Proceedings of the 2003 Winter Simulation Conference
S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, eds.

AGENT-BASED MODELING AND SIMULATION IN CONSTRUCTION

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ABSTRACT

Agent-based Modeling and Simulation (ABMS) is a relatively new development that has found extensive use in areas such as social sciences, economics, biology, ecology etc. Can ABMS be effectively used in finding answers to complex construction systems? The focus of this paper is to provide some answers to this question. Initial experimentation is conducted to understand the advantages of using ABMS either in isolation or in combination with traditional simulation methodologies. The paper provides a summary of this experimentation, conclusions and sets the agenda for future research in this area.

1 CONSTRUCTION SIMULATION

Construction researchers and practitioners have used various techniques for studying complex construction systems. These techniques include the basic networking techniques like CPM and PERT, queuing models, productivity models like method productivity delay model (Adrian 1976), operations research tools like linear programming, game theory, simulation, and industrial planning techniques like line of balance method. The advent of simulation methods in construction, occurred in the form of introduction of simple networking concepts, as a modeling framework for studying construction operations. The earliest of these methods was the so-called "link node" model adapted by Teicholz (1963). After that Halpin (1973) developed the CYCLONE format at the University of Illinois. CYCLONE has become the basis for a number of construction simulation systems. CYCLONE simplified the simulation modeling process and made it accessible to construction practitioners with limited simulation background. The application of the construction process simulation ranges from productivity measurement and risk analysis to resource allocation and site planning. A microcomputer version of CYCLONE was developed by Luch and Halpin (1981) at Georgia Tech. This version is called MicroCYCLONE. Paulson (1987) developed the INSIGHT system which is based on the CYCLONE methodology and has a more interactive interface. Touran (1981) focused on automated real time data acquisition and its integration with INSIGHT. Work at the University of Michigan under Carr led to the development of RESQUE (Chang and Carr, 1987) which is also CYCLONE based with advanced resource handling capabilities. Ioannou (1989) developed UM-CYCLONE for advanced construction process modeling.

More recently advanced construction simulation initiatives have been launched. Simphony developed at the University of Alberta provides an advanced simulation environment specially tailored for construction researchers and practitioners (AbouRizk et al. 1999, Hajjar and AbouRizk 1999). STROBOSCOPE developed at the University of Michigan and now housed at Virginia Tech is another notable development that has mustered a strong following amongst construction researchers (Martinez 1996, Martinez and Ioannou 1999). Numerous other smaller scale initiatives can also been found in literature. Tommelein et al. (1998) and Halpin and Kueckmann (2002) recently expanded the use of construction simulation into areas pertaining to workflow variability and other lean concepts. Tommelein et al. (1998) and Walsh et al. (2002) have now combined the study of construction supply chain management and construction simulation. Sawhney and Deshpande (2000) developed constructs for Java-based simulation for simulating construction operations over the web.

The above described works generally map the history of construction simulation. The common trend has been the heavy use of discrete event approach in construction simulation. Construction simulation has primarily been conducted using discrete event simulation tools (Walsh et al. 2002). This work makes a departure from this well traveled path in that it explores the application of ABMS in construction—as a standalone tool or in combination with discrete event simulation.

2 AGENT-BASED MODELING AND SIMULATION

Agent-based modeling and simulation is a methodology in which a simulation experiment is constructed around a set of autonomous "agents" that interact with each other and their underlying environment to mimic the real-world scenario that they replicate (Sanchez and Lucas 2002). ABMS tends to closely resemble how physical, biological, and social systems work in their natural form (Sawhney 2002, Walsh et al. 2003). Some consider this technique a new development; while others simply deem it as a natural extension of existing paradigms such as parallel and distributed discrete-event simulation, and object-oriented simulation (Davidsson 2000).

ABMS has been used in a variety of fields including social sciences, ecology, economics, political science and marketing and sales (Bonabeau 2002). In this approach each system is modeled as a collection of autonomous decision-making entities (Bonabeau 2002, Axelrod 1998, Axtell 1999, Sanchez and Lucas 2002). These agents sense and stochastically respond to conditions in their local environments, mimicking complex large-scale system behavior (Sanchez and Lucas 2002). Each agent individually assesses its situation and makes decisions based on a set of rules (Bonabeau 2002). Extremely complex behaviors can arise from repetitive, competitive interactions between agents enabled by the computational power of computers. Researchers can thus explore dynamics out of the reach of pure mathematical methods at the system level, and discover the fundamental rules driving system behavior (Axelrod 1998, Bonabeau 2002).

3 ABMS IN CONSTRUCTION

Construction discipline is deeply entrenched in tradition and history. Researchers and practitioners alike are of the view point that there is "central control" behind every construction project; therefore once a plan is created it is assumed that the project will evolve as per this plan and that interaction of construction "entities" will have a minimal impact on this evolution. Few have challenged this approach. Howell (1999) suggested that the happenings within the construction discipline could be better explained based on the agent-based concept.

At a micro-level, onsite activities seem to show more "organic" control as compared to the much subscribed central and coordinated control (Walsh et al. 2003, Howell 1999). Systems that show these kinds of behaviors are amenable to the use of agent-based modeling and simulation based inquiry. However, much research needs to be conducted in this field.

The construction project is routinely described as a setting in which constant change is a rule rather than an exception (Kim and Paulson 2003), and much of the construction management literature is dedicated to change management. Changes to the project plan occur due to design changes, unexpected delays or interruptions in the supply chain, or field conditions that differ from expectations, among others.

Two examples—one from the commercial sector and one from the residential sector—are given here to describe the potential benefits of agent-based modeling and simulation for the construction industry.

The first example pertains to construction site safety. Consider the case of a crew of five skilled workers working on the 20th floor of a high-rise building that is under construction. The first thing that leaps in a constructors mind is the safety climate at the work face, since the construction industry is notorious for its poor safety record when compared with other industries (Mohamed 2002). Current approaches to creating a safe construction climate focus upon use of lagging indicators i.e. past accident statistics for similar circumstances (Flinn et al. 2000, Mohamed 2002). No attempt is made to incorporate and study leading indicators relating to organizational, managerial, and human factors (Mohamed 2002). Much of this can be attributed to the lack of availability of modeling and analysis tools to the construction industry. It seems impossible to construct a computer model of the construction environment under study and experiment with safety factors such as trust and support within a group of workers, safety rules and procedures, available safety devices, use of these devices, amount of time available to plan and carry out the work etc. Construction worker safety is further problematic in that some workers are more risk-tolerant than others, and some situations are more risky than others. Nonetheless, accidents happen to both the risk-tolerant and the risk-averse, although in different proportions. Situations can emerge to become more unsafe based on actions taken by workers and situation can become more complex based on interactions amongst and between the workers and the working environment. An agent-based modeling and simulation testbed on the other hand, can be used to mimic the construction environment in which the workers are performing their work along with a heterogeneous set of agents representing these workers to study various aspects of the safety climate. Various aspects of the construction environment can be adjusted along with "fitness and safety" factors of the instantiated "worker" agents to determine the most effective safety plan. Such a proactive approach, unimaginable otherwise will certainly enhance the ability of researchers and practitioners alike to study construction site safety more pragmatically. Simple "what-if" scenarios would allow one to consider the impact of different safety management philosophies on workers of different risk-tolerance, and allow the work to progress in a realistically variable environment, to identify those management practices most directed to zero accidents.

Second example pertains to the case of the production homebuilding industry. Bashford et al. (2003) reviewed Securities and Exchange Commission (SEC) filings for 23 publicly traded companies whose core business is the construction of single-family dwellings. The filings were the annual operating statements for the 2001 fiscal year for the 23 companies. It is conceded that the sample of 23 companies does not represent a random sample of all homebuilders. However, the 23 companies sampled had combined revenue from sales of $49.8 billion in fiscal 2001, which represents approximately 15% of the total revenue of the US homebuilding industry. The key finding of the analysis is that it took $13.9 billion dollars of inventory to produce 193,515 new homes. Bashford et al. (2003) have shown that due to archaic information processing techniques used by the industry somewhere between 50 to 75% of the construction cycle time is wasted. Eradication of this waste can result in significant reduction in capital requirement for construction. It is easy to imagine the economic impact to the nation if all of this capital were available for investment in other critical areas. Simply stated anywhere from $53 to $90 billion in cash investments can be avoided yearly in the US housing industry (Bashford et al. 2003). Cycle time has been stagnant at 150 to 180 days in various parts of the country, even though there is general agreement amongst stakeholders that homes could be built faster, cheaper, and with better quality compared to current standards if only the industry would invest in research and development. The research team envisions that an agent-based modeling and simulation testbed that allows experimentation in the use of advanced construction methods and technologies could enable the US homebuilding industry to cut its cycle time significantly.

4 CONSTRUCTION APPLICATION

To consider the effectiveness of the agent-based methodology, a residential subdivision was modeled using the agent-based simulation environment StarLogo (Colella et al. 2001, education.mit.edu/starlogo/). StarLogo is a simple agent-based environment in which observer and agent rules can be programmed to allow predefined agents to interact with each other and their environment (defined by on-screen patches). A subdivision was modeled by creation of 50 white patches in a black background, with each white patch representing a home site (Figure 1).

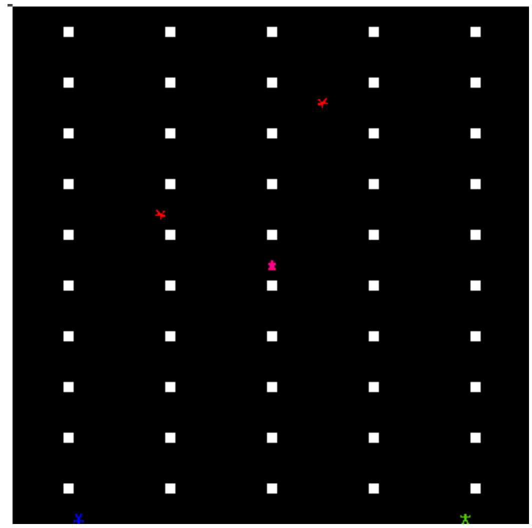

Figure 1: Subdivision Represented in StarLogo Simulation

Trade contractors, represented by agents, are free to move about in the subdivision represented on Figure 1. The trade contractor agents operated by the following rules:

- If located on a home for which the predecessor trade activity is completed, conduct the appropriate work for an amount of time determined by random selection from a statistical distribution.
- If not located on such a home, look for homes for which work of the predecessor trade contractor is completed.
  - If one is found, schedule it.
  - If none is found, move randomly to some other location in the subdivision.

The residential subdivision for a production builder is constructed via the services of some 50 trade contractors, completing collectively some 100 or so activities. The StarLogo environment, while relatively simple to learn and deploy, is not computationally fast. Hence, simulation of the entire construction process using so many agents would be time-prohibitive. Accordingly, the process was simplified by grouping the activities in the manner suggested by Bashford et al. (2003) as presented in Figure 2.

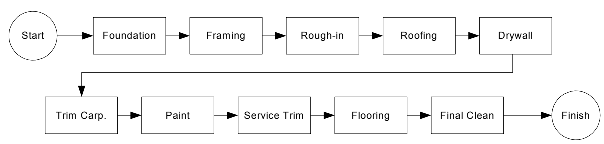

Figure 2: Simplified Residential Precedence Map

The intention of the work presented here being illustrative rather than duplicative of the process (Axelrod 1998), only the first three stages (foundation through rough-in of the building services) were modeled. Thus, there were three different trade contractor agent types, one each for the foundation, framing, and rough-in activities.

The user can control the number of crews provided for each trade contractor, with each crew consisting of an agent of the type for that trade contractor. Thus, if there are three framing crews selected, three homes can be framed simultaneously if the foundation has been completed.

The quality of work conducted by the crews was also captured. The reduction in the skilled workforce in the US in recent years has led to high turnover and relatively low levels of training in many parts of the residential construction sector. Consequently, the work of a crew may be unacceptable to the successor crew, either because it is done poorly or because it is done incorrectly. In these instances, that crew or another crew will have to return to the home to effect repairs, a process which exhibits very high schedule variability depending on the nature of the problem and the availability of a crew to conduct the repairs.

To model the impact of quality deviations on construction progress, a repairer agent was introduced. The repairer agent was given a higher level of variability for the duration of its activity than the trade contractor agents. Repairer agents were activated whenever a quality problem existed in the work of a trade contractor agent, and moved to the home to effect the repairs. Once repairs are complete, the repairer agent moves off the home, and it becomes available to the appropriate successor crew. The user is able to modify the probability that the crew will conduct its work without defects (one minus the probability of a defect).

The duration of the three phases of the work were selected so as to be roughly proportional to their actual durations. The duration was allowed to vary within a normal distribution. The duration parameters for each phase are shown in Table 1. No activity could be completed in less than one day, and in no circumstance was a crew allowed to move on to a home until the day after the previous crew completed (regardless of the time of completion). Two concrete and framing crews were used, along with one rough-in and one repairer crew.

Table 1: Duration Parameters for Subdivision Model

Phase of Work	Mean (days)	Standard Deviation (days)
Concrete	7	2
Framing	5	2
Rough-In	4	2
Repairs	1	3

The simulation was modeled as if it were pre-sold, which is to say all of the home sites are constructed without waiting for sales to trigger each start. This is a common situation for large production builders in high-growth markets in the US. As a result, the concrete activity is unconstrained by availability of work to begin, and is constrained only by the crew availability. Subsequent tasks may be constrained by both work to begin and crews to conduct the work.

5 SIMULATION RESULTS

The key results of interest include the overall time required to complete all three activities for the subdivision, and the utilization of the crews. The effect of the variability has been noted previously, both via direct observation and analysis (Bashford et al. 2003; Tommelein et al. 2002; Howell and Ballard 1996). One objective of the simulation effort was to see if the agent-based approach could effectively illustrate these same behaviors. In fact, the model performed extremely well in this regard.

Figure 3 shows the changes in the total duration (solid symbols) and utilization (open symbols) as the probability of acceptable work increases. Each point represents an average of 50 iterations. As expected, on average the time to complete the subdivision decreases and the utilization of the crews increases with increasing reliability of the predecessor trades. This result is in keeping with the expectations, and demonstrates the importance of construction quality on system performance.

Figure 4 shows a time history of backlog for one of the iterations at the 70% probability of acceptable work. Figure 5 provides a reference for a case with no defects and no variability in activity duration. Because the concrete activity is constrained only by the availability of the crews to conduct the work, the concrete is installed around the subdivision at a fairly steady rate. The framing activity is of slightly lesser duration, but has the same number of crews in the model. As a consequence, other things being equal the framing crews will tend to complete their work ahead of the concrete crews, and then have wait time

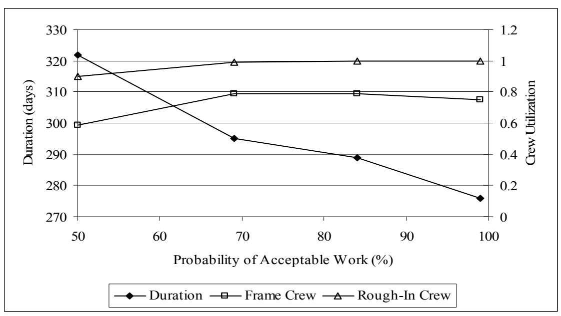

Figure 3: Results of Agent-Based Simulation of Subdivision Construction

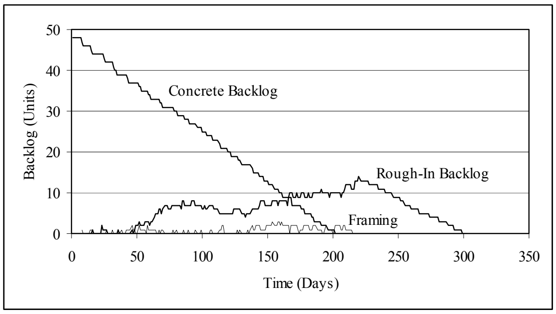

Figure 4: Backlog History for One Iteration at 70%

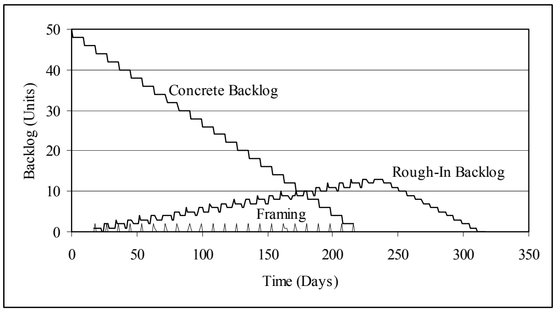

Figure 5: Backlog History for Case with No Variability and No Defects

until the concrete crews complete additional work. Only in the case where quality problems arise can workable backlog build up for the framing crew. The rough-in crews, however, are transitional between the two. Early in the process, the rough-in crews are dependent on release of work from the framing crew, but over time the greater number of crews available to the framing trade contractor leads to a build up of backlog ahead of the rough-in crew. This backlog serves to buffer the rough-in crew from the performance of the framing crews.

Figure 4 shows much less regular patterns than the zero variability case of Figure 5. Backlog for the framing and rough-in phases builds and diminishes over time; these fluctuations mostly arise due to quality problems and the activity of the repair agent. Figure 6 shows the time history of the utilization for framing and rough-in for the iteration depicted on Figure 4. Periods with high backlog yield higher crew utilization, in keeping with the observations of Howell and Ballard (1996).

The response of the system to reduction in the variability of the duration of activities is perhaps less intuitive than the response to improvements in quality performance. Table 2 shows the mean of 50 iterations conducted with the indicated duration variability for all three construction phases, leaving the repair variability unchanged from Table 1. The results in Table 2 come from the case with a probability of acceptable work of 70% (which seems to be about right based on observation and interviews with builders and trade contractors). The results depicted in

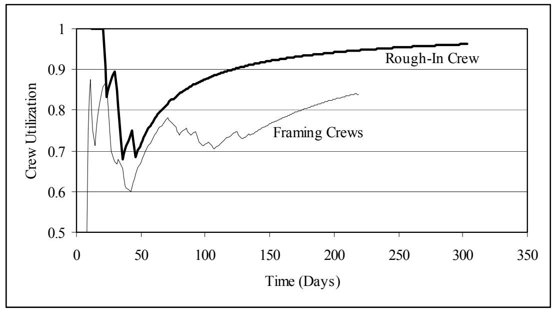

Figure 6: Utilization Time History for One Iteration at 70%

Table 2 demonstrate that some level of duration variability is beneficial to the overall duration to complete the three phases over the whole subdivision. The overall duration decreases with a change in the standard duration from 2 days to 1, but then increases substantially as the variability in the duration of individual activities is eliminated. This result appears to arise from the ability of workers to move on to the home sometimes in cases where the activity is done early, which has more impact on the overall duration than the quality delays in this model because most activities are not resource controlled.

Table 2: Effect of Duration Variability on System Performance (70% Probability of Acceptable Work)

Standard Deviation of Activity Durations (days)	Overall Duration (days)	Framer Utilization
2	295	0.79
1	287	0.78
0	316	0.77

6 CONCLUSIONS AND RECOMMENDATIONS

ABMS is promising area that has the potential of providing answers to many questions that have remained unanswered in the construction discipline. Based on preliminary experimentation it seems that ABMS combined with the traditional discrete event approach will provide added flexibility in modeling of complex construction systems. It provides the basis for further research and education into such areas as the study of emergent behavior of a construction project, proactive study of implications of human factors on issues such as a construction site safety and construction supply chain, creation of a germinal research and education community that participates in the creation of IT-based research and educational initiatives for the construction industry, the training of construction work force, and a broader integration of people in construction, regardless of gender or stature. While ABMS has been used for study of the ecosystem and other complex systems, the fundamental science of complexity will be advanced through its application in the construction sector.

ACKNOWLEDGMENTS

The research upon which this paper is based was performed in the Phoenix Arizona metropolitan area. The study was supported in part by the National Science Foundation through Grant Number PFI 0090559. Opinions expressed are those of the authors and not necessarily those of the Foundation. The authors also acknowledge the contribution of many homebuilders and trade contractors in the Phoenix Arizona area who cooperated and assisted with this study through interviews and providing information about their company operations.

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