Congestion Analysis for Construction Site Layout Planning using Real-time Data and Cell-based Simulation Model

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ABSTRACT

Simulation models are typically developed for construction operations to maximize output of resources and minimize operational cost. Traditional simulation methods deal with development of activity cycle diagrams based on key activities in construction operations. These methods do not consider spatial constraints at the site directly. As a result, spatial conflicts occur and desired output level is not achieved. Congestion analysis in construction site layout planning depends upon such spatial constraints and movement of resources inside the site. This research implements a cell-based simulation model with spatial consideration for construction site layout planning. The objective of this research is to incorporate congestion analysis into simulation process to improve construction site layout plan. A case study is done involving cyclic earthmoving operation. Location data from moving equipment is collected using Global Positioning System for accurate spatial reference. Real data from site is fed into simulation model for realistic representation of the operation. A cell-based continuous simulation model is developed for visualizing congestion. A new method of quantifying congestion is proposed. This method will help decision makers in developing site layout plan based on movement of resources. Potential of congestion can be determined before implementing a layout onto the site. It will aid in comparing alternative site layout plans and provide insight on consequences of varying the number of resources on site congestion. It will also serve as a training and educational tool for construction managers.

INTRODUCTION AND BACKGROUND

In urban construction sites, space is a major constraint. Multiple crews work simultaneously and share same working space and driveways. Especially, in outdoor construction operations, heavy equipment are involved, which have high operation costs. Resource optimization becomes critical for maximizing output and minimizing cost in such cases. Isolating a crew can help in optimizing output for a particular crew but when a work space is shared among multiple crews, desired output might not be attained because of interference and external influence of other crews. For instance, in terms of earthmoving operation, keeping the dump trucks moving is a key to maximize output and avoid congestion at site. But, multiple trucks are loaded by same excavator and they have to wait till the excavator is available to load. In this case, congestion is caused by the members of same crew, which affects the overall output of the crew. On the other hand, continuous movement of trucks on the driveway causes congestion for other crews sharing the same driveway. Congestion, here, means the condition where an equipment has to wait for other equipment for space to perform its regular operation.

Current methods of construction operation and congestion analysis rely on manual observations. Such methods are error prone, consume resources and subjected to human judgment. The decisions are based on incidents occurred at the time of observation which might not represent the actual site condition. Since the judgment parameters cannot be quantified, decisions are highly subjective. A method of avoiding such problems is continuous data collection on site using real-time sensors (Pradhananga and Teizer 2013). Automated operation analysis can accurately determine the actual site conditions. The results of such analysis can be used for planning and decision making process.

Simulation is a proven method for planning and resource optimization. Haplin (1977) developed CYClic Operations NEtwork (CYCLONE) for modeling cyclic construction operations. Newer tools like State and Resource Based Simulation of Construction Processes (STROBOSCOPE) (Martinez 1996) and Simphony (Hajjar 1999) are based on similar concept of Activity Cycle Diagram (ACD). Kamat and Martinez (2001) developed a tool to visualize simulated processes in 3D and detect potential hazards based on results of such ACDs. But these methods are not able to take space into direct consideration and rely on subsidiary methods to represent space constraints.

Spatial simulation for building components have been studied in much detail. Akinci and Fischer (1998) developed a time-space conflict analysis tool to simulate spatial requirements of different construction activities. A method involving sequence of crew acting on geometric work locations was proposed by Akbas (2004). Recent developments include use of Partial Model Qurey Language to incorporate spatial requirements in constraint-based simulation (Marx and König 2013). These researches deal with building components instead of spatial simulation of moving resources.

Zhang et al. (2007) proposed a modelling approach using Cell-based Discrete Event Systems Specification (cell-DEVS) approach. This study considered a bridge re-decking process involving moving resources. Hammad and Zhang (2011) implemented real-time data into construction simulation for collision detection purpose. A method of studying and quantifying congestion on site due to moving equipment is lacking. Such a method will help in planning site layout and making decision on spatial scheduling of crews based on potential interference to each other. Simulating multiple crews together will provide a better judgment on what level of output can be obtained in given site condition, considering that the crews will struggle with each other for shared space and driveways.

OBJECTIVES AND SCOPE

This paper proposes a method of quantifying the result of congestion analysis inside a construction site. The potential of cell-based simulation model in construction operation is explored. The objective of this paper is also to build more realistic simulation model using real-time data from the actual site. The paper does not deal with development of simulation model and only utilizes the result of a case study. This method can only be used for operations in which equipment move continuously and the efficiency of the operation is directly related to the ability of the equipment to move.

CELL-BASED SIMULATION SYSTEM

Like any computational system, the simulation system also consists of three main modules, Input, Simulation and Output. The result of output is used to make revisions on resource selection and site layout plan shown by the feedback loop. These modules are briefly discussed in the following section. Figure 1 shows the conceptual flowchart of the developed simulation system.

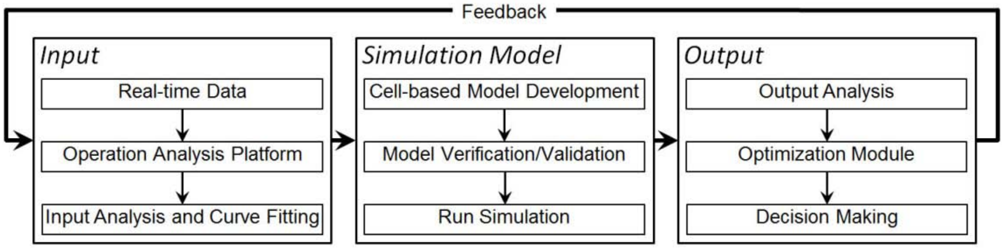


Figure 1. Conceptual model of the developed cell-based simulation system

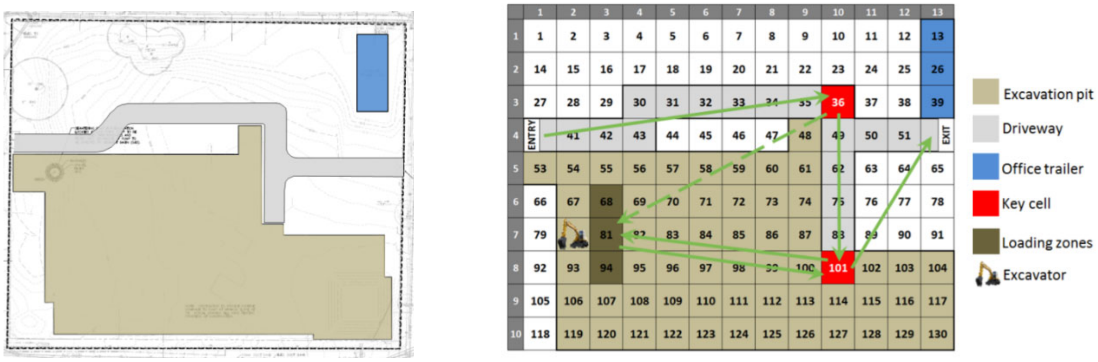
Project Description. The site for Engineered Biosystems Building (EBB) at Georgia Institute of Technology, Atlanta was considered as System Under Investigation (SUI) for validating the concept. Data collection and simulation model for developed for earthmoving operation happening at this 120m x 100m site. The site consisted of an excavation pit, driveways, material storage areas and an office trailer for site office. Figure 2 shows an overview of the construction operation. The major resources involved in the earthmoving operation were excavators and dump trucks. The dump trucks entered the site from the “Entry Point” in Figure 2 and exited the site from the “Exit Point”. They had to wait for the excavator, go down to the excavation pit and get loaded with dirt before exiting the site. The dirt was hauled to a distant site.

Figure 2. Overview of system under investigation (SUI)

Input. Real-time location data was obtained by attaching Global Positioning System (GPS) tags on excavators and dump trucks as they performed their regular operations. Data was collected during the entire excavation process which lasted for about 40 days. Daily working hours started at 6:30 AM and ended at 5:30 PM. Data was downloaded from the devices at the end of each day. The frequency of data collection was 1 Hz. Pradhananga and Teizer (2013) provides a detailed description of the devices and the automatic operation analysis tool used to identify and analyze cyclic earthmoving operation in this project. Inter-arrival times of trucks into the site and loading time for excavators were identified as two stochastic processes. After these times were obtained using the tool, the distribution was fitted to a standard distribution.

Simulation Model

Figure 3 (a) shows the site layout map of the SUI. The site is divided into different distinct zones shown in different colors. This site layout map was used as a blueprint for developing cell-based simulation model. Figure 3(b) represents the cell system that was based on Figure 3(a). The simulation system was developed in Matlab. Detail on working mechanism of cell-based model can be found in Hammad and Zhang (2011). The development of the cell-based system used in this paper has been described in detail in Pradhananga and Teizer (2014). The grid size of 9m x 9m was adapted. The choice was made based on a fact that a dump truck was about 8m in length and a cell of 9m will represent a truck and spacing between two trucks in a row. Since one cell can represent one truck or one excavator, the simulation time advanced by 3 seconds in every update. Three seconds represents the time a truck would take to cross the 9m grid at 10km/hr. A bound-horizon simulation for 8 hour period without a break was performed.



	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	2	3	4	5	6	7	8	9	10	11	12	13
2	14	15	16	17	18	19	20	21	22	23	24	25	26
3	27	28	29	30	31	32	33	34	35	36	37	38	39
4	ENTRY	41	42	43	44	45	46	47	48	49	50	51	EXIT
5	53	54	55	56	57	58	59	60	61	62	63	64	65
6	66	67	68	69	70	71	72	73	74	75	76	77	78
7	79		81	82	83	84	85	86	87	88	89	90	91
8	92	93	94	95	96	97	98	99	100	101	102	103	104
9	105	106	107	108	109	110	111	112	113	114	115	116	117
10	118	119	120	121	122	123	124	125	126	127	128	129	130

(a) (b)

Figure 3. (a) Site layout map for excavation site, (b) Excavation site divided into grids

Figure 3(b) shows the working mechanism of the cell based model. Different zones at site are marked in different colors. The ramp joining driveway and the excavation pit could only support one-way traffic. That means, when a truck is on the ramp, another truck trying to enter the ramp from opposite side has to wait till the ramp is cleared. This creates an interesting situation in the simulation model.

Output and Feedback. The result obtained from simulation run is used for future planning and decision making. It is done by simulating multiple resource combinations and site layout plans and selecting the one yielding optimum output minimizing congestion on the site. Detail on output and feedback loop is not included in this paper. A part of output is used for congestion analysis which is discussed below.

Congestion Analysis and Congestion Index. Since every movement of equipment is simulated in cell-based model, it is possible to track their movement and determine if the movement was hindered because of congestion. Dump trucks can slow down or stop while making turns or entering a different zone in the site. But they are not desired to remain stationary inside the drive way or inside the excavation pit. This means that, in ideal condition, the dump trucks should be in motion at all times inside the site except while being loaded. The proposed Congestion Index (CI) is the measure of the ratio of the number of moves that the dump trucks make in the simulation to the actual number of attempts to move. Some attempted moves cannot be made because of the neighbor cell being occupied or unavailable. Mathematically, for each dump truck,

$$CI = \frac{No.of\ successful\ moves}{No.of\ attempts\ to\ move}$$

The simulation time advances by 3 seconds in each iteration. Hence, each dump truck makes an attempt to move after every 3 seconds in the simulation model. The CI ratio provides us a number which represents the inability of the dump trucks to proceed in spite of its tendency to move forward. In the condition where CI is 0, there are no instances when the movement of dump truck is impeded by other dump trucks or equipment on the driveway. Higher the value of CI, higher the number of instances that the dump truck had to wait inside the site. The maximum value of CI is 1 in which case, the system goes into deadlock and no equipment can move. This is an imaginary case. It should be noted that only movement inside the construction site has been considered for simulation and any congestion occurring outside the site is excluded from the analysis. In this particular project, inability of the trucks to proceed might also be caused due to the ramp that connects the excavation pit to the driveway. Since the ramp only supports one-way traffic at a time, this ratio also includes the instances when a truck has to wait for another truck on the driveway to cross the ramp. CI can be calculated for individual resource or for the entire crew collectively. If a simulation is run with multiple crews working in the same area, the impact of movement of one crew to another can be quantified.

PRELIMINARY RESULTS

Real-time data for an entire day of earthmoving involving 2 excavators and 15 dump trucks was considered for input analysis. A total of 201 loads were hauled from the site on that day. Based on these 201 records, curve fitting analysis was done for inter-arrival times and loading times. A gamma distribution with shape = 1.1815 and scale = 71.2667 was fitted for inter-arrival times of the trucks. A fixed time of 36 minutes was added to each truck to compensate the time it spends outside the construction site while travelling to the dump site to complete the cycle. Similarly, a gamma distribution with shape = 0.625 and scale = 59.1485 fitted the loading times.

Simulation was run for an 8 hour period without any break. In real site, the excavator has to stop after a certain time to adjust its position and to pile up dirt. The trucks are cleaned before they leave the construction site and enter the road. These activities have also not been considered in the simulation. Three simulation runs were performed each time while gradually increasing the number of trucks in the system. Figure 4 shows the resulting number of loads that can be hauled out respective to the number of trucks. Figure 4 represents the result of total of 54 simulation runs each of 8 hour period with varying number of trucks.

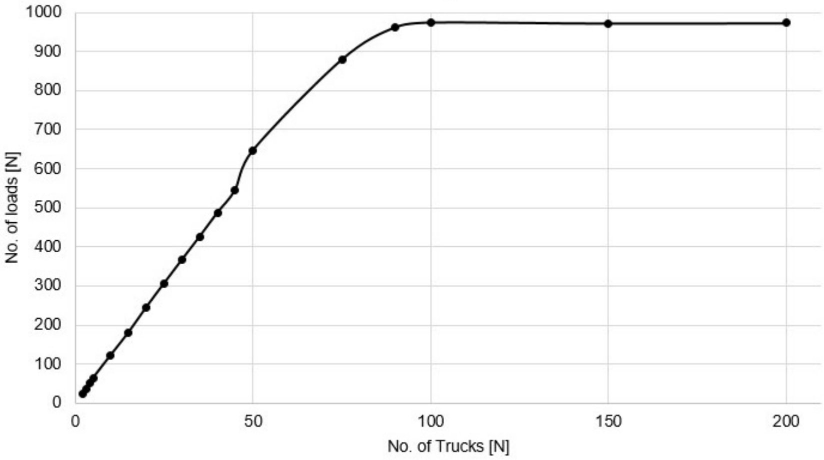


Figure 4: Effect of increasing the no. of trucks on no. of total loads hauled

It is observed that, initially, the number of loads increase with the increasing number of trucks. Later, when the capacities of the excavators are exhausted, increasing the number of trucks does not increase the number of loads. This also means that additional cost incurred on deploying the additional trucks does not yield any benefit. This is a significant part of resource optimization. Figure 5 shows similar plot for CI against the number of trucks.

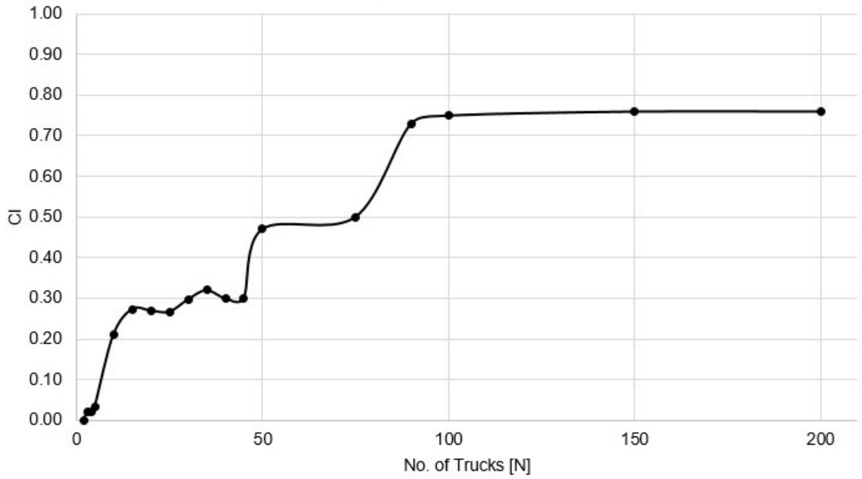


Figure 5: Effect of increasing the no. of trucks on site congestion

It can be observed that, at the point when the line gets flat in Figure 4, Figure 5 also demonstrates similar property. When we increase the number of trucks till the excavator is busy up-to its capacity, the driveway will be full of trucks waiting for the excavator. In this situation, no trucks can enter the construction site to increase the value of CI.

The plot of CI is not as smooth as the number of loads. The trucks had the tendency to travel in groups outside the site. Hence, usually multiple trucks arrive the site together and wait for the excavator. Then, after loading, the excavator stayed idle till next group of trucks arrive. A uniform distribution of inter-arrival times would yield a less congested site for the same production level but because of this tendency of the drivers, irregular congestion condition was observed at site. This might have caused the irregularity in the curve. Also, performing more number of runs for each scenario might yield a smoother curve. Each point in Figure 5 represents result of only 3 simulation runs.

CONCLUSIONS

A cell-based simulation system was developed to analyze congestion condition at a construction site. A method of quantifying congestion was proposed. Result from analysis of real data from site was fed into simulation model to leverage real-time data collection at site. It was observed that the CI can show the trend of congestion at site and on further research, has the potential to be used for site layout planning. The preliminary result only considered a single crew. The change in CI by changing the number of trucks indicates that involvement of other crews at the same place would have further increased the value of CI. A simulation model involving multiple crews interacting in the same work space should be modelled and the effect of movement of crews on other crews should be observed in terms of CI. Running simulation runs for different site layout and different number of resources will help project managers and decision makers to identify the potential spatial conflict that can affect the output of the crews sharing a work space. Best site layout plan yielding optimum output and least congestion can be chosen. It can also be used for training and educational purpose for construction managers.

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