the assembly process of wood framing construction using BIM data as input. The framework of the methodology integrates BIM and robotics to simulate the assembly process in the context of offsite wood construction. The methodology was validated in three BIM test cases with different configurations of robotic systems, including two industrial robots (ABB IRB 4600 and KUKA KR 150-2), in the framing and fastening operations. Although both robots are industrial arms, they have different parameters (e.g., joint limits, link lengths, base diameter) to analyze in the simulations. For example, the diameter of the KUKA KR 150-2's base was larger than that of the ABB IRB 4600, which required a larger offset distance in the x-axis. These differences were appropriately considered through the variation of the parameters, and successfully simulated. In addition, the proposed approach suggests that assembly operations of offsite frame construction can be simulated and analyzed for using different robotic systems.

The presented methodology addresses the adoption challenges of construction robotics in three main ways. First, knowledge and concepts from the robotics and construction domains were applied together in the development of the simulation-based approach and algorithms for the assembly operations. Second, data from BIM design model are used as input in the simulation-based methodology, harnessing the synergy and value of BIM and robotic simulation in the design and construction phases. Third, stakeholders can have a better conceptualization of the benefits and limitations of automation in the assembly of wood components in this simulation environment. The proposed simulation-based approach serves as a tool for researchers and practitioners to develop simulations for construction applications using different robotic systems.

Some limitations of this research are acknowledged as follows. Despite that the proposed methodology is applicable to any frame configuration by adjusting the robotic system configurations and behaviors, the test cases focused on rectangular frames mainly. Moreover, this study only tested Webots in a Windows system, which might be limited in terms of path planning and integration with other platforms' (e.g., ROS and Rviz) capabilities. Furthermore, this paper tested the proposed method in a simulation environment, which despite the realism and reliability of such simulations demonstrated in literature, it is still an approximation of the reality. The transfer of results from the simulation to physical robots may require further tuning on the transfer mechanism (e.g., remote control, cross-compilation) [60].

In future work, the authors plan to extend the methodology to other types of geometric shapes and interior configurations (e.g., openings) of wood frames. In addition to wall frames, the testing of other types of building components (e.g., floors) and configurations of robotic system components (e.g., robots, fixtures, feeding devices) will also be considered. Although the proposed methodology was implemented in Webots due to its numerous features as described in Section 5.1, a comparison with the proposed methodology’s implementation in other robotic simulators such as Gazebo and V-REP, would be a meaningful topic to explore. In addition, the authors plan to develop a unified system that integrate the current simulation approach with a logic-based approach to facilitate the analysis of BIM and robotic system for construction, in a more efficient and comprehensive way.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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