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QUANTIFYING THE IMPACT OF CONGESTION ON CONSTRUCTION LABOR PRODUCTIVITY USING AGENT-BASED MODELING

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Several findings from the construction field stipulate that productivity falloffs are primarily management-related; however, this notion does not consider the direct impact of these same management decisions on the workers themselves. For instance, the planning of the workspace layout delves in a spatial configuration which if not properly managed can potentially result in congestion that, in turn, directly affects labor productivity. Previous research efforts developed models to analyze the effect of congestion on labor productivity but failed to capture all the complexities of this mechanism and its dynamics. Therefore, this paper puts forward the groundwork of an agent-based simulation model (ABM) and presents work targeted at quantifying the impact of congestion on the productivity of construction crews. More specifically, the ABM model takes into account two construction trades working in the same area and tackles five scenarios each depicting different congestion and interaction levels. At the heart of this simulation is a quantitative model that defines essential congestion metrics and outputs space interference values. Experiments were conducted and results highlighted that the higher the space interference values the less productive the crews become. Additionally, these values will constitute an integral part in future work when studying the impact of congestion on the crews' learning curve, whereby the latter being a major gauge for levels of productivity.

Keywords: Management, Site layout, Spatial configuration, Space interference, Crews' interaction, ABM.

1 INTRODUCTION AND BACKGROUND

Site congestion has mainly been associated with stacking of trades, lack of space on confined sites, ineffective workforce management, mismanagement of material delivery and storage, out-of-sequence work, and poor waste management on site (Thomas and Ellis Jr 2017). For instance, stacking of construction trades happens whenever multiple tradespeople work simultaneously in a single work area. It is a common secondary action taken by contractors using overmanning to speed up the schedule, although it sometimes takes place under normal schedule (Reichard and Norwood 2001). However, crews need enough room to comfortably maneuver and work with their necessary tools, material, and equipment. Therefore, stacking of trades creates congestion and crew interferences negatively impact productivity (Hanna *et al.* 1999).

On the other hand, prior research efforts studied the issue of workspace availability as a new decision factor for establishing the construction schedule (Thabet 1992). A scheduling model was developed to quantify workspace parameters for any activity (i.e. space demand and space availability/supply). The developed model also provided a procedure to compare the space demand and supply in order to sequence construction activities. Furthermore, Mallasi (2006) and Dawood and Mallasi (2006) introduced the Critical Space-Time Analysis (CSA) concept to quantify the congestion degree between the overlapping workspaces, and visualize workspace congestions in architectural projects. Watkins *et al.* (2009) used agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions. The goal of the latter work was to efficiently utilize construction space and develop plans and schedules that account for congestion arising from crew interactions in a given space. Another research work discussed spatial demand and supply from the perspective of construction operators and a modeling methodology based on spatiotemporal utilization was proposed (Chua *et al.* 2010). Pradhananga and Teizer (2014) developed a cell-based continuous simulation model to quantify congestion for operations in which equipment move continuously.

Therefore, previous research efforts developed models to either quantify congestion or analyze its effect on labor productivity. However, no single work attempted at quantifying the impact of congestion on labor productivity while capturing all the complexities of this mechanism and its dynamics. This paper, on the other hand, uses the agent-based modeling (ABM) technique (Bonabeau 2002) to simulate spatiotemporal interactions of activities and study how resulting congestion can impact construction productivity. Additionally, the proposed ABM model studies the interactions in a granular fashion for each activity block rather than for the whole activity.

2 METHODOLOGY: IMPLEMENTING THE ABM MODEL

2.1 Underlying Quantitative Congestion Model

The quantitative model of congestion adopted throughout this study is inspired from the work by Yeoh and Chua (2010) that quantifies workspace congestion based on the concept of space and time utilization or space-time-volume. In this case, the congestion factor, represented in Eq. (1) by an index called “dynamic space interference” (DSI), measures the extent to which a work operator can accommodate the interferences due to other activity workspaces.

$$DSI_A = \rho_A + \sum_i \rho_i \times \frac{s_{iA} t_{iA}}{s_A t_A} \quad (1)$$

More specifically, Eq. (1) consists of two parts whereby the first part (ρ_A) is the individual spatio-temporal utilization factor of the activity, while the second part is an incremental component that includes the effect of interfering space entities. More details on the adopted quantitative congestion model can be found in Chua *et al.* (2010). In this study, it was assumed that the absence of congestion corresponds to a DSI value of 0.85 and its presence corresponds to DSI values greater than 0.85 and, as such, require greater attention from the construction manager (Yeoh and Chua 2012).

2.2 Agents, Environment, and Interaction Rules

In this study, two different trades were considered to perform and execute tiling and false ceiling activities in a research office area of (8m x 40m). As such, two active agents, namely the ceiling and tiling crews, were modeled to interact in this environment. The tiling crew consists of one skilled worker and one helper performing 20 m^2/day, while the false-ceiling crew consists of two skilled workers completing 25 m^2/day. The durations of both tiling and false-ceiling were set to 13 and 10 days respectively. This construction environment was chosen as it can witness workspace conflicts and interferences.

Furthermore, in order to better mimic the various management decisions that can possibly take place in reality, the model was designed to allow the user to select out of five different scenarios that may occur on the construction field. In this case, each scenario delineates the path along which each trade moves to complete the tasks and, as such, presents a different congestion level whenever the two activities get close to each other from any direction. These scenarios were established by consulting with construction professionals while taking into consideration work continuity. Figure 1 illustrates the layout adopted for one of the designed scenarios, whereby both crews follow the same path/direction of work. More specifically, the tiling crew goes first and the false-ceiling crew, having higher productivity, is assumed to overlap with the other crew and create congestion around blocks H and I and towards the end.

Scenario 1: Tiling and False-Ceiling paths.

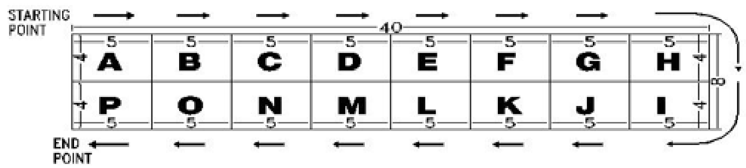

Figure 1. Case study layout.

It is worth mentioning that, within the proposed model, the user can opt to select the operating space and the total boundary comfort space for both activities. The operating space is the actual space needed to perform the activity while the comfort space is the total area depicting the entire activity (i.e. operating space) in addition to path spaces, on-site inventory (i.e. material storage area), and a safe/comfortable distance between the current activity's crew and all other neighboring crews. In fact, beyond that safe distance, comfort space interferences are likely to happen and trigger congestion at different locations which would impact work efficiency and, in turn, would negatively impact labor productivity. As such, in this study, reasonable operating space for a certain working area could be taken as a 0.7m offset from the working area boundaries while the comfort space can be assumed to extend an offset of 2m from the working area boundaries. Nonetheless, the model is flexible enough to allow the user to compare results based on various offset values.

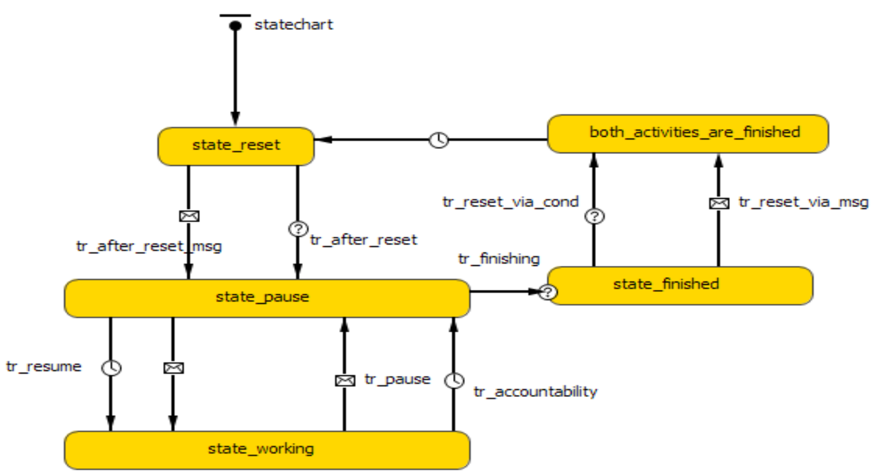

Figure 2. State-chart of the false-ceiling agent.

Figure 2 illustrates the ABM state-chart of the ceiling agent. A similar state-chart is also constructed for the tiling agent to allow interaction between the two activities depending on the selected scenario.

The state-chart provides a (*state_pause*-*state_working*) loop that is created to complete all iterations of a certain path before the activity finishes (i.e., *state_finished*). The ABM simulation generates specific congestion DSI values for each unit block in the layout (Figure 1) given a particular activity and at a specific time and location. When both activities are completed (i.e. *both_activities_are_finished*), DSI values generated, and congestion levels analyzed, the user can then run another scenario or path.

It is good to note again the contribution lying in the proposed ABM model that represents each activity block by a generalized DSI value to portray overall congestion, unlike previous studies that only represented the whole activity (Chua *et al.* 2010).

3 RESULTS AND ANALYSIS

Table 1 illustrates the DSI values output from the ABM model for each activity (i.e., Tiling, T or Ceiling, C) and varying according to the degree of congestion established under each of the five designed scenarios (i.e., S1-S5). Furthermore, every experimental scenario includes sixteen iterations for each activity, whereby each iteration represents a different block depending on the path followed in each scenario.

Table 1. DSI values output from the ABM simulation.

	DSI Values									
	S(1)		S(2)		S(3)		S(4)		S(5)	
Iteration	T	C	T	C	T	C	T	C	T	C
1	0.799	0.799	1.331	1.331	0.799	0.799	0.799	0.799	0.799	0.799
2	0.746	0.746	1.203	1.241	0.746	0.746	0.746	0.746	0.799	0.799
3	0.746	0.746	1.162	1.173	0.746	0.746	0.746	0.746	0.746	0.746
4	0.746	0.746	1.121	1.137	0.898	0.746	0.898	0.746	0.746	0.746
5	0.746	0.746	1.080	1.101	0.746	1.023	0.799	0.799	0.746	0.746
6	0.746	0.746	1.040	1.066	0.746	0.746	0.746	0.746	0.746	0.746
7	0.746	0.746	0.999	1.030	0.746	0.746	0.746	0.746	0.829	0.746
8	0.799	1.331	0.799	1.118	0.799	0.799	1.175	0.746	0.746	0.746
9	0.816	1.012	1.018	0.799	0.799	0.799	0.746	0.802	0.746	1.078
10	0.835	0.995	0.876	0.746	0.746	0.746	0.746	0.912	0.974	0.746
11	0.990	1.078	0.835	0.898	0.829	0.746	0.746	0.746	0.746	0.746
12	1.078	1.161	0.794	0.852	0.760	0.746	0.799	0.799	0.746	0.746
13	1.182	1.244	0.753	0.817	0.746	0.746	0.746	0.746	0.746	0.746
14	1.285	1.327	0.746	0.781	0.746	1.078	0.746	0.746	0.746	0.746
15	1.389	1.410	0.746	0.746	0.746	0.746	0.746	0.746	0.799	0.799
16	1.597	1.597	0.799	0.799	0.799	0.799	0.799	0.799	0.799	0.799

In order to analyze the obtained DSI values and relate them to labor productivity, several interviews were conducted with construction project managers and practitioners, resulting in the fifth-degree polynomial curve (R^2 value= 0.998) depicted in Figure 3 that mainly reflects a decline in productivity for a construction crew as congestion increases (i.e., DSI increases).

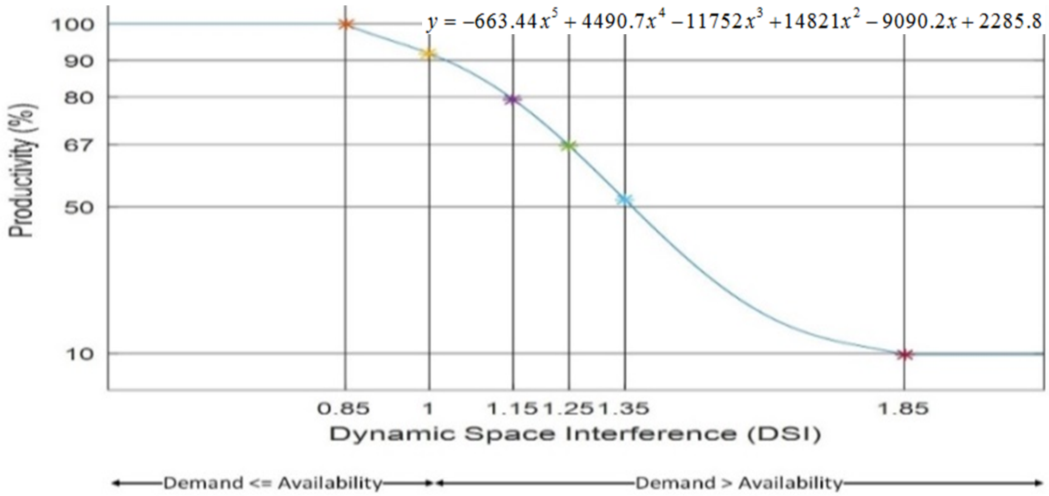

Figure 3. Productivity-DSI curve.

Accordingly, obtained DSI values (Table 1) ranging from 0.85 to 1.15 reflect acceptable levels of congestion that typically take place in the construction industry and a productivity level ranging from 80-100%. On the other hand, values ranging from 1.15 to 1.35 are considered critical and alarming values that require serious attention from site engineers. The upper bound of 1.35 is considered the maximum tolerable congestion value beyond which productivity is reduced by 50% compared to its initial value. Furthermore, DSI values above 1.35 represent severe congestion levels and drop in productivity that may lead to inefficiencies in workflow/labor-flow, bottlenecks, interruptions, etc.

4 CONCLUSIONS AND FUTURE WORK

This paper aimed at quantifying the impact of workspace congestion on construction labor productivity using agent-based simulation. More specifically, the ABM model takes into account two consecutive trades working in the same area and tackles five scenarios depicting different congestion and interaction levels based on spatial interferences among activities. The outcome of this paper supports the fact that unnecessary congestion and workspace conflicts can be minimized or alleviated by taking better planning/management actions, which, in turn, positively affect labor productivity.

Future work will further develop the ABM model to:

1. Show the impact of congestion on the crew learning curve through a mathematical function.
2. Calculate the individual duration timeouts for all iterations using different learning curve models and consequently obtain the overall cumulative timeout for each scenario.
3. Conduct different simulation experiments using factors that affect positively and negatively the learning rate.

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