Development of a Cell-based Simulation Model for Earthmoving Operation using Real-time Location Data

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ABSTRACT

Simulation is a proven technique for effective construction site layout planning and resource optimization. Historical data is used as input for task durations in traditional simulation approaches. This data is fed into activity cycle diagrams which do not consider spatial constraints. Cell-based simulation with real-time location data can be implemented for more realistic modeling and incorporating spatial changes on the site during project execution. Despite the potential, very little research has been done towards it. The objective of this research is to develop a framework of utilizing real-time data for spatial simulation of cyclic activities on a construction site. Continuous data was collected using Global Positioning System and cell-based simulation model was developed for spatial consideration of earthmoving cycles. The potential of analyzing and visualizing the effects of varying resource combinations on productivity and traffic congestion on site were explored. The approach will aid in increasing insight and awareness for decision making in resource management, site layout and internal traffic control plan. It will also serve as an education and training tool for project managers.

INTRODUCTION

Earthmoving operation is a classic example of construction simulation. Simulation in construction industry is done primarily to optimize resource productivity and save money. It is also done in decision making phase to estimate the number of resources needed or to schedule the operation based on available resources. Traditional way of developing a simulation model is using Activity Cycle Diagrams (ACDs). ACDs are precedence diagrams with connected nodes representing idle resources and activities (Martinez 2001). A queue of events is generated in such simulation models. The simulation is event driven and conditions are checked only when an event occurs in the queue. Such diagrams easily get complicated when the number of events increases or the numbers of conditions grow. Besides, these diagrams do not consider spatial constraints on site and tremendous effort has to be put to incorporate space as a resource in the diagrams.

In today’s construction site, space is regarded as a resource and activities need to be scheduled based on space constraints. Construction site layout planning involves identifying problems and opportunities existing in the construction site

(Ning et al. 2011). Conditions like congestion and proximity cannot be handled if spatial constraints are not taken into account. Cell-based systems have proven to be very effective for modeling complex systems involving spatial considerations (Mitchell 2009). This paper describes a methodology for developing a cell-based simulation model for cyclic earthmoving operations. There are myriads of benefits of choosing cell-based system over traditional ACDs. Firstly, cell-based systems are known for the ease in modeling complex systems. Unlike traditional simulation where the activities or resources act as entities, each cell in a cell-based system can update its state based on predefined conditions. Construction resources occupy cells in the grid and move to adjacent cells following a calculated path. The cells interact with the neighbor cells and affect their state based on the neighbors. Since spatial consideration is taken into account, location data from resources can be directly related to the cells for input analysis. Also, the entire simulation can be visualized without any additional effort as occupancy of cells directly gives the location of the resource at any given simulation time. This paper describes the procedure of developing a cell-based simulation system for an earthmoving operation. It also outlines the parameters to be considered for modeling the cells and algorithms required to program the truck load cycles.

BACKGROUND

CYClic Operations NEtwork (CYCLONE) (Halpin 1977) was developed by Halpin in 1977 specially focusing on typical cyclic construction operations. Based on similar concept, State and Resource Based Simulation of Construction Processes (STROBOSCOPE) (Martinez 1996) was developed that represented a newer generation system for construction simulation based on ACD. Other tools like Simphony (Hajjar 1999) have also been developed focusing on special purpose simulation. These systems provide services that developers can use to control different system behaviors and also provide platform for graphical representation of operations, animations and statistical tools for input and output data. However, these systems do not consider spatial constraints and spatial interactions directly. In order to overcome this, a system coupling ACD based simulation with 3D visualization for detecting potential hazards was created (Kamat 2001). The process was to use the result of ACD based simulation for visualization of operations. Although basic spatial reference was introduced to simulation, the system could not handle space optimization problems. Akbas (2004) proposed a geometry-based modeling and simulation approach for construction processes represented by triangular meshes. Elbeltagi et al. (2004) studied representation of facilities with number of grids. Their focus was both productivity and safety on site.

Cellular Automata (CA) based model are extensively used for spatial simulation. Wolfram termed CA as “A New Kind of Science” (Wolfram 2002) and it has been used to model and solve complex problems in wide variety of sciences. Wainer (2010) presented a Cell-based Discrete Event Systems Specification (cell-DEVS) in which the systems were composed of DEVS and cell-DEVS models. Zhang et al. (2007) implemented cell-DEVS modeling approach for spatially distributed resources in a construction site. Steps for creating a cell-based model were described and a case study of a bridge re-decking process was demonstrated. The case study involved removing old sections and installation of new panels. Feasibility of the approach was tested for construction environment by comparing the results to that obtained from MicroCYCLONE. Hammad and Zhang (2011) introduced a method of construction equipment collision detection by feeding real-time data into simulation model. The objective was to overcome the drawback of traditional simulation modeling that used historical statistical data instead of real data from site. Two radio controlled hydraulic crane models scaled 1:18 were tagged with UWB for feasibility study. The research only focused on collision detection and was based on cell-DEVS model.

OBJECTIVES AND SCOPE

The main objective of this paper is to demonstrate the process of development of a cell-based simulation system for a cyclic earthmoving operation. The paper also explores the potential use of real-time data in a simulation model and proposes a feedback system for monitoring and iterative planning earthmoving operation. The results from analysis of real-time data from the site are fed into the simulation system. The results from simulation are then analyzed for making decision for continuation of the operation. This paper deals only with the model development part. Input and output analysis, justification of this model and comparison of this model with traditional model are out of scope of the paper. The model development process is described as a case study. The framework can only be used for cyclic processes with repetitive interactions among same resources.

CELL-BASED SIMULATION SYSTEM

Figure 1 shows the conceptual model of the simulation system. It is constituted of three major modules, namely, Input, Simulation Model and Output, with a feedback loop. The project is first introduced and the modules are then described with major emphasis on Simulation Model.

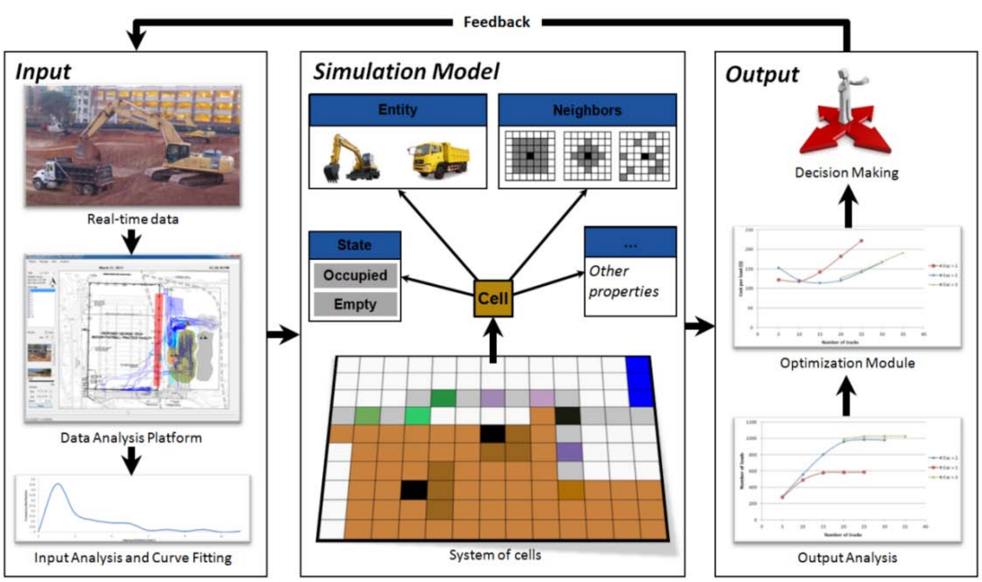


Figure 1. Conceptual model of the cell-based simulation system

Project Description

The system under investigation (SUI) is the excavation process for foundation of a building. The earthmoving operation at Engineered Biosystems Building (EBB) being constructed at the Georgia Institute of Technology, Atlanta premises is considered for this research. The dimension of the site was around 120m x 100m. The total volume of excavation was 30,600 m^3. The site contained an excavation pit, driveways, material storage areas and an office trailer for site office. The earthmoving operation involved excavators for excavating and loading and dump trucks for hauling the earth away. Figure 2 shows the site with resources involved in the operation. The dump trucks hauled the earth away to a distant site.

Figure 2. Overview of project under consideration

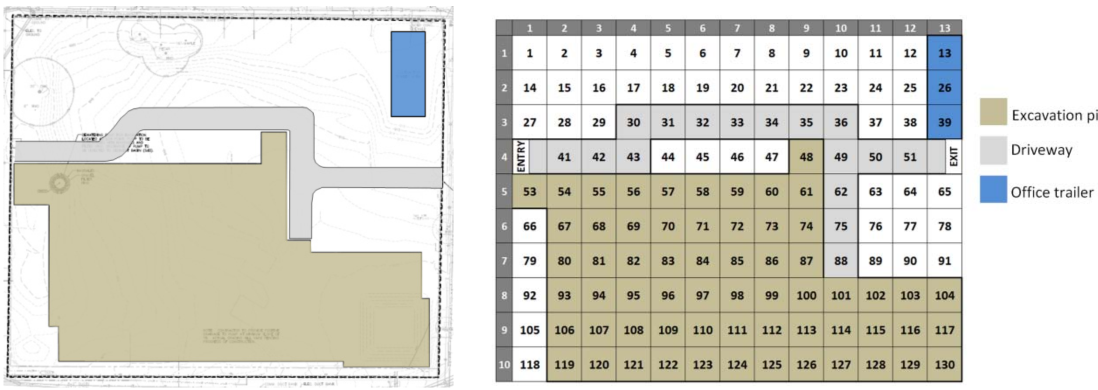
Input

Global Positioning System (GPS) tags attached to the excavators and trucks are the source of real-time data for this project. The excavators were tagged during their entire day-shift while the trucks were tagged as they entered the site and the tags were removed when they left the site. Detail about the tags and data has been described in Pradhananga and Teizer (2013). Data from the tags were downloaded at the end of each day from each resource. Data was collected at the frequency of 1 Hz. The crew started working at around 6:30 AM and stopped at around 5:30 PM. Data was collected for the entire excavation process which lasted for about 40 days.

Inter-arrival times of trucks into the site and loading time for excavators were identified as two stochastic processes. These times were calculated using algorithms developed for automatic operation analysis (Pradhananga and Teizer 2013). When all the inter-arrival times and loading times were obtained, a distribution was adapted for the data using standard curve fitting process. This distribution is utilized in the simulation model.

Simulation Model

A cell-based simulation system was developed in Matlab. Figure 3 shows the cellular layout of the site (Figure 3(b)) based on site layout map (Figure 3(a)). The cells are numbered in Figure 3(b) for ease of reference. A truck was a little more than 8m in length. Hence, the grid size was selected to be 9m x 9m considering the length of the truck and space between two trucks in a row. A truck could be represented by a single cell by doing this. Also, the average speed of the trucks on site was 10km/hr. Selecting a 9m grid implied that a truck would take roughly 3 seconds (at 10.8 km/hr) to cross a grid. The frequency of one update per 3 seconds could appropriately represent the system. The simulation to be considered was bound-horizon simulation for an 8 hour work day without break.



(a) **(b)**

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

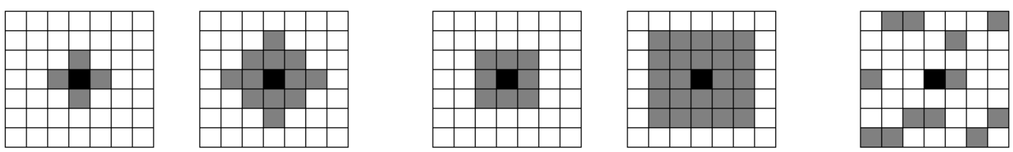
In Figure 3, different zones have been marked in different colors. The cells in white represent the part of the site where no activity occurred. Those cells never needed to be updated. The trailer area represented the office area and need not be updated as well. The excavator is located inside the excavation zone at all times. The simulation starts as the truck enters the site through Cell 40 (“Entry”). Then the truck follows the driveway to Cell 36 and down the ramp to Cell 101. From Cell 101, the truck would move to the loading area of an excavator and wait for loading. The inter-arrival times of trucks and the loading time for the excavators are the two stochastic processes in this system. The loaded truck returns to Cell 101 and then up through the ramp to Cell 52, which is the “Exit”. From exit, an inter-arrival time is assigned to the truck along with a fixed time that it would take to travel to the distant site, unload the dirt and return back to the site through Cell 40.

The interesting part of the simulation is the ramp which connects the excavation pit to the driveway entering and exiting the system. Only one truck can pass through the ramp at a given time (Cell 49 vertically through Cell 88). So, checking only the immediate neighbor could lead to head on collision of the trucks on the ramp and resulting to a deadlock. Details on how movement through the ramp has been handled are described in following sections. The capabilities of the system to handle different parameters of the cells are listed below.

Properties of the developed cell-based model

Lattice geometry: A two dimensional grid was considered for the system representing the site area and ignoring the elevation difference among parts the site. The elevation difference between the driveway and excavation pit was addressed by demarking them with different zones.

Neighborhood size: In this system, von Neumann neighborhood was assigned to the cells on driveway to prevent trucks from passing each other on the driveway. Moore neighborhood was assigned to cells on the excavation pit to allow free movement in absence of dedicated lanes. And for exceptional cells that controlled the flow of trucks from one zone to another, arbitrary neighborhood was implemented. It has been discussed in detail in following sections.



(a) von Neuman **(b) Moore** **(c) Arbitrary**

Figure 4. Different types of neighbors

Boundary conditions: Fixed value boundary condition best represented the site conditions. Periodic or reflective boundaries extend the boundary beyond the SUI which was not desired.

State set: The state of a cell was labeled “Empty” if it was unoccupied and “Occupied” if it was occupied by a truck or an excavator at a given time.

Initial conditions: The information about the zones in which the cells lie was provided through a csv file. The zones included: 0 for cell not considered for any activity, 1 for driveway, 2 for excavation pit, 3 for loading area of the excavator and 4 for the trailer. Similarly the position of the excavator and corresponding loading area was also fed into the system during initialization through a csv file.

Transition rules: Unlike direct specification or probabilistic rules, a multi-step transition rule based system was adopted. This means different ranges of cells would compute different parameters before making next move. The algorithm followed for transition rules is shown in Figure 5.

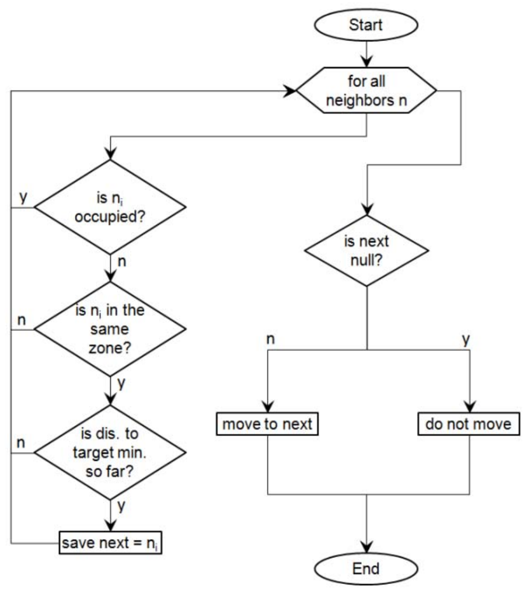


Figure 5. Algorithm for transition rule

The algorithm loops through all the neighbors of the cell into consideration. Each cell is assigned to a target cell towards which the movement is directed. For each neighbor of that cell, an occupancy test is performed to assess if the cell is already occupied. If the cell is available, a zone test is performed on the cell to confirm that the movement would be constrained to the same zone. Now, the cells passing both these test are compared for distance to the target cell. A movement is made only if moving to that cell reduces the distance towards the target. More sophisticated optimal path algorithms can be implemented in this step based on requirement. Figure 6 shows the trajectory that a truck follows in the system. Cell 36 and Cell 101 are controlling cell and are governed by special transition rules.

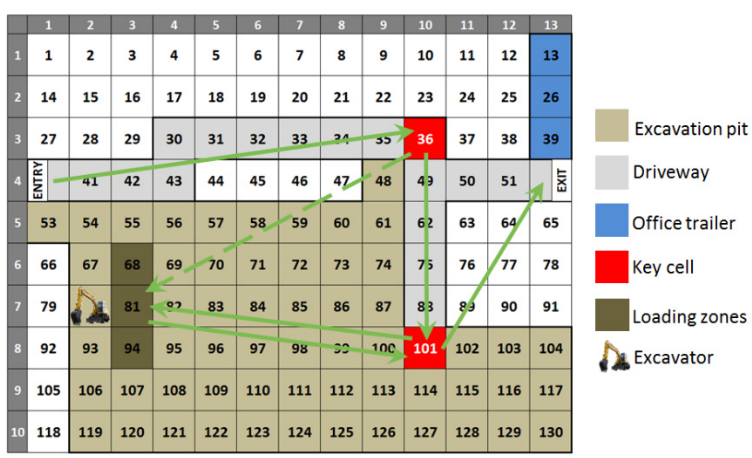


Figure 6. Grid system with transit rules

The trucks run in the system based on its origin and target. The origin and target for a truck is set by key frames. Following is the description of what happens at key cells in the system.

Cell 40("Entry"): Truck enters the system. Cell 36 is assigned as target cell.

Cell 36: This cell checks if any loading area is available around any excavator in the pit. If yes, it will check if any loaded truck is still in the pit. If a loaded truck is there, it might block the ramp in future. If no loaded trucks are inside the pit, it checks if any loaded truck is already on the ramp. If none of these are present, it will set the truck's target cell to Cell 101 and also assign a loading zone to the truck. Loading zone next to the excavator having least number of trucks around it is assigned to the truck.

Cell 101: This is the bottle neck cell which has to be passed by both empty and loaded trucks. So, before any truck enters this cell, it should be made certain that no cells are currently on the ramp in opposite direction. The truck may, however, follow another truck moving in the same direction on the ramp.

This cell also exhibits different rule for loaded and empty trucks. If an empty truck enters this cell, it will be redirected to the loading zone which has been assigned to that truck. If a loaded truck enters the cell, it will be forwarded to Cell 52, which is the exit. This is also the only cell in the system where a truck moves from one zone to another (i.e., from driveway zone to pit and back).

Cell 52: This is the exit cell. It assigns next arrival time for the truck and moves the truck out of the system. The trucks arrive at the entry cell based on the inter-arrival time assigned here.

Output

One major advantage of a simulation model is to be able to predict the productivity of the operation for different resource combination using sensitivity analysis. Productivity of an earthmoving operation can be represented by cost per unit volume hauled or number of truck loads hauled on a given day. This analysis can be used to optimize the number of resources (trucks and excavators) to minimize total cost and maximize efficiency by predicting productivity for different resource combination. The most obvious advantage of using a cell-based simulation model is the ability to visualize the simulation and observe the effect of varying parameters of the model. For e.g.; by increasing or decreasing the number of trucks or excavators, the congestions developed can be not only observed but also quantified. This can aid in detecting unforeseen conditions at site due to overcrowding and their effect on productivity can be analyzed.

Feedback

The valuable information obtained by simulating the site in different site condition is applied in future operations through a feedback loop. New decisions are implemented and real-time data is continuously collected that will further enhance the simulation system and provide better decision making capacity.

PRELIMINARY RESULT

Figure 7 shows an instance of visualization of the simulation in Matlab. Same color coding has been followed as in Figure 6. The black cells represent the excavator and cells in other colors represent trucks. Trucks next to the excavator indicate that loading activity is taking place. As the simulation time increases by 3 seconds in each step, the trucks can be seen moving from "Entry" towards the excavator through the ramp and back up to the "Exit" point cell by cell.

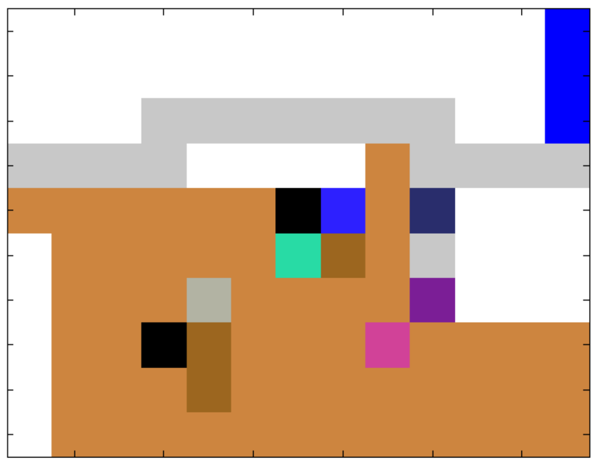


Figure 7. Simulation visualization in Matlab

CONCLUSIONS

A cell-based simulation system was developed to model cyclic activities that occur in a construction site. A method of developing cell-based simulation model was described. The capabilities of the system to handle complex system were demonstrated and the parameters of the cells were explained using a case of an earthmoving operation. The advantages of using cell-based system over traditional simulation model included easy visualization, simplicity in modeling spatial constraints (e.g.; ramp restricting the traffic flow to one-way), identifying and analyzing congestion problems and assisting in effective layout of site while optimizing productivity of the resources. The system of cells also provided full control over the flow of resources using predefined rules or algorithms. It also simplified the design process as except some special key cells, other ordinary cells follow the same rules and need not be programmed individually. Implementing real-time data into the simulation and using the feedback loop will help in creating more realistic model. Future development in this system should include multiple crews competing to share resources where the members of the crew do not interact with each other but share same workspace. Workspace conflict and effect in productivity of one crew because of congestion due to other can be analyzed for such cases. This system will help decision makers to make better decisions on resource allocation and site layout planning. It can also be used as a training tool for project managers to get familiar with effect of changing resource combinations on site.

REFERENCES

Akbas, R. (2004). “Geometry-Based Modeling and Simulation of Construction Processes”, Doctoral dissertation, Stanford University.

Elbeltagi, E., Hegazy, T., and Eldosouky, A. (2004). “Dynamic layout of construction temporary facilities considering safety”. *Journal of construction engineering and management*, *130*(4), 534-541.

Hajjar, D., and AbouRizk, S. (1999). “Simphony: An Environment for Building Special Purpose Construction Simulation Tools”, *Proceedings of the 31st conference on Winter simulation: Simulation, Volume 2* (pp. 998-1006).

Halpin, D.W. (1977). “CYCLONE: Method for Modeling of Job Site Processes.” Journal of the Construction Division- ASCE 103(3):489-499.

Hammad, A., and Zhang, C. (2011). “Towards real-time simulation of construction activities considering spatio-temporal resolution requirements for improving safety and productivity”. *Winter Simulation Conference (WSC), Proceedings of the 2011* (pp. 3533-3544).

Kamat, V. R., and Martinez, J. C. (2001). “Visualizing simulated construction operations in 3D”. *Journal of Computing in Civil Engineering*, *15*(4), 329-337.

Martinez, J. C. (1996). “STROBOSCOPE: State and Resource based Simulation of Construction Processes”, Doctoral dissertation ,University of Michigan.

Martinez, J. C. (2001). “EZStrobe: general-purpose simulation system based on activity cycle diagrams”. *Proceedings of the 33nd conference on Winter simulation* (pp. 1556-1564).

Mitchell, M. (2009). *Complexity: a guided tour*. Oxford University Press.

Ning, X., Lam, K. C., & Lam, M. C. K. (2011). A decision-making system for construction site layout planning. *Automation in Construction*, *20*(4), 459-473.

Pradhananga, N., and Teizer, J. (2013). “Automatic spatio-temporal analysis of construction site equipment operations using GPS data”. *Automation in Construction*, *29*, 107-122.

Wainer, G. A. (2010). *Discrete-event modeling and simulation: a practitioner's approach*. CRC Press.

Wolfram, S. (2002). *A new kind of science* (Vol. 5). Champaign: Wolfram media.

Zhang, C., Hammad, A., Zayed, T. M., Wainer, G., and Pang, H. (2007). “Cell-based representation and analysis of spatial resources in construction simulation”. *Automation in construction*, *16*(4), 436-448.