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Simulating the behavior of trade crews in construction using agents and building information modeling

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ABSTRACT

Simulation is particularly useful for testing different production control and information flow methods in construction, because field experiments suffer from difficulties with isolating cause and effect. Existing methods such as Discrete Event Simulation are limited in their ability to model the behavior of crews and of individuals who make decisions subject to their perceptions of uncertain conditions. Agent-Based Simulation may offer a better solution because agents can be applied with behavioral models. The aim of this work was to build an experimental tool capable of reflecting the emergent nature of production in construction. This required capturing trade crew behaviors through interviews and encapsulating the behavior in software agents. The system models trades' decision-making and situational awareness while using a Building Information Model to define the physical and the process environment for the simulation. The resulting simulation tool was validated by testing predictable scenarios, which resulted in similar patterns to those found in an actual construction site. It was then applied to explore the emergent outcomes of more complex scenarios.

1. Introduction

Research of production control systems in construction is limited by the capabilities of the available research methods. Among research methods used to date are work studies [1,2], action research [3–6] and simulation [7–9]. Both work-studies and action research are performed ‘in situ’ and thus can only study one control system in one project at a time. They cannot be used to compare or to evaluate the different outcomes that would be obtained if changes were made to the control paradigm or its parameters on a given project; projects cannot be repeated. Given the inherent variability and uncertainty of parameters that influence the outcomes of construction projects – such as material, labor, equipment and information flows [10, p.3, 11] – these methods also suffer from significant drawbacks in terms of isolating cause and effect. It is very difficult to differentiate the effects of any given experimental intervention from the influences of parameters that the researchers cannot control, such as design changes, material shortages, weather effects, unstable subcontractor resource allocations, etc. The Hawthorne effect [12] and the learning curve effect add to the problems of measuring the impact of interventions on site.

For these and other reasons (such as the limitations of research budgets), computer simulations have become the method of choice for comparative research of production systems in construction. Discrete Event Simulation (DES) applications, implemented in languages such as STROBOSCOPE and CYCLONE, have provided general and special purpose frameworks for simulating construction operations and construction management processes [13,14]. Examples abound: Tommelein et al. [9] used DES to illustrate the effect of variable production rates on productivity and cycle times in the ‘Parade of Trades’ simulation; Brodetskaia et al. [8] used DES to test the impact of production control policies on throughput (TH),on quantities of work in progress (WIP) and cycle time (CT) in high-rise apartment construction; and Bashford et al. [15] demonstrated the relationship between system loading and cycle times for the case of custom house building.

However, due to the nature of DES, these simulations did not model the decision-making behavior of the trade crews nor the effect of movement within a geometrically realistic working environment. Their use has been limited to predetermined events of specific construction processes and general purpose frameworks for developing simulations of construction operations [14,16]. Such research typically uses a “top-down” approach to modeling and understanding the impacts of production control on labor productivity. In a top-down approach, the sequence of events is governed by the availability of crew, materials, information and other preconditions at each time step as events are evaluated, but the subjective behavior of trade crews and their human leaders who function within a certain perception of the construction project reality, is not modeled and does not affect the outcomes [17].

Like many economic systems, building construction projects can be considered to be emergent production processes whose outcomes are the results of the actions of the individual economic agents who participate in them [18]. When conditions change unpredictably, such as when a crew arrives at a location and finds that some of the pre-

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requisite conditions for its work have not matured, agents must make go or no-go decisions at the workface [19]. Thus, given the shortcomings of DES in its ability to represent such systems, and motivated by the understanding that the production control system of construction works leads to dynamic complex behavior that affects work efficiency and productivity, the EPIC (Emergent Production in Construction) approach is proposed. EPIC uses Agent-Base Simulation (ABS) together with Building Information Models (BIM), offering a new method for researching production systems in construction. The goal of this research was to test the feasibility of the EPIC approach by building a suitable simulation capable of evaluating different production control methods in construction.

The following section reviews the literature and builds the argument in favor of using ABS and BIM for simulating construction processes. The subsequent sections present a pilot for using ABS for construction processes, a field study aiming to identify and formulate economic behavior of the trading crew agents, and a review of the simulation prototype. The last sections present validation tests and results of further, more complex scenarios that were used to validate the simulation. Finally, the discussion, conclusions and future work are presented.

2. Background

2.1. Agent-based vs. Discrete Event Simulation in construction management

In general, when applying a discrete-event simulation to model building construction, the construction crews are represented as "machines" along a "production line", while the work locations are represented as "products" which move along the production line from one construction crew to another. For example, Brodetskaia et al. [8] developed a simulation that examines the impact of production control on productivity and workflow. In this simulation, the products (apartments) were split into sub-products (rooms) which are then processed by the machines (trade crews). Significantly, the "machines" in the simulation that represent the trade crews lack any decision-making mechanism. Their behavior was pre-programmed using probability data that was not context-driven. Tang et al. [20] pointed out that most simulations in construction research model uncertainty within decisions and operations, but do not model the interactions between them, in part due to the narrow selection of research topics and in part due to the limitations of DES tools.

The roots of DES are in operations research and production [21], whereas building construction is performed by independent contractors who are economic agents. Economic agents are decision-making actors who function in contexts that include aspects of economic behavior. Accordingly, each agent makes decisions by solving a well or ill-defined optimization problem [17]. DES models are limited in modeling complex, realistic building construction scenarios and they cannot directly model agents. DES tools do not enable integration of the constructed project as a building information model to simulate the physical environment, and thus dynamic changes to physical aspects such as walking distances and obstacles need to be artificially preprogrammed. Another drawback of DES is that they do not allow experimentation with trade crew behavior that manifests as independent decision-making under uncertainty. Moreover, different contract situational parameters for each participant and the subsequent behavior cannot be modeled.

DES approaches are strongly dependent on pre-construction estimations of production rates and other inputs that can change under varying circumstances during the construction process. Some of these circumstances emerge as interactions among resources. Considering working crews on site as unique entities with varying production rather than an averaged resource, further adds to the adaptive complexity of the simulation [17].

Tang et al.'s Interactive Construction Decision Making Aid (ICDMA) simulation proposed to overcome some of these limitations by introducing a human decision-maker at various points in a simulation in order to apply different strategies to correct the process of a simulated construction project. However, it does not endow trade crews with the ability to think and act independently, but maintains centralized control in the hands of the decision-maker.

Recent thinking suggests that production in construction may be better understood as emergent, dependent on the individual motivations and behaviors of individual crews and workers. According to Laufer [22] construction operations exhibit substantial dynamism and uncertainty, which makes preplanned control systems inadequate. Bertelsen and Koskela [23] charted and analyzed the different management frameworks that address and cope with the inherent complexity and unpredictability within project production systems. Sacks et al. [18] formulated the subcontractor resource allocation behavior, using economic game theoretic approaches. In their work, they emphasized the need to adopt decentralized methods of control in managing projects.

According to Howell [24], lean construction methods tend to shift the focus toward decentralized control, while onsite construction activities at a micro-level seem to show more "organic" control, compared to the much subscribed central and coordinated control. Subsequently, in his work he suggested that the happenings within the construction discipline could be better explained based on the agent-based concept.

Agent-Based Simulation (ABS) is a methodology in which a simulation experiment is constructed around a set of autonomous "agents" that interact with each other and with their underlying environment to mimic the real-world scenario that they imitate [18]. ABS tends to closely describe how systems work in their natural form and it has been used in a variety of fields including social sciences, architecture, biology, ecology, economics, political science and marketing and sales [25, 26]. The agents in ABS sense and stochastically respond to conditions in their surrounding environment, mimicking complex large-scale system behavior. Each agent individually assesses its situation and makes decisions based on a set of rules. Based on their interactions, the agents can make autonomous decisions [26–28]. The ability to study emergent large-scale outcomes by modeling interactions among individual actors is based on the assumption that the system has distributed control rather than central control. This assumption is essential to the applicability of ABS to construction [25].

Siebers et al. [29, p.4.] lists nine features of a domain that make it a good candidate for ABS application. Production in construction has six of these features: individuals that have dynamic relationships, create social networks, cooperate, collude, have geo-spatial aspects to their behaviors, and are engaged in strategic behavior while anticipating other individuals' reactions when making their decisions.

For all of the above reasons, ABS is suitable for simulation of trade crews' workflow on construction sites and of production control, and was selected for implementation of the EPIC system.

2.2. Applications of ABS in construction engineering and management

Previous research efforts using ABS in Construction Engineering and Management illustrate that an ABS can mimic the construction environment effectively. Taghados et al. [30] showed how agents (for resource allocation, weather, production units and visualization) could be combined in 'federated' models to simulate different construction project scenarios by using a standardized High Level Architecture.

Sawhney et al. [25] discussed the perception of control and the understanding of construction projects by simulating "what-if" scenarios, and planning for contingencies by performing initial experimentation using Agent-Based Modeling and Simulation (ABMS) either in isolation or in combination with traditional simulation methodologies. Using agents to compose a complex system, alternative setups were applied to evaluate the impact of different production management strategies on the progress of production trade crews and to identify management policies most suited to minimizing cycle time and WIP.