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# SIMULATING AND VIZUALISING EMERGENT PRODUCTION IN CONSTRUCTION (EPIC)USING AGENTS AND BIM

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## ABSTRACT

We present an agent-based simulation model developed for studying and improving production control in construction processes. The model represents individuals' decision making, knowledge and uncertainty.

Simulation methods are particularly useful for assessing the impacts of different production control methods and information flows on production on site because field experiments in building projects suffer difficulties with isolating cause and effect. Existing methods such as Discrete Event Simulation (DES) are limited to model decision-making by individuals with distinct behaviour, context and knowledge representation. Agent-Based Simulation (ABS) may offer a better solution. The simulation developed exhibits the interdependence of individual crews as they interact with each other and share resources, reflecting the influence of crew leaders' perception of the project state on their workflow decisions. The model uniquely distinguishes between reality and perceived reality. Significantly, this allows experimentation with uncertainty as agents function within the context of what they know. Different management policies, such as the LPS, can be tested, as can the impact of different site information-flow systems. Unlike the few existing agent-based simulation models for construction, the simulation is situated in a realistic virtual environment modelled using BIM, allowing future experimental setups that can incorporate human subjects and real buildings.

## KEYWORDS

Agent-based modelling and simulation, building information modeling (BIM), information flow, production control, visualization.

## INTRODUCTION

Until the 1990's (approximately), most researchers and practitioners held the view that there is effective "central control" behind every construction project even at the

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production level. The traditional approach supported implementing “central control” in production, in which a detailed construction plan and schedule are created in advance based on well-defined resource and temporal constraints (Morris, 1997; Hendrickson, 1998). Once a plan was created it was assumed that the project would (or should) evolve according to the plan and that interaction of construction crews and individuals would have a minimal impact on this evolution. Conversely, recent thinking suggests that production in construction may be better understood as emergent, dependent on the individual motivations and behaviours of individual crews and workers. Laufer (1997) emphasized the role of dynamism and uncertainty and therefore inherent inability of pre-planned control systems in construction, offering a set of principles for simultaneous management. Lean construction has highlighted the impact of variation in production due to misalignment of the flows of materials, crews, information, equipment and information, and the lack of management of space and external factors (Koskela, 2000).

Whereas the school of 'determinate' or 'central control' thinking pursued research to develop and refine tools based on the Critical Path Method (Antill, 1990; Lu and Li, 2003), lean construction researchers exploring production systems found simulations more appropriate. Given the availability and accessibility of Discrete Event Simulation (DES), this has been the research tool of choice (Tommelein, Riley and Howell, 1999; Esquenazi 2002; Schramm, et al., 2007; Sacks, Esquenazi and Goldin, 2007; Brodetskaia, Sacks and Shapira, 2012). DES tools such as STROBOSCOPE and CYCLONE have provided general and special purpose frameworks for simulating construction operations and construction management processes (Martinez, 1996).

However, when modelling construction work using a DES, workers are not modelled as individual entities with individual properties; rather they are treated as homogeneous resources with variation that is predetermined (usually defined by simplified, fixed probability distributions) (e.g. Brodetskaia, Sacks and Shapira, 2012). Construction crews are represented by static "machines" located along the production line, while the construction products (locations or spaces) are represented as dynamic "products" which move along the production line from one 'crew' to another. Significantly, the entities (workers, crew leaders, subcontractors, etc.) are not utility driven and lack any autonomous decision-making mechanism (Sawhney, et al., 2003; Watkins, et al., 2009). In general, the DES models have limited ability to model decision-making by crew leaders who have distinct individual behaviour that varies according their context: knowledge, perception of given conditions, commercial terms of their subcontractor employer, material supply policies, etc.

Howell (1999) points out that lean construction methods tend to shift the focus toward decentralized control, suggesting that events could be better explained based on the agent-based concept, which enables decentralization of the production. Sacks and Harel (2006) used game theoretic approaches in order to study subcontractor resource allocation behaviour, while emphasizing the need to adopt decentralized methods of control in managing projects. Thus the need arises to explore and test the possible utility of an emergent, self-organized mode of production control on a construction site. Agent-Based Simulation (ABS) (Macal and North, 2005) appears to be the most appropriate simulation tool for the task.

There have been a few attempts to use ABS to model the behaviour of individual construction entities. Some have focused on the flow of construction equipment rather than on the workers (e.g. Kim and Kim, 2010), and most use highly simplified virtual environments represented as planar grids and agents with limited decision-making mechanisms (e.g. Sawhney, et al., 2003; Watkins, et al., 2009; Lahouti and Abdelhamid, 2012).

The underlying production principle of this work is that self-organization in construction situations may give rise to decentralized, distributed, self-healing systems, which may yield productive work-flow. The envisaged emergent mode functions through interactions between individual crews as they flow through the project and communicate with the other crews, the site administration, and use a Building Information Model (BIM) that describes both the process and the product. The ABS tool described in the following sections is intended to provide researchers a multi-agent-based simulation system to evaluate different production control methods in construction, including systems designed to exploit self-organization. The system aims to mode individuals' decision making under uncertainty and the quest for information as well as the execution of work.

## METHOD

The research method was to design a new experimental setup (the ABS model), devise validation tests, implement the simulation as a software tool, and validate the tool using the prescribed tests. The simulation method implements a “bottom-up” approach to model the interactions between individual agents. Agents were programmed with decision making rules and utility functions and applied to a ‘to-be-built’ environment represented using BIM. The rules and utility functions were based on knowledge of construction work processes and behaviour parameters acquired through field interviews and observations of site superintendents and trade crew leaders. By varying behavioural and situational parameters of the individual agents, such as reliability and consistency in adhering to plan, it was possible to generate aggregate system performances and outcomes similar to those observed in building projects on construction sites and to validate the system using scenarios with predictable outcomes.

## SIMULATING EMERGENT PRODUCTION IN CONSTRUCTION (EPIC)

The EPIC simulation model was designed for researchers to experiment with different production control regimes. It allows them to evaluate the emergent flow of work and labour according to conditions established using behavioural and environmental parameters set by the researcher. There are two types of agents: subcontractor crews, modelled by 'crew leader' agents, and site managers ('superintendent' agent). Crew leader agents make decisions about their movement and work within the site according to their perception of the state of the project and their expected utilities. Each run of the simulation results in comparable outputs, such as the flow line of the project and time distribution charts.

Modelling the information known to each agent individually and their relative confidence in the certainty of that information is a central feature of the EPIC system because many of the candidate production systems that will be tested are decentralized and expose subcontractors to project state information in different ways. Agents acquire information as they move through work locations (represented using a BIM model), and meet other agents. The agents calculate the expected production rate as a function of their trade crew size, the congestion in the intended work locations, and the expected quantity of work, all based on their perceived or current information. They then make decisions considering both the current work plan and the potential utility. The crew leaders' utilities, and thus their decisions, are dependent on the expectations of both their employer (the subcontractor company) and the site manager (the superintendent).

The steps required to develop the simulation were:

1. Field study to observe and formulate the behaviour of the different agents.
2. Development of the detailed decision making model.
3. Implementation of the experimental simulation tool according to the observations and the constructed model.
4. Validating the tool by through test simulations of predictable scenarios.
5. Experimentation with simulations of unpredictable scenarios.

## FIELD STUDY

The knowledge needed to define the agents' behavioural algorithms was collected through in-depth interviews of 13 construction employees (subcontractors, crew leaders and superintendents) engaged in finishing works in four high-rise tower projects. Data for production rates, material consumption quantities and other parameters was collected at the same time. The most interesting observations from the interviews were the following:

**Economic Utility Function**. Crew leaders take into account their employer's perceived profitability, attributing importance to the subcontractor's economic utility.

**Maturity Factors**. The perceived maturity of a certain work package, according to the crew leaders, was observed to increase whenever there were sufficient clear design information, available sufficient materials and equipment, and the space is ready in terms of pre-work. They intuitively understood and acted on their perceptions of the maturity of the work packages.

**Reliability of Information**. The actual maturity of the pending works and their scope often differ from the superintendents’ and/or the crew leaders’ perceptions of the maturity and scope.

**Working Prior to Receiving Design Information**. Crews are often sent by the superintendent to perform work where design information is still missing, with the intent to prevent further delays in subsequent trades. This often causes re-entrant flow and re-work.

**Leaving Small Parts of Work Packages for Later Completion**. Crew leaders tend to prefer to maintain productivity, leaving small parts of work packages that have lower than average productivity for later completion.

**Conflicting Instructions**. Crew leaders are employed by the subcontractor, their direct employer, whereas in their day to day routine they are subject to the superintendent, the manager nominally in charge of production on the construction site. Under these circumstances (having two sources of authority), crew leaders often find themselves conflicted as to which tasks should be performed at any given time. In day to day practice, crew leaders deliberate whether to prefer the subcontractor's utility or the superintendent's instructions.

**Primary Decision Outcomes**. When faced with the option of what to do next, crews chose between four main paths: to select a new task and begin work, to continue working on their current task, to wait for work to become available, to gather information (where certainty was low concerning the project state), or to abandon the construction site.

## DECISION MAKING MODEL

The agents' behaviour was modelled using Behaviour Trees (BT), an Artificial Intelligence (AI) technique for modelling decision making used in commercial games. Behaviour trees allow simple and scalable solutions for editing logic. Processing begins from a root node and child nodes are evaluated from left to right in order of priority. From the interviews with the crew leaders, the following routine was observed and modelled as a crew leader agent BT:

**Sensory System** (sight of other objects and agents).The agents exchange information while meeting (coming in contact with) the superintendent agent. Moreover, the crew leader agents copy actual information observed in their surroundings.

**Perform Work in the Chosen Location**. Working activity will occur if all the sufficient conditions are held: Presence of materials, availability and that there is still some amount of work to be completed.

**Select Where to Work**. If working activity fails, then the agent will evaluate its future utility from all available work packages. This node incorporates a utility function derived from the work of Sacks and Harel (2006) but modified to account for perceptions the maturity of different pre-conditions.

**Gather Information Regarding the Maturity of the Different Work Packages**. If the work selection activity fails, and certainty towards available work packages is low, then the crew leader agent will try to gather information. The information gathering activity may be done be several communication methods: by going physically to the working location to collect the information, or by requesting information from the superintendent.

**Wait at the Construction Site**. When gathering information fails (for instance if the certainty of low utility is high, but the time until a high utility work package will become available is shorter than the appropriate parameter), then the agent will wait.

**Abandon the Construction Site**. Finally, the agent will choose to abandon the construction site if waiting activity fails. Failure of waiting activity may occur if the time until a mature work package is long. In future models, abandonment may also occur if a work package with sufficiently higher utility is available on an alternative project.

## IMPLEMENTATION OF THE EPIC SIMULATOR

The full-scale ABS model was implemented in the UNITY 3D game engine. One of the novel features of the simulation is the ability to reflect the influence of project state perception on crew leaders' workflow decisions. The BIM model objects each have a property that reflects their state of completion through the performance of work on them for each trade. A separate Excel table, also with cells for the state of completion of each BIM element for each trade, is maintained for each crew leader agent. At any given time during a simulation run, a crew leader's table reflects the 'knowledge' of that crew leader about the project state, which may or may not be the same as the actual state. Crew leader's decisions are made on the basis of their own knowledge table. Their tables are updated by mechanisms that can be controlled by the researcher: through interaction with the supervisor, through meetings such as LPS, or by 'seeing' the physical state when present in a location. An artificial 'full information' state can be modelled by copying the BIM object property values to the crew leaders' knowledge tables whenever they are changed.

Thus different management policies, such as the LPS, can be tested, as can the impact of different site information-flow systems. The model reflects the reliability of information, and distinguishes between reality and perceived reality. Significantly, this allows experimentation with uncertainty as agents function within the context of what they know.

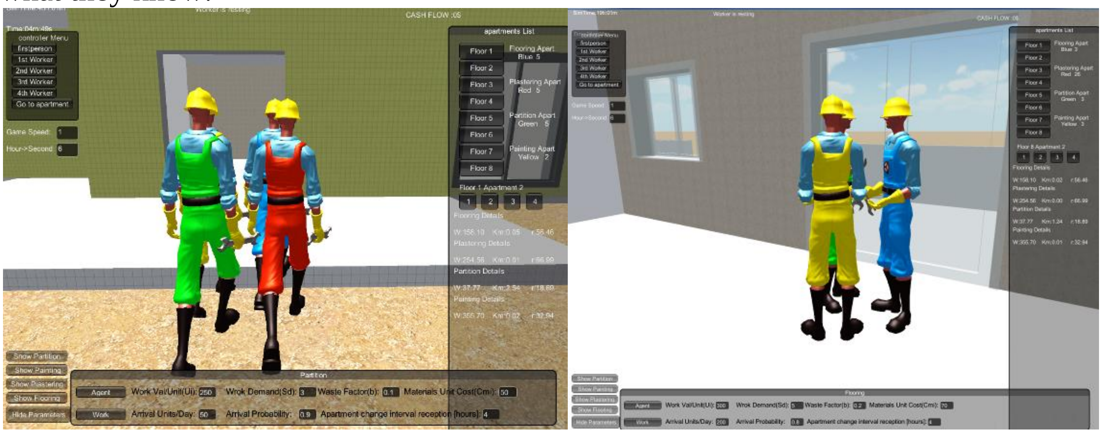

*Figure 1: Different views from the simulator prototype.*

## VALIDATION AND TESTING

The EPIC simulation was validated by running it for seven scenarios whose results could be predicted without simulation, and comparison of the results. Examples are scenarios in which all crew leaders conform to the initial construction plan and all materials and information are delivered on time, or all crew leaders ignore the plan and prefer their own productivity. The test results confirmed that the input parameters, when varied independently of other parameters, had the predicted effect.

The system was also tested with three additional experimental scenarios in which a variety of input parameters were mixed, such as with or without LPS weekly work planning meetings, different information transfer patterns, different degrees of variation in the rate of supply of design information, and different degrees of discipline in adhering to plan. These experiments demonstrated the emergence of different patterns of flow of construction trade crews, generated due to agents' characterization, materials and design information supply, as well as work conditions. In general, agents that organize their work flow according to economic utility generated lower amounts of re-work and re-entrant flow, while having greater amounts of transition time between work packages, due to the preference of work packages with high maturity, even if not adjacent to current location. Accordingly, the model allows modification of the transition fee within the economic utility function, giving rise to proximity preference.

Figure 2 shows the flow line and the arrival intervals of new design information for a scenario in which different crew leaders' agents have different motivations. Agents representing crew leaders of trade crews A,B and C are work plan driven: they will prefer to work according to the initial plan, which in this case is chronologically ordered from the first to the last floors. It can be seen that due to their rigidity to the work plan, they work in work packages though no design information has arrived, returning to some amount of rework. In contrast, agent D is economic utility driven. Accordingly, agent D does not attempt to execute tasks which were completed by previous trades while missing complete design information. It is only when the trades complete their re-work that the crew leader attempts to perform the work package.

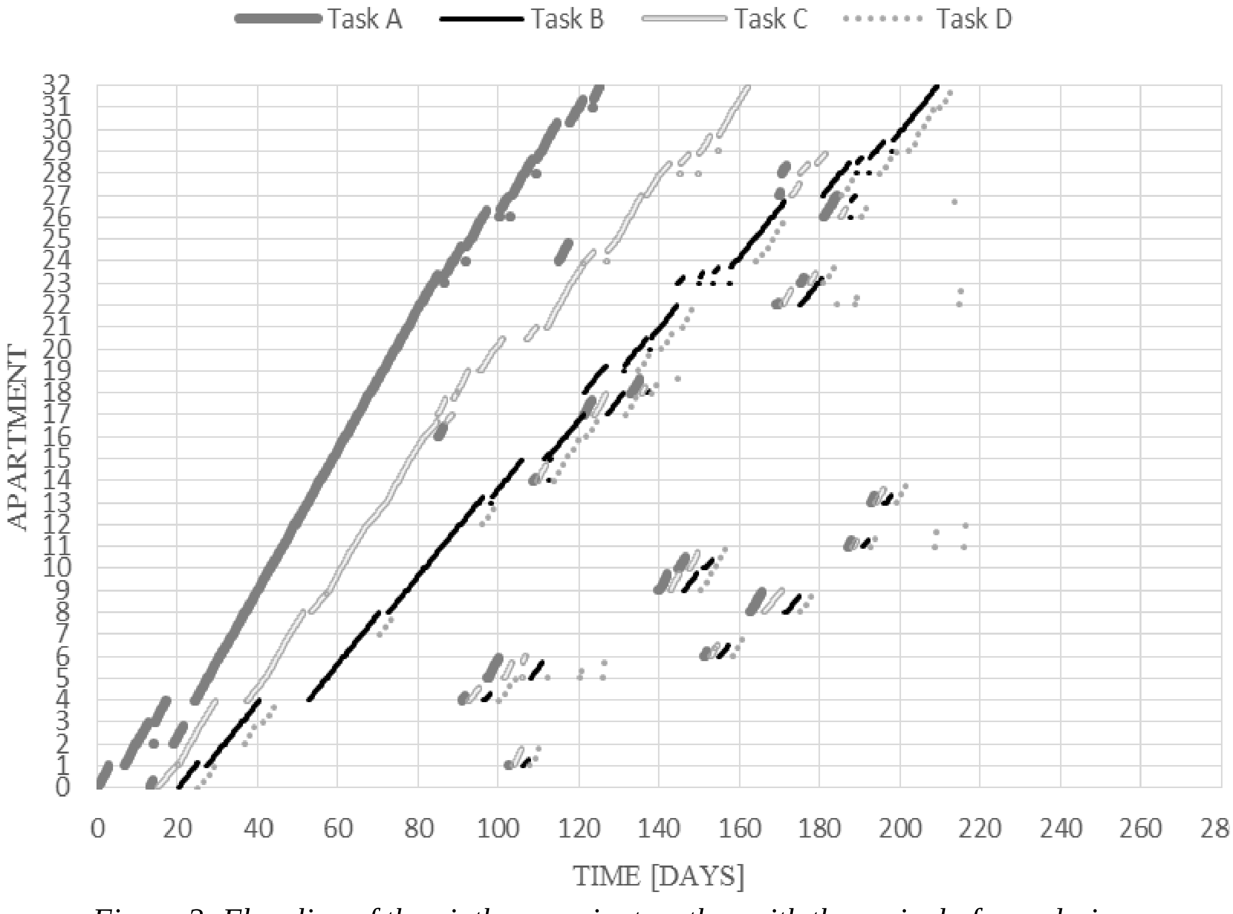


*Figure 2: Flow line of the ninth scenario, together with the arrival of new design information (in plans)*

As expected, the time distribution of crew leader D, as shown in Figure 3, exhibits no tasks performed without design information, as well as no re-work. However, the agent has a long period of waiting, due to the need to wait for completion of prior trades.

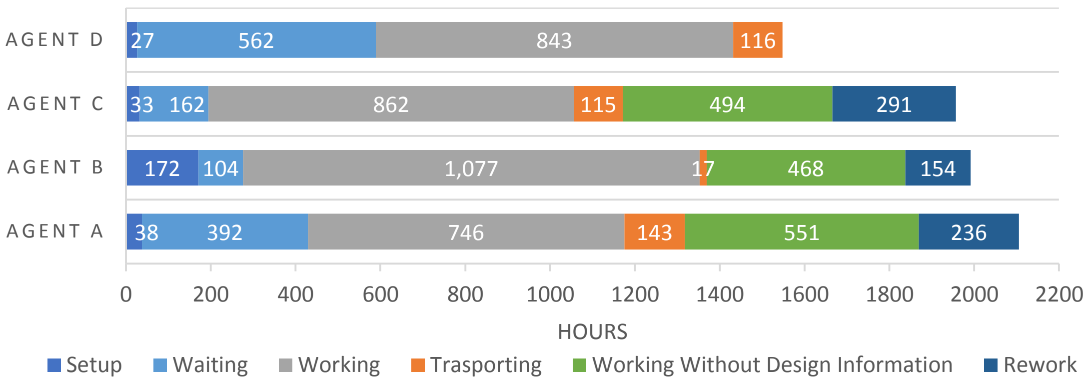


*Figure 3: The time distribution of each of the crew leaders' agents in scenario 9.*

# CONCLUSION

The results exhibit the interrelation between the researchers' input parameters, the trade crew agents' decision-making, and the emergent patterns of production sequence and productivity. By varying parameters of material supply stability, arrival of design information, and agent' behaviour (which varies from agent to agent according to contextual parameters like contract type, work demand, motivation etc.), we were able to generate different aggregate system performances. The resulting patterns for known conditions proved similar to those found in an actual project context on a construction site. Significantly, simulation runs with arbitrary parameter values resulted in production patterns that could not be predicted, demonstrating the emergent nature typical of real project outcomes.

The contribution of this research lies in the development and testing of the ABS and demonstration of its utility for testing the potential of different modes of production control and commercial terms on a construction site. Lean construction and BIM research has revealed the potential of novel ways to organize production on site that exploit the benefits of pull flow and thorough yet flexible planning. The EPIC simulation platform is uniquely capable of testing their impact because it models the complex, emergent patterns of production behaviour that result from the interaction of the myriad subcontracting teams and suppliers that perform construction work on and off site. In particular, the influence of each participant's knowledge, context and motivations on their day to day decisions about resource allocation and work sequence can be modelled in the ABS, while they could not be modelled using DES. Thus EPIC provides the first thorough, yet straightforward and reliable, tool to test different ideas for production control paradigms in construction that takes individual behaviour and uncertainty into account.

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