Introducing Agent-Based Modeling Methods for Designing Architectural Structures with Multiple Mobile Robotic Systems

Samuel Leder[1,2](✉) and Achim Menges[1,2]

[1] Institute for Computational Design and Construction, University of Stuttgart, Stuttgart, Germany
samuel.leder@icd.uni-stuttgart.de
[2] Cluster of Excellence IntCDC: Integrative Computational Design and Construction for Architecture, University of Stuttgart and Max Planck Institute for Intelligent Systems, Stuttgart, Germany

Abstract. As technology for multiple robotic systems (MRS) is becoming more and more robust, such systems are beginning to be introduced for various applications, such as within the Architecture, Engineering, and Construction (AEC) industry. Introducing MRS to construction requires a radical change to the current practices in the AEC industry as there currently exists little to no precedents for small, agile machines working on construction sites. Beyond the physical hardware, sensing communication and coordination strategies necessary to deploy MRS, the methods for designing structures assembled by MRS must be considered as they can influence what is possible with the novelties inherent to construction with such systems. In order to approach the question of design, this paper aims to break away from current standards of top-down design methods by introducing two agent-based modeling and simulation (ABMS) approaches for designing structures to be assembled with MRS that consider geometric and fabrication constraints in the process of design. Each approach is outlined at a conceptual level, further explained using an existing MRS at the operational level, and then analyzed based on its general workflow, interactivity, and adaptability. By providing the various approaches, we aim to understand how, not only the MRS themselves but, the method for designing structures with such systems can help to achieve the goal of inexpensive, adaptive, and sustainable construction promised by the application of MRS in the AEC industry.

Keywords: Multiple robotic systems (MRS) · Collective robotic construction (CRC) · Agent-based model and simulation (ABMS) · Robotic fabrication · Generative design

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1 Introduction

From wheeled robots vacuuming our living spaces to drones delivering packages between retailers and consumers, mobile robots are currently revolutionizing our everyday lives including applications in both the public and private sectors. Current research on multiple robotic systems (MRS) is showcasing their potential application within the Architecture, Engineering, and Construction (AEC) industry [1]. This has included the co-design of mobile robots together with architectural systems that allow for the robots to build structures much larger than the machine themselves (Fig. 1). In contrast to existing practices in construction automation which generally deploy fixed position industrial robots, MRS are composed of teams of small, inexpensive mobile robots, which navigate the construction site. These teams of mobile robots can further inhabit the structure which they assemble, giving them the ability to rearrange, maintain and disassemble a building on the fly according to site, user, or environmental conditions. Therefore, the application of MRS in the life cycle of a building requires a transformation to current practices in the fields of AEC.

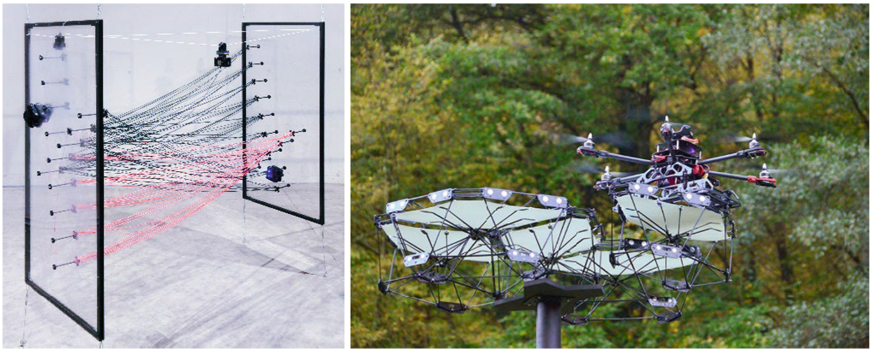

Fig. 1. MRS developed for construction processes. Heterogeneous team of bespoke robots for filament structures [2] (Left) and unmanned aerial vehicles (UAV) for the assembly and rearrangement of canopy structures [3] (Right).

The process of designing an architectural structure to be assembled or even further rearranged by a MRS is one of such practices that must be completely reenvisioned from existing architectural practice. The process of designing such a structure is a complex question which must not only address the novelties of the MRS and its highly unrestricted workspace but furthermore address issues of the material system, design intent or changes in the construction environment. However, the most common method for designing structures to be built with MRS takes a top-down approach by defining and then refining blueprints without specific relationship to the MRS. This highly traditional approach, which limits consideration of many of the potential benefits of deploying a MRS including the potential of using the intelligence, movement, or collaboration of the physical robots to inform or influence the design process, is mismatched to the technologically advanced construction automation systems in which it deals.

Recent research, on the other hand, is showcasing how agent-based modeling and simulation (ABMS) can integrate generation and materialization processes into a single workflow in order to break away from the rationalization based process of top-down design [4]. The characteristics, properties, and constraints of a physical building system as well as any of the accompanying fabrication or assembly system can be encoded in the ABM to allow for the complexity of the systems to be considered. ABMS is therefore one promising method to explore structures which can be built by MRS as it would allow for a bottom-up design process, in which the active drivers of design inform the exploration of emergent complexities.

The approach to how the agent-based model (ABM) is defined, however, can have direct implications on the overall design process, which can result in processes not dissimilar to top-down design processes where blueprints are algorithmically post-processed to derive assembly sequences for the robots to build the structure. To clarify the range of design processes for structures to be assembled by MRS and provide a framework for further discussion, this paper introduces and discusses two ABMS approaches. First, the conceptual model behind both approaches is explained and then sample operational models for each approach are elaborated on using an existing MRS.

2 Background: Agent-Based Models (ABMs) in Architecture

ABMS is a computational approach that aims at understanding complex systems through simulating autonomous agents and their interactions within an environment. Due to the ability of the approach to integrate varying constraints across the disciplines of AEC, which potentially even further change over time, ABMS is currently being utilized in architectural research as a design exploration modeling method [5]. This has largely led to the implementation of digital simulations in which the agents represent part of the physical building system and behaviors of the agents are based on the physical properties or constraints, which affect them. Specifically, ABMS for the exploration of fabrication-informed Zollinger lamella structures [6] or shells [7] and the generation of facade designs based on environment, structural and user preference information [8] have been systematically tested and evaluated for architectural design.

More recently with the growing robustness of MRS, ABMs have been created for architectural design exploration in which the agents represent the physical robots themselves. Therefore, the models are not focused on the negotiation of parts of a building, but rather on the movement of the robots in their environments and how they relate to design generation. Although some research was made on path correction for physical robots [9], ABMs that relate to physical hardware are generally used to iterate design options which are then afterwards sent to the physical robot [10, 11]. Furthermore, existing ABMs for MRS are generally derived for specific material-robot systems, therefore not addressing the overall implications of ABMS as applied to the designing of architectural structures with MRS.

3 ABM Approaches

The focal point of this paper is the definition and analysis of two different ABMS approaches aimed at designing structures with MRS. In order to define the two approaches, we used the instructions for defining a simulation as presented by Heath et al. [12]. First, we will outline a conceptual model for each and then further translate the conceptual model to an operational model using an existing MRS co-designed specifically for construction. To describe the conceptual model, we answer the first four questions for the initial development of an ABM from Macal and North [13]. The questions prompt the definition of (1.) the purpose, (2.) agent, (3.) environment and (4.) behaviors of the model.

The answer to the first question, the purpose of the model, is the same for both approaches: the models should derive architectural designs that can be assembled by a MRS. However, the further questions diverge between the two approaches and will be discussed further in following subsections (Fig. 2).

	Approach 1	*Approach 2*
1. Purpose	Architectural design exploration	
2. Agent	Building Material	Mobile Robot
3. Environment	Continuous Euclidean Environment	Physical Environment
4. Behaviors	Geometrical Constraints Fabrication Constraints	Fabrication Constraints (Seek, Collaborate, Locomote, Assemble)

Fig. 2. Outline of conceptual models for ABM approaches based on questions developed in [13].

3.1 Approach 1: Agent Represents Building Material

Agent Representation. Approach 1 considers the agent to represent the building material that is assembled by the MRS into the design outcome of the model. In the case of continuous materials such a fibers, an approach for breaking down the material into discrete parts must be conceived. The attributes which define the agent are the geometric properties of the building material.

Environment. With this approach, the ABM negotiates the placement of the agents in digital space. The environment is thus a continuous digital Euclidean space.

Behaviors. Behaviors, which control the interaction of the agents, are based on the definition of the geometrical and fabrication constraints from the material system and the MRS that are being deployed. Geometric constraints inform the position of the agents relative to each other considering allowable orientations and connections between the material, while fabrication constraints maintain the ability of the design outcome to be assembled considering for example the reachability of each agent by a physical robot.

3.2 Approach 2: Agent Represents a Mobile Robot

Agent Representation. Approach 2 considers the physical mobile robots which are assembling the structure to be the agents. The attributes of the agents relate to the abilities of the robots themselves including such parameters as battery life and degrees of freedom (DOF).

Environment. In Approach 2, the environment transitions from an empty Euclidean space in which the agents interact to include information from the physical environment in which the robots are acting. This includes the status of the already assembled structure as well as other information known about the physical environment, for example the free volume in which the agents can build.

Behaviors. In this approach, the behaviors relate explicitly to how the robots would act in the real world. This can vary based on the instance of the mobile robot being used. Figure 2 expresses some examples of what these behaviors might be: seeking material to be assembled, locomoting in the environment, collaborating with another robot, or assembling material into the structure. In examples of MRS which work with continuous materials, the placement of material is a result of the movement of the robots, meaning that locomotion and assembly can be conflated into one behavior. Geometric constraints in this approach can be embedded in the assembly behavior of the agents, giving definition to how and where in the structure an agent can assemble something.

4 Case Study: Implementation of the ABM Approaches

To help clarify the two approaches and test their feasibility, two operational ABMs were created using the ICD ABM framework developed at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart (Groenewolt et al. 2018). The goal of the framework is to provide an open code base written in both C# and Python to aid researchers and professionals in the AEC industry in the creation of ABMs. The core of the framework provides the basic functionalities for developing ABMs, while further application-specific and expert libraries have been developed since the creation of the framework, to aid with more targeted problems. The creation of the ABMs for this research have continued to lay the foundation for a new application-specific library for MRS (Fig. 3).

The two operational models are based on an MRS developed as a part of the Cluster of Excellence Integrative Computational Design and Construction for Architecture at the University Stuttgart [14]. The MRS within the research is composed of single-axis robotic actuators which must leverage linear timber struts for any form of locomotion or general movement (Fig. 4). Planar timber structures are assembled through the arrangement and rearrangement of multiple robotic actuators together with the timber struts.

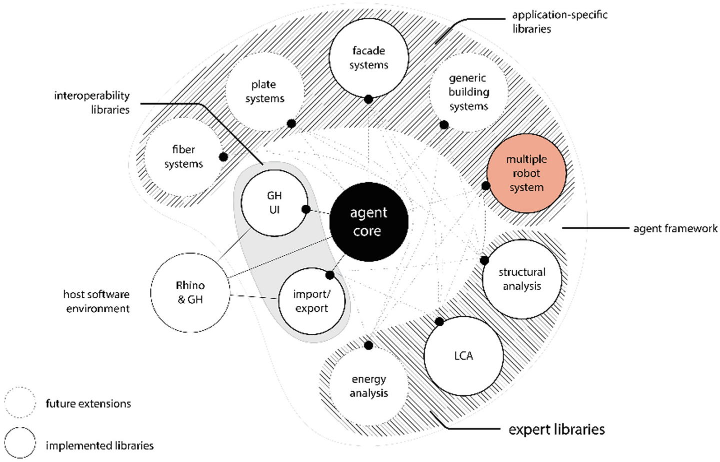

Fig. 3. Schematic overview of ICD ABM Framework, introducing MRS application specific library.

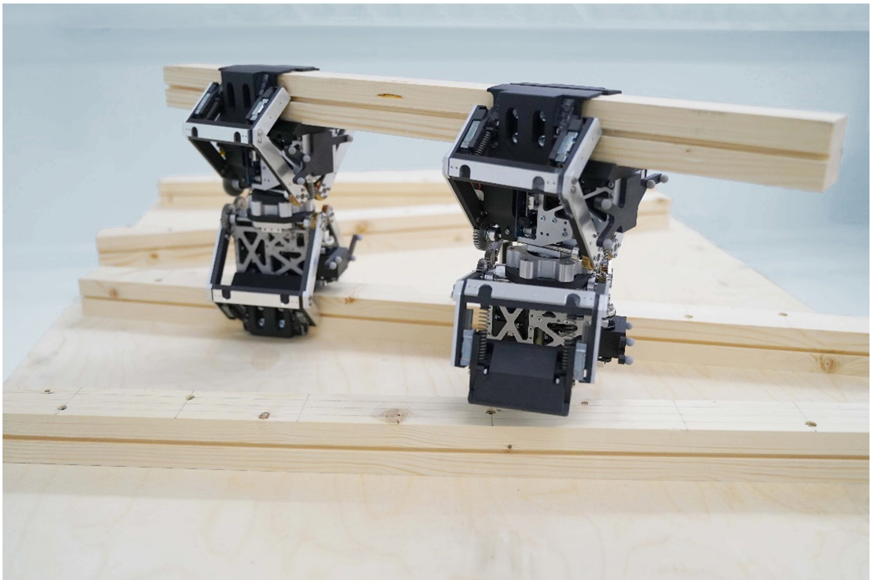

Fig. 4. Photograph of a MRS based on collaboration of single axis robotic actuator and timber struts for which the two operational models were developed.

For each approach as visualized in Fig. 5, the agent classes are derived from the CartesianAgent class of the ICD ABM Framework, inferring their ability to move in cartesian space at each iteration of the model. Figure 6 shows a Unified-Modeling-Language (UML) description of how the agent classes are derived from the framework. Using Approach 1, the agents represent timber struts, containing information on their cross section and length, and adjust their position with each iteration of the model to form planar assemblies (Fig. 7 Left). With Approach 2, the agent, rather than representing a single robotic actuator, represents a kinematic chain or combinations of timber struts and robotic actuators. As actuators cannot move on their own, defining the agent as a kinematic chain would give specification to the locomotion and manipulation abilities of each agent. At each iteration of the model, the agents change their position based on their current state with the aim of assembling a new strut into the environment (Fig. 7 Right).

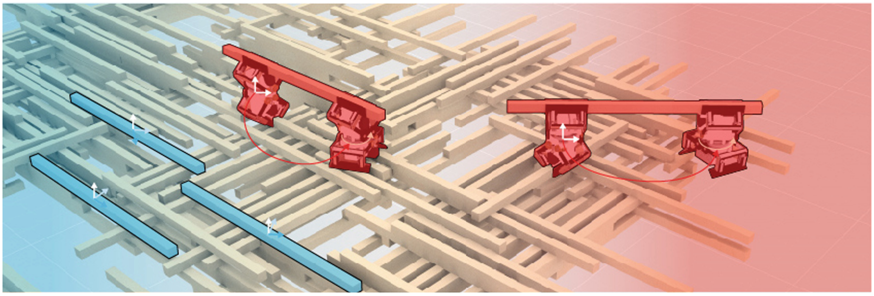

Fig. 5. Two ABM approaches graphically expressed using the MRS from [14]. Agent represents a timber struts, in blue, and Agent represents a kinematic chains composed of robotic actuators and timber struts, in red.

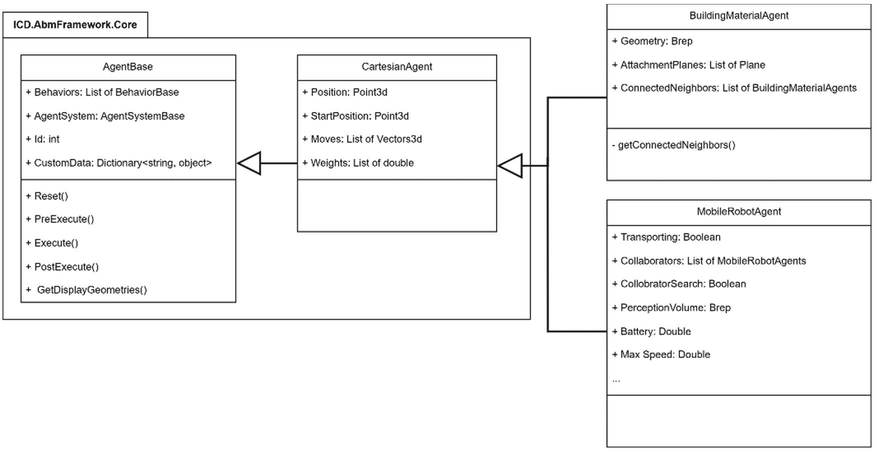

Fig. 6. UML description of agent classes derived for the two approaches

To give further definition to the behaviors of the agents in each approach, specifically how the agents move in Approach 1 and how the agents assemble material in Approach 2, mathematical fields were used to express design intent for the design outcome and stored in the environment of the agents (Fig. 7). The fields can give definition to the design outcome on a local or global level depending on its scale as related to the size of a single timber strut. Scalar fields are utilized to define the general density of timber struts and the priority of placing struts in specific areas, while vector fields define the general orientation of struts. The fields are an additional mechanism for a designer to interact with the ABMs, beyond adjusting the behaviors of the agents.

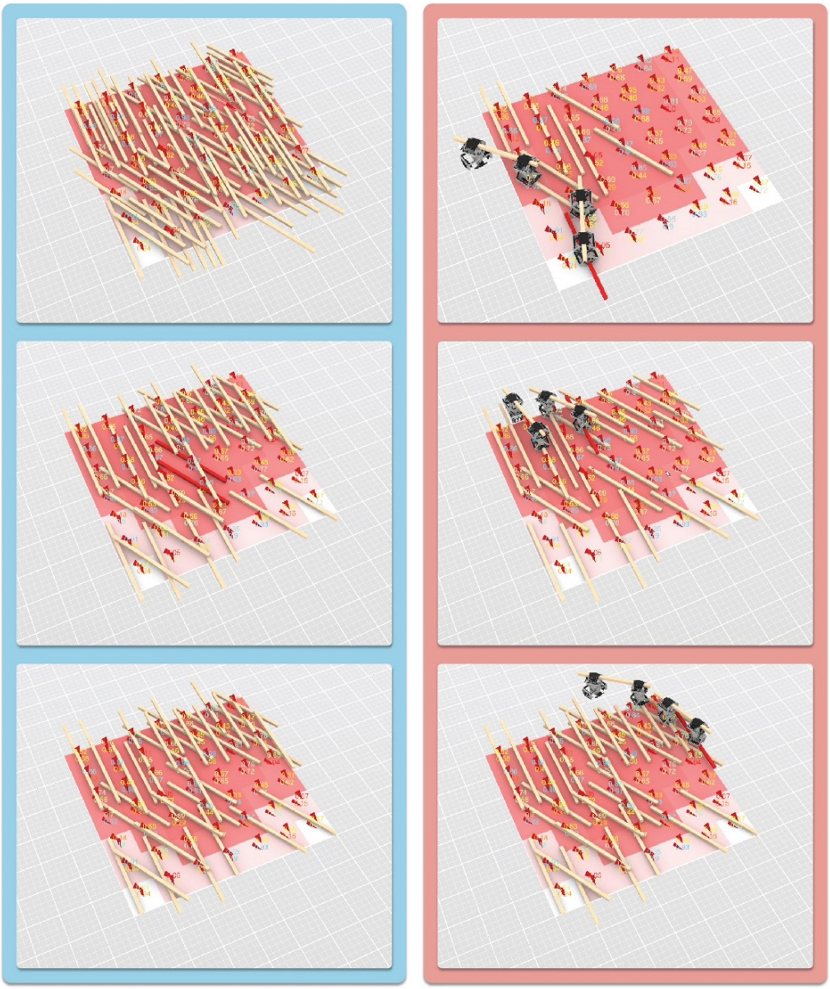

Fig. 7. Two ABM approaches shown as the model iterates with visualized design intent: Agent represents building material (Left) and agent represents a mobile robot (Right). The colors of the mesh faces represent a scalar value for density between struts, vectors represent orientation of struts and the numbers indicate placement priority.

5 Design Process Discussion

Although the two ABM approaches are viable options for designing structures using teams of mobile robots, each approach has a direct implication on how the (i) general workflow, (ii) interactivity, and (iii) adaptability of the overall design process functions. The observations in this section were made after conducting design explorations with each of the two operational ABMs described in the previous section (Fig. 8).

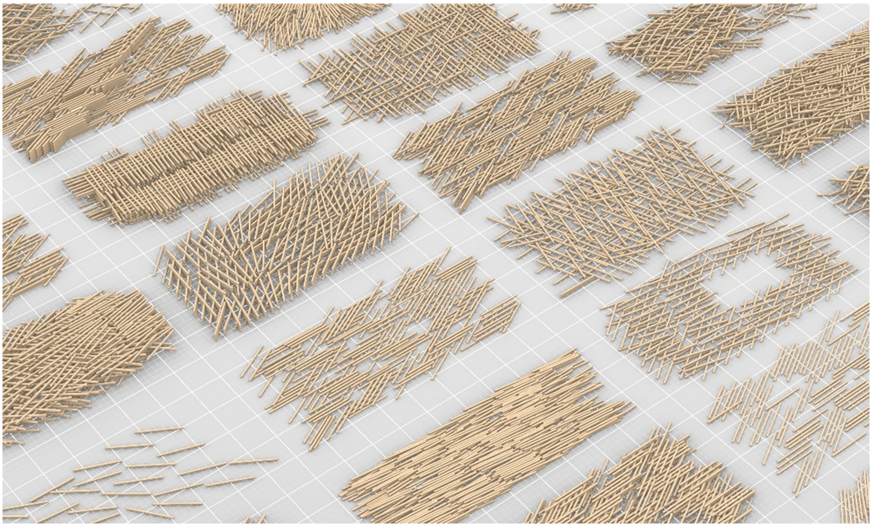

Fig. 8. Design explorations made using both approaches.

5.1 General Workflow

In the terms of general workflow, the use of each approach to ABM as it relates to the existing phases of building construction was analyzed (Fig. 9).

When implementing Approach 1 in which the agent represents building material, the ABM model converges on possible design outcomes. Each design outcome generated from the model must be then decomposed into an assembly sequence and then further into robotic motion plans, which can then be sent to the physical system for execution. As such, the design phase of the structure ends once the planning phase begins. Although the generation of the design outcome differs from the linear organization of current design practice in that it integrates geometric and fabrication constraints, the entire design process is similar in that the design, planning and construction phases of a building are explicitly delineated.

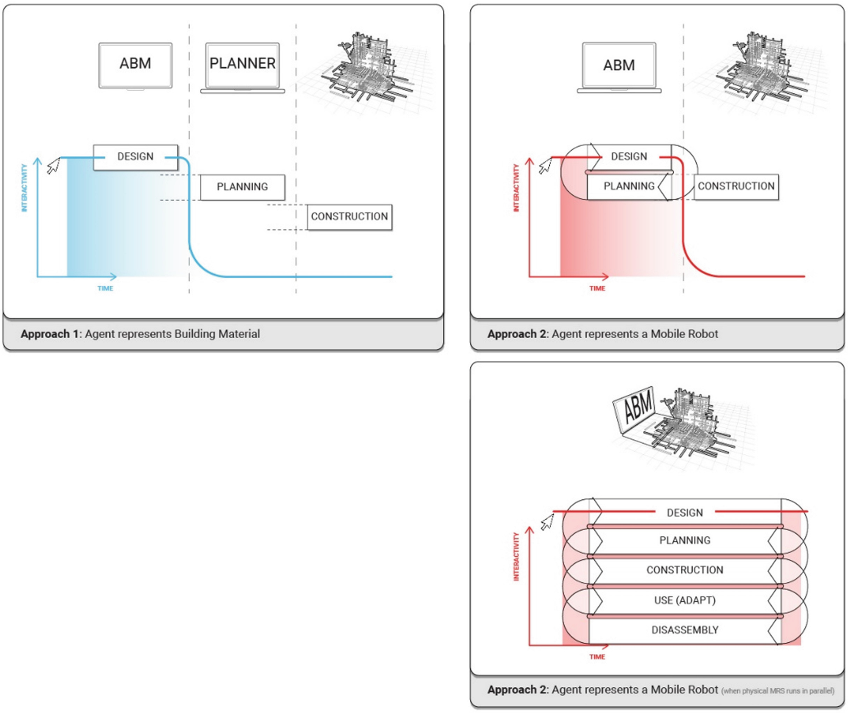

Fig. 9. Description of the phases of building construction and the level of interactivity associated with the two approaches. When the agent represents a mobile robot, further potential to incorporate construction, use, and disassembly phases into a single process is possible when the MRS runs at the same time as the ABM.

On the contrary, the motion of the robots is explicitly related to the design outcome in Approach 2. As the architectural design emerges, the planning required to achieve the design is determined in parallel. Syncing of the ABM to the physical MRS can allow for the construction phase of the structure to occur at the same time and even further accommodate any adjustments in the use or performance of the structure and its eventual disassembly.

5.2 Interactivity

In Approach 1, the position of the agents self-organize based on the defined behaviors in order to converge to a dynamic equilibrium. As such, the model begins with a visualization of the building material present in the system. As the model is running, the behaviors of the agents negotiate to reveal a final design outcome, which can be visualized in real time. A designer can therefore interact with the model with direct visual feedback on how the final design outcome would change. The various modes of interacting with the model developed for Approach 1 includes adding and removing agents, fixing or moving agents to specific positions, adjusting weights of behaviors on an individual agent or global level and adjusting the design intent fields (Fig. 10).

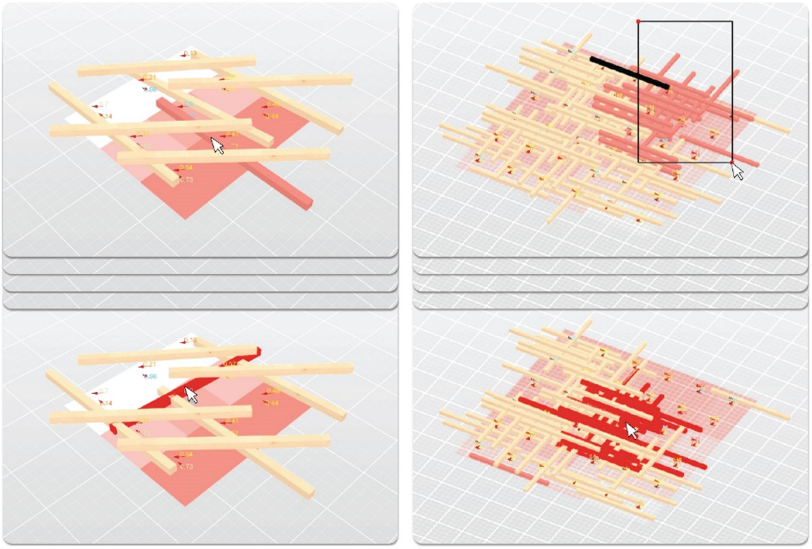

Fig. 10. Two modes of interactivity with ABM Approach 1: Single strut selection and rotation (Left) and multiple strut selection and movement to a fixed position (Right).

In Approach 2, the generation of final design outcomes is completed iteratively, considering the process of assembly. The agents assemble material to the structure as the model runs. In interacting with the model, direct feedback can be visualized on how the agents behave, however, not on how the final design outcome of the model will appear. As the agent represents the physical robots, the interaction of the designer becomes less about adjusting a final form but rather as a choreographer of the entire process, considering its general rhythm and flow. The various modes of interacting with the model developed for Approach 2 included adding, removing, or repositioning single struts, starting and stopping the design/assembly process, adjusting weights of behaviors on an individual agent and adjusting the design intent fields.

5.3 Adaptability

One opportunity provided by MRS is the potential of robots to rearrange the structure as they can inhabit it over its lifetime. The adaptability of the design outcome in the design process is such another evaluation criteria. In Approach 1, any changes to the design requires new plans to be generated, which can result in extended processes of exchange of information between the designing and planning sides of the overall design process. However in Approach 2, any desired adjustments to the design outcome as it is being assembled can be reflected in real time.

6 Further Discussion and Outlook

A majority of previous research on MRS for construction assumes that a designer can develop a blueprint for a proposed structure from scratch, as in the notable example from [15]. However, with more complex MRS, the ability of the robotic system or design space of the material system can be hard to decipher and therefore impossible to consider in the design process. Thus, this work outlines two ABM approaches, which are delineated by what the agent represents as either building material or a mobile robot. Each approach can be utilized to design structures to be assembled by a MRS in which the parameters of the robotic and construction system are integrated in the design process. In presenting each, this paper attempts to analyze the overall design process that would occur when implementing the respective approaches to ABM for design exploration with MRS. The major benefit of the approach in which the agent represents building material is the ability to visualize all the material giving a sense of the final design outcome, while the approach in which the agent represents the mobile robots capitalizes on the strengths of MRS, providing a highly interactive method for design in which the structure can be constantly adapted and the respective phases of a building into one.

Considering the goal of inexpensive, adaptive, and sustainable construction promised by the application of MRS in AEC, criteria of the automation system, construction system, and potentially even changing design intent should be considered in the design process. One promising design methodology to do this as outlined in this paper is ABMS. Further research will therefore be conducted to explore the potential of ABMS as it relates to the assembly of structures with MRS. Integration of global performance metrics beyond the more abstract mathematical fields into the ABMs will be considered for the generation of design outcomes with varied architectural and structural properties.

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