UNDERSTANDING LABOUR PRODUCTIVITY AS AN EMERGENT PROPERTY OF INDIVIDUAL AND CREW INTERACTIONS ON A CONSTRUCTION SITE

Matt Watkins[1], Amlan Mukherjee[2], Nilufer Onder[3] and Kris G. Mattila[4]

ABSTRACT

The construction site is a complex system composed of interactions in space between individual crewmembers and crews. Congestion often leads to lowered productivity. Lean construction research has shown that effective work flow management can improve construction labour performance, and labour flow contributes to lean work flow. The existing body of research in the study of construction labour productivity has primarily used a top-down approach to modelling and understanding the impacts of space congestion on labour productivity. In this paper, we propose a bottom-up approach and explore whether labour productivity on a construction site can be treated as an emergent property resulting from interactions between individual crewmembers and different crews. We present our pilot implementation and initial results depicting the relative value of various areas of space and the effect of the number of available tasks on congestion.

KEY WORDS

Agent Based Modelling, Productivity, Space Allocation

INTRODUCTION

Research in lean construction and the allied field of labour productivity has shown a strong dependence between work flows on a job-site and labour flow (Ballard and Howell 1998) and identified that variability in labour productivity can be reduced by appropriately matching labour resources to the available work to be performed (Thomas 2000). Congestion is one of the factors that reduces workflow and negatively affects productivity. The existing body of productivity research focuses on empirical relationships that aim to associate worker efficiency to space needed per person. It uses a top-down approach to modelling and understanding the impacts of space congestion on labour productivity are used widely. In a top-down approach, workers are not identified as individual entities with individual production rates, but as a resource with expected average production rates that are inevitably variable. For example, Thomas and Horman (2006), recognize that for maximum efficiency, craftsmen need between 250-300 ft^2 (77-92 m^2) per person. This value is calculated by averaging the number of people over the area of the entire site. This measure does not reflect concentrations of labour in isolated

[1] Graduate Research Assistant, Department of Computer Science, Michigan Tech. USA Phone +1 906-487-1952, mtwatkin@mtu.edu

[2] Assistant Professor, Department of Civil and Env. Engineering, Michigan Tech.. USA Phone +1 906-487-1952, amukherj@mtu.edu

[3] Associate Professor, Department of Computer Science, Michigan Tech.. USA Phone +1 906-487-1641, nilufer@mtu.edu

[4] Associate Professor, Department of Civil and Env. Engineering, Michigan Tech.. USA Phone +1 906-487-2523, mattila@mtu.edu

locations, often resulting in work areas that are highly congested even though the space per capita is quite high. Hence, further research is needed to measure or understand the impact of congestion on worker productivity, worker flow and by association, work flow on a construction site.

Agent based modelling (ABM) is a computer simulation technique that allows the examination of how system rules and patterns emerge from the behaviours of individual agents (Epstein and Axtell 1996). ABM creates artificial agents that represent individuals that have the ability to perceive and interact with each other and their environment. It is a suitable tool to describe the behaviour of complex systems as it employs a "bottom-up" approach to capture the interactions between individual agents, recognizes each entity as heterogeneous rather than identical, and allows the agents to dynamically evolve and adapt. This is in contrast to traditional, "top-down" models that predict the expected behaviour of a system as an aggregate of individual behaviours. Thus, the ABM approach to describing a complex system is based on the assumption of distributed control rather than one of central control.

Using the existing body of research as a point of departure, we explore the following question: can worker productivity be modelled as an emergent property on a construction site, dependent on interactions between individual workers and crews as they interact with each other for shared resources? We use agent based modelling methods to simulate space congestion on a construction site and to explore the impacts of individual interactions on productivity and labour flow. This is motivated by the fact that space is a shared resource on a construction site and congestion has a negative impact on labour efficiency.

SYSTEM DESIGN

We have used an agent-based model in which we represent each worker and task as an autonomous agent. The agents are placed in a regular grid representing the environment in which they interact. Each agent occupies one square of the grid, and interacts with neighbouring agents based on a simple set of rules defined as follows:

- There can be two kinds of agents: workers and tasks.
- There can be two kinds of workers: skilled and helper.
- Each task is ascribed a number representing how much work needs to be done to complete the task.
- Each worker is ascribed a skill level, each of which is chosen independently from a normal distribution.
- A worker with a higher skill value will complete a larger portion of a task than a worker with a lower skill value.
- A separate value, productivity, is maintained for each worker, representing what percentage of the worker's expected productivity is achieved. It can be thought of as the efficiency of the individual workers at a micro-level, but in order to keep the emergent essence of this system, we are considering it simply as an indicator of the variability in individual productivity.

- The overall worker productivity is defined as the average of individual worker productivities.
- Multiple worker agents may occupy the same grid square.

The environment in which the agents function is defined as follows:

- A planar grid represents the floor space of a construction site (Figure 1).
- Agents occupy squares on the grid. Each square is labelled by the type of the agent that occupies it.
- An agent's neighbourhood is given by a Von Neumann grid of range r.

The Von Neumann neighbourhood is a diamond-shaped neighbourhood (Figure 2) that can be used to define a set of cells surrounding a given cell (x_0, y_0) which is occupied by an agent. The Von Neumann neighbourhood *N* of range *r* surrounding a cell (x_0, y_0) is defined by:

$$N((x_0, y_0)) = [(x, y) : |x - x_0| + |y - y_0| <= r] \quad (1)$$

Figure (2) illustrates Von Neumann neighbourhoods of ranges r=1 and r=2. The productivity of an agent is negatively impacted when there is congestion in its neighbourhood of range r=3. The number of cells in a neighbourhood of range r, including the cell occupied by the agent (x_0, y_0) is given by equation 1.

$$2\, r\, (r + 1) + 1 \quad (2)$$

As the scheduled work proceeds, we simulate interactions between the agents based on a set of interaction rules, and study the net productivity on site as an emergent property. Agent interactions are based on the following premises:

- Skilled Workers in a congested area have reduced outputs than workers have in less congested areas. Each iteration of the simulation, each worker's productivity is updated on the according to the following formula, with c_1 being a project specific parameter:
- $$\prod_{Helpers}\left[1+\frac{prod * skill}{dist}\right] * \prod_{SkilledWorkers}\left[1-\frac{c_1}{dist}\right] \quad (3)$$
- Higher values of c_1, means that congestion affects workers more. The value of this constant ideally will be based on empirical studies.
- Helpers are less effective if there are too many around. At each iteration, a helper's productivity is updated according to the following formula, with c_2 being a project specific constant:
- $$\prod_{Helpers}\left[1-\frac{c_2}{dist}\right] \quad (4)$$
- Greater values of c_2, means that congestion affects helpers more.

- A skilled worker is defined as idle if the worker is not currently working on any task. During each iteration, if the worker is idle, the worker will find the nearest task (if it is a skilled worker) or skilled worker (if it is a helper) that needs work, and will target that agent.
- If a worker has a target but is not adjacent to the target agent, then the worker will move one square toward that agent.
- If a worker is adjacent to a targeted agent, then the worker will either complete a portion of the task (if it is a skilled worker) or boost the productivity of a skilled worker (if it is a helper).
- The amount of work completed on a targeted task each iteration by a skilled worker is: skill * productivity.

VALIDATION

In order to run the simulation, values for c_1 and c_2 must be selected. These two values should ideally be selected based on observed data. They should be selected such that the difference between productivity measured from a construction site and productivity measured from a corresponding simulation are minimal.

Developing and validating the simulation will require two distinct sets of data. Selecting c_1 and c_2 is akin to training the model and does not test its predictive power. The second data set can be used to validate the model. The model must predict the values for new data that has not been used in generating the model before it can be considered validated.

PRELIMINARY EXPERIMENTS

Based on the above definitions, we conducted a simulation for two masonry crews intersecting in space. Each crew consists of 3 brick layer agents and 2 helper agents as shown in Figure (1). The bricklayer agents are designated with the letter S, and the helpers with the letter H. The masonry walls that are being installed are designated by the letter W. The user interface shows two graphs on the right hand side of the grid. The top one shows the productivity over time for an individual agent, which is selected by clicking on its grid square. The bottom graph shows the average productivity of all worker agents in the simulation. In this implementation, the average productivity is scaled to unity and is essentially the same as average efficiency. This relative measure was used in this simulation as preliminary emphasis is on reproducing emergent productivity trends. In the future, when this simulation is used with production rates from real project data, the plots will reflect expected production rates.

The simulation explores the relative importance of space on a construction site in the face of crews interacting in space as the project progresses. In the simulation, as the labourers proceeded around the outer wall and constructed it, the centre of the room was never used. This shows that for the purposes of modelling the congestion in this particular simulation, the centre of the room is unimportant. Likewise, if a piping crew were laying pipes in the centre of the room, the edges of the room would be unimportant in computing their lost productivity due to congestion. However, if both crews needed a particular area, then congestion would be very high as the both the spaces would have very high value, and the crews would have more interactions resulting in greater congestion. This observation leads us to conclude that the value of space on a site is not the same everywhere. It is highest in the areas of highest work concentration.

Figures (3a) and (3b) show the tracking system based on equations (2, 3 and 4) at the end of the simulation. This data represents the productivity at each step of the simulation, as shown on the *time* axis of the graphs. During the simulation, a drop in the productivity of an individual agent as seen in figure (3a) is reflective of loss due to congestion. A drop in productivity in figure (3b) reflects reduced net productivity over the entire simulation. There is a notable dip towards the end of the simulation. This leads to another important result: as the simulation draws to a close, while there is a smaller quantity of work left most of it is concentrated in the same area. Thus, as the number of incomplete tasks decrease, congestion increases, and the overall productivity on site goes down resulting in a drop off in the both the productivity charts. At this time, the value of space is very high in the immediate vicinity of the work left and almost negligible elsewhere. In complex projects with varying space demands and multiple crews moving around, such a simulation can be very effective in dynamically allocating value to available space as the project proceeds. In future, this simulation is expected to provide scheduling strategies for managers by allowing them to apprehend where congestion is likely to occur and devise alternative starting points which will avoid congestion during and specifically towards the end of the project.

This simulation was also intended to study the effects of the sizes of labour crews on productivity. In the current implementation, the skilled workers proceed toward the wall, and complete their nearest tasks. Then, the agents on the right start working on the wall to the right, while the left-most agents move to the left. This divides the group, and is not something that would happen in a real construction environment. Further advances in the simulation will be needed to avoid unrealistic situations.

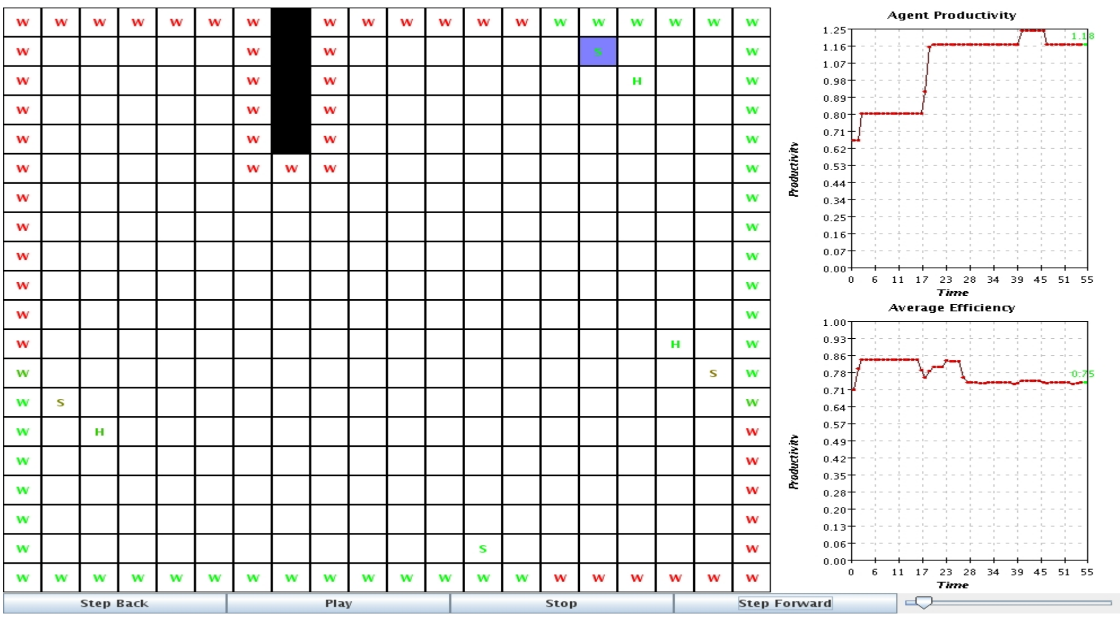

Figure 1: The grid representing the agents' environment

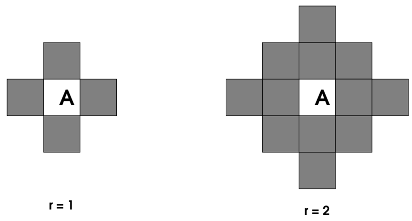

Figure 2: Von Neumann neighbourhoods of range 1 and 2

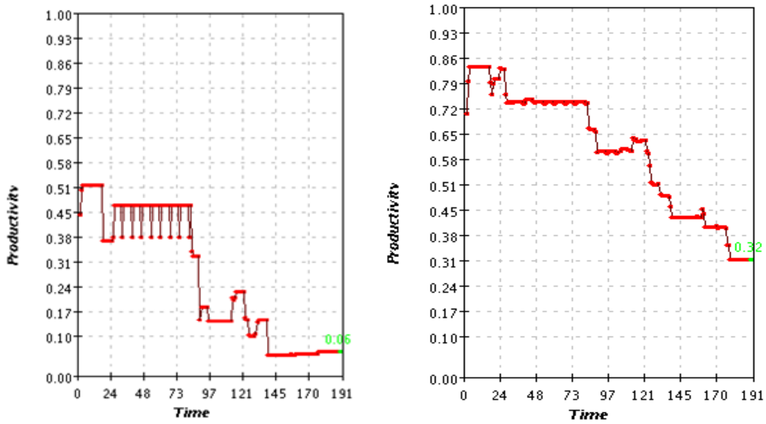

Figure 3: (a) Trace of a particular agent’s productivity and (b) trace of average productivity of all agents

CONCLUSION

In this paper, we have explored if construction labour productivity can be modelled as an emergent property using an agent based simulation. The preliminary experiments conducted show that the current framework can be used to model the impact of congestion on labour productivity. Future research will further validate the model by using comparing construction site productivity with simulated productivity and congestion related inefficiencies. This paper is a first step in that direction.

REFERENCES

Ballard, G. and Howell, G.A. (1998) ``What Kind of Production Is Construction?" Proceedings IGLC 1998.

Epstein, J.M. and R. Axtell (1996) Growing Artificial Societies, MIT Press, Cambridge MA.

Thomas, H.R. (2000) “Schedule Acceleration, Work Flow, and Labour Productivity” *Journal of Construction Engineering and Management*, Vol. 126, No. 4, July/August 2000, pp. 261-267.

Thomas, H.R., and Horman, M.J (2006) “Fundamental Principles of Workforce Management” J. Constr. Engrg. and Mgmt., Volume 132, Issue 1, pp. 97-104.

Thomas, H.R., Riley D.R., Sinha S.K. (2006) ``Fundamental Principles for Avoiding Congested Work: A Case Study," Practice Periodical on Structural Design and Construction, Vol. 11 (4) November 2006, pp. 197-205.