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AGENT-BASED SIMULATION OF CONSTRUCTION WORKFLOWS USING A RELATIONAL DATA MODEL

Ling. Ma[1] and Rafael. Sacks[2]

ABSTRACT

To what extent is uncertainty concerning process status a cause of waste in construction workflows? Work studies and action research are expensive methods for investigation of such questions concerning construction workflow control policies and their results have limited applicability. Agent-based simulation (ABS) is particularly suitable for modelling peoples’ behavior and interaction in complex settings, like in construction, and therefore represents an alternative. We present a parametric ABS system (EPIC 2.0) developed using a relational data model for modelling construction workflow; the model enables users to specify the construction subjects (subcontractor trade crews), their work methods, the amount of work, the workspaces (locations), dependencies between the works, etc. The simulation encapsulates both variability and uncertainty in the construction workflow. Variability arising from design changes, quality checks and working conditions may lead to random change in workload and performance. Uncertainty arises from the fact that agents do not have full or perfect information. The major advantages of this ABS system are its ability to run differently configured virtual projects in terms of work crews, locations and production system control policies and to test the relative impacts of various approaches to communication of process status information. Simulation results conclude information asymmetry causes erroneous task maturity judgments and inappropriate work assignments, and of course affects the construction workflow.

KEYWORDS

Agent-based simulation; construction workflow; uncertainty; relational data model.

INTRODUCTION

Sacks et al. (2015) presented computer simulation as a powerful alternative to expensive ‘in-situ’ work study (e.g., Amaratunga et al. 2002) and action research (e.g., Azhar et al. 2009) for research of production flow in construction. Discrete-event-simulation (DES) has been the most commonly used method (e.g., Brodetskaia et al. 2013; Sacks et al. 2007; Tommelein et al. 1999). DES of construction projects execute the virtual site activities according to pre-planned construction operations with predetermined inputs and view construction production as a centrally controlled

[1] Postdoctoral Researcher, National Building Research Institute, Technion, Haifa, Israel, lingma@technion.ac.il

[2] Assoc. Prof., Faculty of Civil and Env. Eng., Technion, Haifa, Israel, cvsacks@technion.ac.il

process. However, they fail to incorporate the inherent variability and emergence that arises from the independent construction subjects' behavior as they interact on a construction site (Watkins et al. 2009). Modern construction management theory has highlighted various kinds of variability (Koskela 2000), the inherent limitations of pre-planned control (Laufer 1997) and the presence of decentralized control in construction (Howell 1999). DES is limited in applying these principles in the simulations.

Agent-Based Simulation (ABS) is an appropriate method to model those principles of emergence that apply to social activities (Sanchez and Lucas 2002). It focuses on modelling the distinct behavior of individual subjects and their interactions (Macal and North 2009). ABS has been implemented to model construction activities for different purposes (Sawhney et al. 2003). Watkins et al. (2009) used ABS to investigate the space congestion problem on a construction site; Tah (2005) presented the use of ABS to explore different project supply chain networks; and Kim and Kim (2010) used ABS to evaluate the traffic flow of construction equipment on a construction site. These efforts have highlighted the advantages of using ABS to model construction activities for different research purposes.

However, none of these attempted to model emergent outcomes resulting from the information-dependent decision-making of individual agents, which is central to the problem of researching the flow of crews on construction sites. Ben-Alon (2015) presented a unique ABS named EPIC (Emergent Production In Construction) which models the impact of product and process information flows on site superintendents' and trade crew leaders' decisions about workflow in construction. The agents were driven by tailored utility functions and an emergent production environment. However, the system was restricted to a given project configuration without the ability to parametrically configure the variety of different project setups needed for such research. It also stopped short of quantifying and monitoring the information flows.

This paper presents a new ABS system (EPIC 2.0) and developed for modelling the subcontractor trade crews' short-term work planning in a construction site subject to variability and uncertainty. The system facilitates investigating the impact of information flow on construction workflow. The following sections present the development of this system using a relational data model, a typical project configuration used to demonstrate the system's capabilities, the results of this project, and brief conclusions. The example highlights the ability to parametrically configure a project, to simulate different information exchange principles, and to quantify and measure the information flows and the resulting workflows. It illustrates how the impact of information transparency on the construction workflow can be explored. The potential to extend the simulation to investigate more complex emergent phenomena in construction is discussed.

DATA MODEL AND SYSTEM DESIGN

The ABS system is based on a relational data model and relational algebra. Relational modeling is an approach to formalize certain concepts in reality using a structure and language consistent with first-order predicate logic. It has been widely implemented in database management systems. A relational model is both human-readable and computer-readable; it clearly reflects human's communication and thinking manners. Relational modeling is therefore appropriate for modeling the information flows through communications on site and the crews' perceptions of project state. Relational algebra operations such as Selection (σ), Rename (ρ), Projection (Π), Group (γ), Natural Join (⋈), Union (+) and Minus (-) are used to model the project progression, crews' information processing and their short-term task planning.

The Entity-Relationship diagram of the data model is shown in Figure 1. It has three major parts:

Project configuration data have a prefix '*Fact_*';

Project progression data have a prefix '*Log_*';

Project event data have a prefix '*Event_*'.

MODELLING CONSTRUCTION PROJECT CONFIGURATION AND WORKFLOW

Construction project configuration includes relations among project, crew, work method, task, task dependency, and workspace. In the project configuration data, the user can define different crew trades, their workload and production rates, their workspaces and workspace priority, and also work dependencies ('*Fact_*' data in Figure 1).

The simulation is executed iteratively, and each iteration simulates one day in the virtual construction site. The project progression is logged, including date, crew ID, location ID, production rate, and remaining workload ('*Log _*' data in Figure 1). The crews can decide their subsequent location to work or wait based on their perceptions of the work readiness in that day. Due to the concerns of task dependency, workspace capacity and other constraints in task planning, each crew holds a perception about the project status as a whole, including not only their work but also others' ('*KnowledgeOwner'* in '*Log_*' data in Figure 1). For example, if crew A think all the precedent work for their work is not complete, they would wait; if crew A think crew B is working on floor 1, they won't go there. The simulation performs the Group (γ) operation on project progression data to retrieve the agents'/crews' latest perceptions of the project state in the following way:

$$\sigma(latestTaskState) = \sigma(Log\_Task) \bowtie \rho_{ID/Max(ID)}\left(\gamma_{KnowledgeOwner,TaskID,Max(ID)}(Log\_Task)\right) \quad (1)$$

MODELLING THE UNCERTAINTY AND VARIABILITY IN WORKFLOW

The simulation encapsulates both variability and uncertainty in construction workflow. Variability arises from design changes, quality checks and changes in working conditions Uncertainty, as a subsequence of the variability, arises from the fact that agents do not have full or perfect information about the project state. Only the data representing crews' perception of their own work manifests the true state of the project. The simulation performs Selection (σ) operation on result in Eq (1) to get the fact data in following way:

$$\sigma(latestTaskStateTrue) = \sigma_{SubName=KnowledgeOwner}(latestTaskState) \quad (2)$$

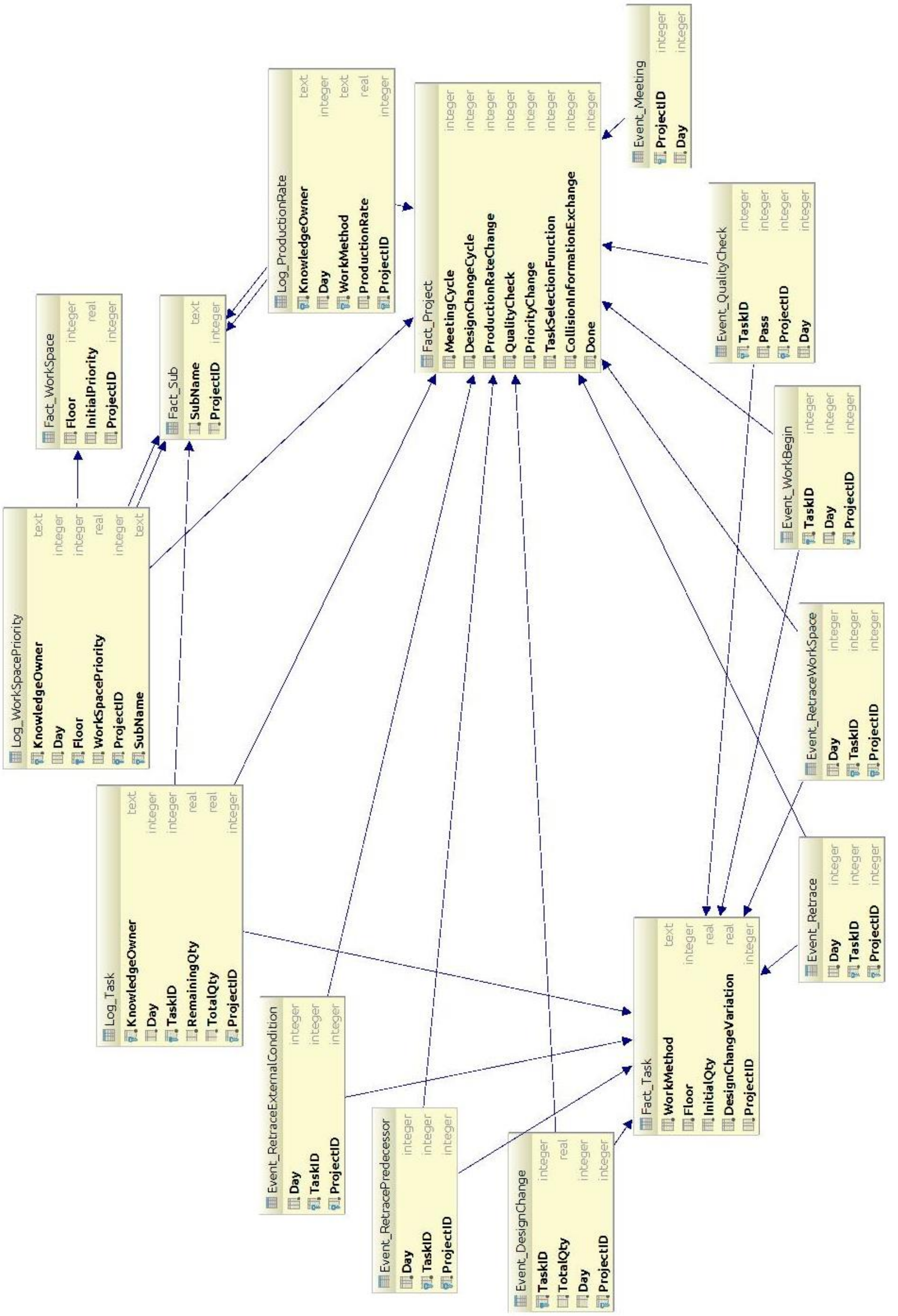


Figure 1. The data model of the simulation

The uncertainty exists, because the result in Eq (1) may not consistent with the result in Eq (2). For example, on day 7, A may think that B finished its work on floor 3 on day 5, based on his earlier observation and perception of B's production rate. But in fact, B is still working on floor 3 but at a lower production rate. At this time, if A makes a wrong decision to work on that floor, he will face a workspace conflict and waste one day on site, and data entry of such occurrence will be added to project event data (‘*Event_Retrace’* table in data model having a prefix ‘*Event_*’). However, whenever A goes to a floor *i*, having workspace conflict or not, he will update his perceptions of all the work belong to floor *i*. To simulate this fact, the system gets the result in Eq. (2), selects the data part of floor *i*, change the knowledge owner to A, and copy this result to the project progression data. In addition to the variability in production rate, design change and quality check events also cause variability (changes in remaining workload) in the simulation.

User can set a periodical design review, and a higher project’s completeness (CP) results a lower probability of design changes in the review. Therefore, in the simulation the occurrence of a design change follows a binomial distribution with a probability of 1-CP. If the value drawn from this binomial distribution is 1, the design change event is triggered; a task is randomly selected, and the remaining workload is either increased or decreased by a randomly selected proportion of the original work.

User can enable a quality check once a work is complete, and the work is assigned a base quality rate (QR) representing its average historical quality conditions. A frequently repeated work has higher probability passing the quality check due to the learning curve effect. Therefore, a calibrated quality check pass rate is:

$$QR' = 1-(1-QR)(1-WC) \quad (3)$$

WC is the percentage of the completed workload in all the workload of the same type indicating the crew’s proficiency in this type of work. The quality check result is drawn from a binominal distribution with probability of QR'. If the value is 0, the task fails to pass the quality check. Both the design change and quality check are logged in project event data (‘*Event_*’ data in Figure 1).

The variability causes uncertainty in agents’ perceptions, but such uncertainty can be reduced by agents’ communications in site meeting and random meeting. The user can specify the frequency of site meetings, in which the agents synchronize their perceptions of poject progression and other agents’ production rate. To simulate such phenomena, the system duplicates the result of Eq. (2) in project progression data for each agent. Agents’ random meeting also triggers this operation, but the information synchronization is only executed among the agents meet in the same workspace. In both situations, since the agents’ latest perception is updated, the result of Eq. (1) will also change accordingly when it is retrieved next time.

SIMULATION EXAMPLE CASE

An example project simulates the execution of interior finishing work in a residential building with five floors. Four crews perform the same four work on each floor under 'finish-start' work dependency (Figure 2).

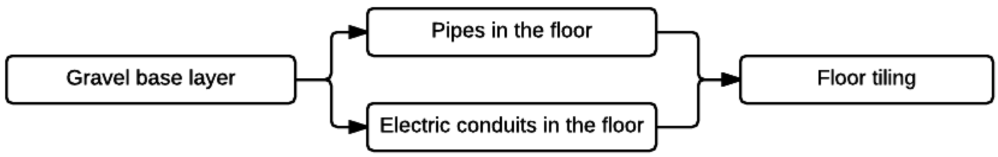


Figure 2. Task dependencies in the project

Table 1 specifies the initial production rate, productivity variability, quality rate, and workload. The quantity and production rate are normalized to comparable non-unit values.

Table 1. Initial parameters in the simulation

Crew name	Work method	Initial production rate	Quality check pass rate	Producti on rate std.	Total work qty. per floor
Gravel	Gravel base layer	1	0.9	0.1	5
Plumbing	Pipes in the floor	1	0.9	0.1	5
Electricit y	Electric conduits in the floor	1	0.9	0.1	5
Tiling	Floor tiling	1	0.9	0.1	5

Only one agent can work at the same space ad the same time. The design review occurs every 10 days. The simulation ran 20 times: in 10 run the agents synchronize the information in 7-days site meetings, but in the other 10 run they only update their perceptions of project progression in a work space when they go there, but they never get update when they meet each other.

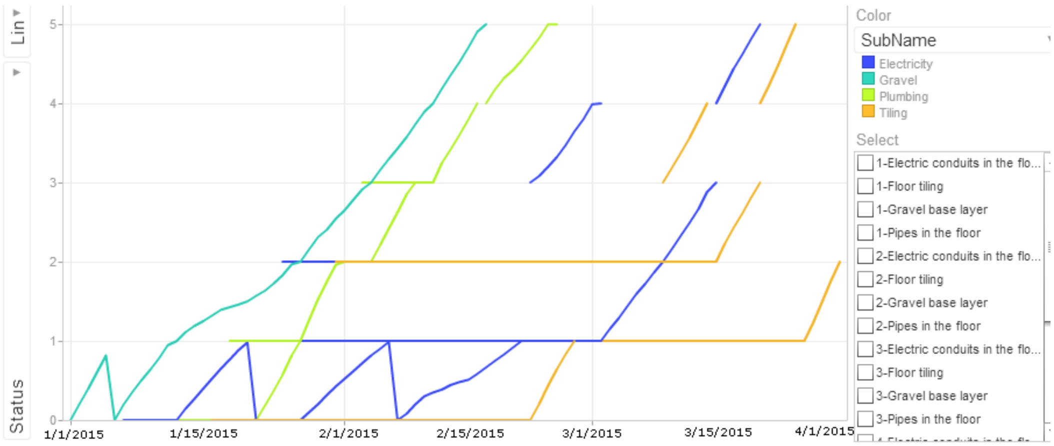
RESULTS OF THE EXAMPLE SIMULATIONS

The simulation results differ in different information exchange configurations. The system compared such difference quantitatively based on logged project progression data.

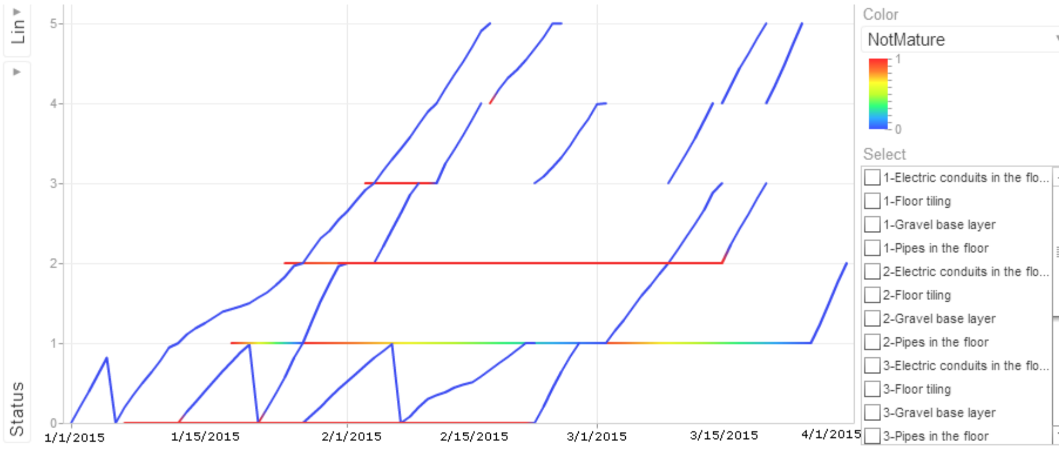
VISUALIZATION OF THE RESULTS

The construction workflow is presented in Color-coded flow line charts (Figure 3). The horizontal axis represents the time starting from 1/1/2015; the vertical axis represents workspace starting from floor 1 to floor 5. The system can group and color the lines by agents'/subcontractors' name (Figure 3a), work methods and events. For example, the agents' error decision of working on an unready work is colored in red at that time spot (Figure 3b), and failures of tasks in quality check are colored in red (Figure 3c). The line becomes blue when the agents enter the space and the work is actually ready.

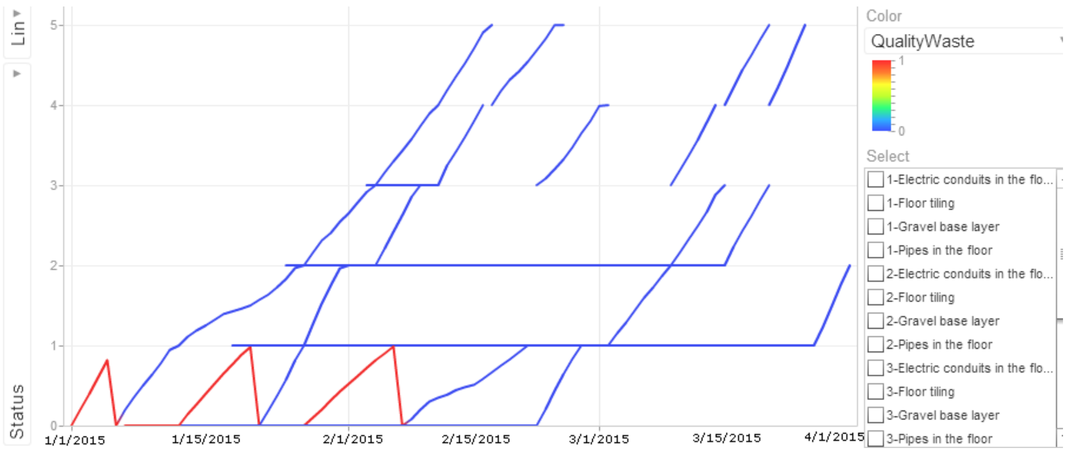
By combining the three figures, the project workflow can be quantitatively analyzed. The electrician thought he could work on the electricity in floor 1 on 1/7/2015 (Figure 3a), however, he found the work was not mature until he re-entered there on 1/15/2015 (Figure 3b), because his precedent work - gravel base layer was completed late (Figure 3a). The gravel agent's failure of quality check on 1/6/2015 (Figure 3c) caused his delay and also affected the plumbing and tiling (Figure 3a).



(a) A view of the work flow color-coded by work method



(b) Color-coding representing task maturity level



(c) Color-coding indicating failure of quality checks.

Figure 3. Workflow chart of a typical simulation.

The system can also visualize the information flows. The pieces of data the agents synchronized represent the volume of information they exchanged in each day (Figure 4). In a site meeting event all the crews would report the status of their tasks, so the volume of information exchanged is the rows of result in Eq (2). When agents meet randomly, the volume of information exchanged is the rows of the data entry the system added. The two scenarios are colored differently in Figure 4.

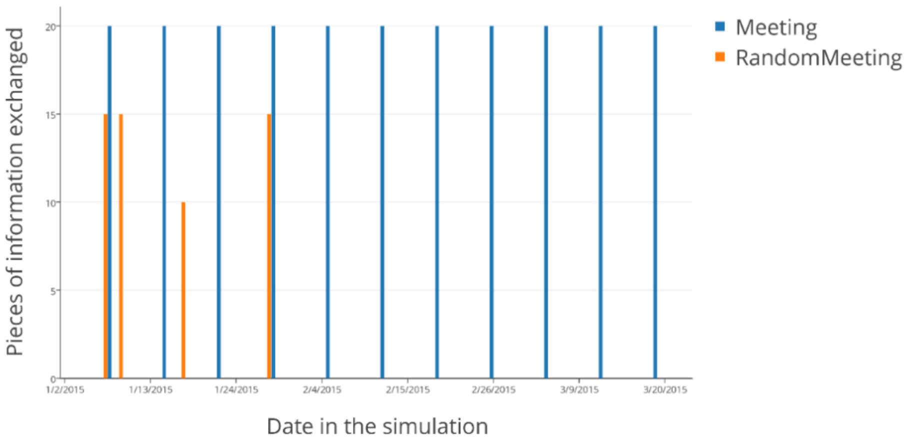


Figure 4. Information flow about task status

ANALYSIS OF SIMULATION RESULTS

The simulation run 40 times, and in each time metrics were recorded as shown in Table 2.

Table 2 Project performance metrics of 4 of the 20 simulations

Information exchange	Total duration (T)	Work conflict times	Quality failure times	Design change times	Total waste days	Sum of add value days (A)	Percentage of value-adding work (A/T)
No	187	28	27	2	29	134	72%
Yes	124	6	6	10	16	105	85%
No	189	31	0	35	35	132	70%
			……				
Yes	134	8	0	5	5	122	91%

A/T reflects the quality of construction workflow (Kalsaas 2013). Table 3 compares the A/T of the two simulation scenarios with information exchange or not.

Table 3 Summary of the A/T ratios for 20 simulations in two groups

Groups	Count	Sum	Average	Variance
No exchange	10	8.0503	0.8050	0.0086
Exchange	10	8.9580	0.8958	0.0028

An Analysis of Variance (ANOVA) is performed on the two groups of data with a null hypothesis that they have the same mean value (Table 4). The P-value is smaller than an acceptable α value of 0.05, so the null hypothesis is rejected. In other words, the added-value portion in the two groups of simulations have statistically significant differences. As a result, it can be concluded that improving information flow in construction has a positive effect on construction workflow.

Table 4 Analysis of variance of the variable - add value portion in two simulation groups

Source of Variation	SS	Degree of freedom	MS	F	P-value	F critical value
Between Groups	0.0412	1	0.0412	7.1907	0.0152	4.4139
Within Groups	0.1031	18	0.0057			
Total	0.1443	19				

CONCLUSIONS

An ABS system (EPIC 2.0) for modeling the emergence of construction workflow has been developed based on a relational data model. The system models the variability and uncertainty in construction, the information exchange between construction agents, and the changes in their perceptions of project progression that affect their decisions in task selection. The system can generate rich datasets and visualize the construction process using enhanced line of balance charts. A case study demonstrates its suitability to investigate and confirm the positive effects of information transparency on the construction workflow performance.

The system can perform more complex simulations than the example project by changing the parameters such as more agents, more complex task dependencies, higher task granularity etc. The data model can also be extended to incorporate additional aspects of the construction workflow, such as individual utility motivated decision-making, dynamic material supply, learning curves in productivity etc., by adding new fields to the data model. These are the focus of future research, and the simulation system needs to be tested in a real project.

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REFERENCES

Amaratunga, D., Baldry, D., Sarshar, M., and Newton, R. (2002). "Quantitative and qualitative research in the built environment: application of “mixed” research approach." *Work study*, 51(1), 17-31.

Azhar, S., Ahmad, I., and Sein, M. K. (2009). "Action research as a proactive research method for construction engineering and management." *Journal of Construction Engineering and Management*.

Ben-Alon, L. (2015). "Simulating and Visualizing the Flow of Trade Crews using Agents and Building Information Models." MSc, Technion.

Brodetskaia, I., Sacks, R., and Shapira, A. (2013). "Stabilizing Production Flow of Interior and Finishing Works with Reentrant Flow in Building Construction." *J. Constr. Eng. Manage.-ASCE*, 139(6), 665-674.

Howell, G. A. "What is lean construction-1999." *Proc., Proceedings IGLC*, Citeseer, 1.

Kalsaas, B. T. (2013). "Measuring waste and workflow in construction." *Proceedings IGLC21. Fortaleza, Brazil*.

Kim, K., and Kim, K. J. (2010). "Multi-agent-based simulation system for construction operations with congested flows." *Automation in Construction*, 19(7), 867-874.

Koskela, L. (2000). An exploration towards a production theory and its application to construction, VTT Technical Research Centre of Finland.

Laufer, A. (1997). Simultaneous management: Managing projects in a dynamic environment, Amacom.

Macal, C. M., and North, M. J. "Agent-based modeling and simulation." *Proc., Winter simulation conference*, Winter Simulation Conference, 86-98.

Sacks, R., Esquenazi, A., and Goldin, M. (2007). "LEAPCON: Simulation of lean construction of high-rise apartment buildings." *J. Constr. Eng. Manage.-ASCE*, 133(7), 529-539.

Sacks, R., Gurevich, U., and Belaciano, B. (2015). "Hybrid Discrete Event Simulation and Virtual Reality Experimental Setup for Construction Management Research." *Journal of Computing in Civil Engineering*, 29, 04014029.

Sanchez, S. M., and Lucas, T. W. "Exploring the world of agent-based simulations: simple models, complex analyses: exploring the world of agent-based simulations: simple models, complex analyses." *Proc., Proceedings of the 34th conference on Winter simulation: exploring new frontiers*, Winter Simulation Conference, 116-126.

Sawhney, A., Bashford, H., Walsh, K., and Mulky, A. R. "Agent-based modeling and simulation in construction." *Proc., Simulation Conference, 2003. Proceedings of the 2003 Winter*, IEEE, 1541-1547.

Tah, J. H. (2005). "Towards an agent-based construction supply network modelling and simulation platform." *Automation in Construction*, 14(3), 353-359.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999). "Parade game: Impact of work flow variability on trade performance." *Journal of construction engineering and management*, 125(5), 304-310.

Watkins, M., Mukherjee, A., Onder, N., and Mattila, K. (2009). "Using agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions." *Journal of Construction Engineering and Management*, 135(7), 657-667.