Sensitivity Analysis of Construction Simulation Considering Site Layout Patterns

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Abstract

This paper presents a new construction simulation approach using Cell-DEVS techniques, which allows considering site spatial constraints and the sensitivity analysis of different site layout patterns. The proposed approach includes three phases: pre-processing to configure the simulation, main-processing where the simulation is executed, and post-processing, which incorporates animation and sensitivity analysis of the results. Using Cell-DEVS modeling, spatial resource allocation, worksite layout, as well as the movement of equipment can be explicitly analyzed and visualized. Spatial conflicts can be detected, resolved, and compared based on different site layout patterns. As a result, the accuracy of simulation is improved, especially for situations where spatial conflicts are critical. A case study is presented to illustrate the procedure for modeling and analyzing the sensitivity of simulation results considering several site layout patterns. The difference between the results of MicroCYCLONE and Cell-DEVS illustrates that in some cases the impact of spatial constraints on productivity is significant and should not be neglected. Based on the present study, it has been found that Cell-DEVS simulation is an effective tool for space-related analysis in construction project.

Introduction

Discrete-event simulation has been used in construction industry to minimize cost, improve productivity, and locate the bottlenecks or overflows. Modern construction simulation tools share some characteristics: (1) They provide more flexibility in modeling complex situations and adapting to a wide range of application requirements (Martinez and Ioannou 1999). Early simulation systems, such as

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CYCLONE (Halpin 1977), are simple and effective to model most of construction operations. However, they incorporate many assumptions that may lead to incorrect or inaccurate results. Advanced simulation systems, such as STROBOSCOPE (Martinez and Ioannou 1994), allow programming to adjust to complex operations; and (2) They can consider spatial constraints. Tommelein et al. (1992) mentioned that site space is a resource that is as important as money, time, material, labor, and equipment. Therefore, good site layout is important to promote safe and efficient operations, minimize travel time, decrease material handling, and avoid obstructing material and equipment movements. Some researchers added space constraints to existing simulation systems to accommodate the dimensions required by various resources and available space on site. For example, Kamat (2003) proposed an interference detection method that can identify and report conflicts among static, dynamic and abstract construction resources. VITASCOPE (Kamat and Martinaz 2006) provides 3D animation based on the simulation data. However, work space and spatial conflicts are not explicitly represented in these simulation tools. Moreover, collision detection is checked only after the simulation using computer animation. Therefore, finding possible solutions to spatial conflicts is not integrated within the simulation. For instance, when C-Collide, an add-on in VITASCOPE, detects a spatial conflict, the simulation model has to be modified and rerun.

The authors believe that spatial constraints should be considered explicitly in construction simulation in order to allow for better support to the site layout planning process. In their previous work, the authors applied a new approach to construction simulation using Cell-DEVS models to examine the effects of spatial conflicts on productivity (Pang et al. 2006; Zhang et al. 2007). Cell-DEVS (Wainer 2002) is ideally suited to describe spatial allocation of resources because it describes cell spaces as discrete-event models using the DEVS formalism (Zeigler 1976). The previous research shows the feasibility and advantages of Cell-DEVS, such as the explicit representation of the space occupancy and the ability to find possible solutions to spatial conflicts by defining rules. Moreover, the Cell-DEVS running environment, CD++, provides a tool which can automatically animate the simulation results in 2D. The objectives of this paper are: (1) To improve this approach for more complex construction conditions; (2) To investigate the impact of different site layout patterns on productivity; and (3) To analyze delays resulting from spatial problems.

Proposed Cell-DEVS Approach

The procedure of Cell-DEVS simulation includes three phases: pre-processing, main-processing and post-processing (Figure 1). Pre-processing focuses on system modeling; main-processing focuses on site layout planning; Post-processing includes analyzing, validating and animating the simulation results. The following sections will introduce these steps briefly applied in a case study.

Case Study

The Jacques Cartier Bridge re-decking project in Montreal is used as a case study to illustrate the proposed approach. The following re-decking activities are considered: Saws were used to cut the old deck into small sections. Work teams (each including two telescopic cranes) moved to the locations of old sections, removed

them and installed new panels. Two types of trucks were used: Old section (OS) trucks transported the old sections from the bridge to the dump area, and new panel (NP) trucks transported the new prefabricated panels from the plant to the bridge. Several teams worked in parallel at different locations on the bridge during the nights of weekdays from 8:30 p.m. to 5:30 a.m. of the next day. Due to these spatio-temporal constraints, this project needed a good plan to finish on time and with high productivity. The present research examines the effect of spatial constraints by testing different resource combinations and site layout patterns.
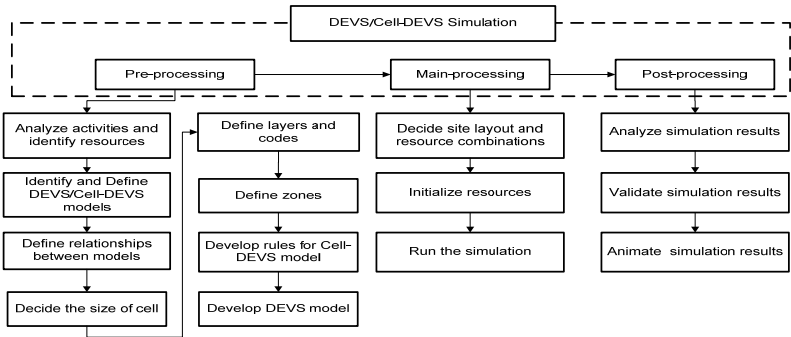

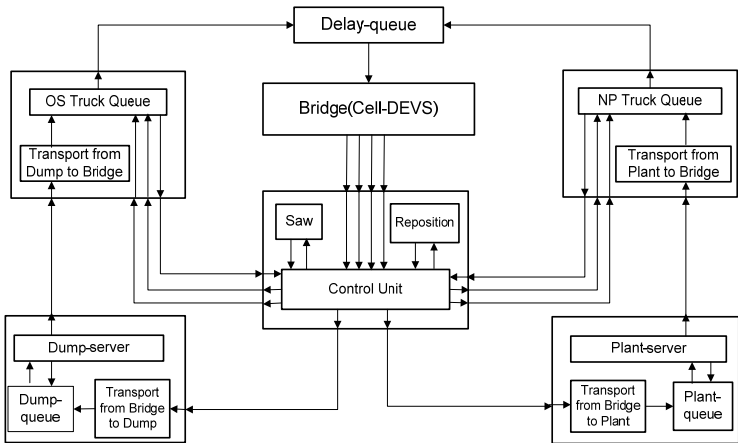Figure 1. Procedure of Cell-DEVS Simulation

Figure 2. Relationships between Models

Pre-Processing

(1) Analyze construction activities and identify involved resources. Construction activities should be broken down to recognizable construction processes according to the required level of details. Based on the activity analysis, the

available resources involved in the case study are: *Teams, Saws, OS Trucks,* and *NP Trucks*.

(2) Identify and define DEVS/Cell-DEVS models. Since Cell-DEVS models provide a virtual space to represent the worksite, they are employed where the visualization and spatial representation are emphasized. On the other hand, DEVS models are used for processes for which spatial representation is not needed. In the case study, the *Bridge* model is defined as a Cell-DEVS model because it has spatial constraints; while queues and other models that only represent time delays are defined as DEVS models. Figure 2 shows the system structure.

(3) Define the relationships between models. Models can communicate with each other through input/output ports. The arrows in Figure 2 show the directions in which messages are sent.

(4) Decide the suitable size of cells and the dimensions of each Cell-DEVS model. Different levels of details can be used to decide the size of the cells depending on the size of objects. In this case study, we defined the size of cells as 3x3 meters and the deck of the main span of the bridge is approximately represented by 200x6 cells. Cranes are represented by 3x1 cells located beside the old sections which are also represented by 3x1 cells. A truck is represented by 4x1 cells. The cell representation of the *Bridge* model is shown in Figure 3(b).

(5) Define layers and codes for each model. A layer contains the attributes of objects. Each layer describes one aspect of these attributes. In Figure 3(a), the *Bridge* model has three layers. *Occupancy layer* describes the occupancy state of the cells, which means what type of object is occupying a cell; *Control layer* defines the mobility state, detects/resolves conflicts between objects, and sets the moving priorities; *ID layer* contains the ID number of each object. Table 1 shows the predefined codes assigned to cells on each layer.

(a) The Three Layers Used to Model *Occupancy, Control*, and *ID* Attributes
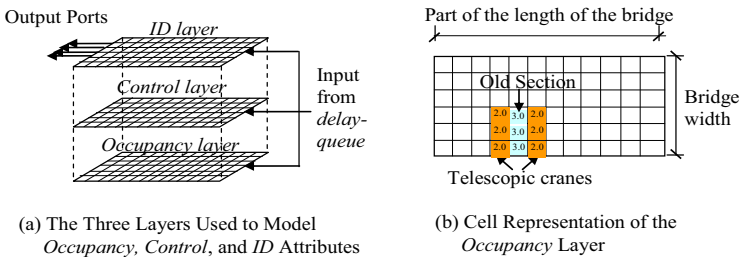
(b) Cell Representation of the *Occupancy* Layer

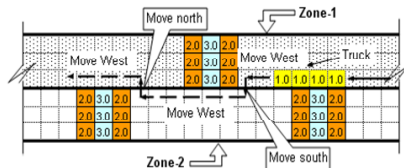Figure 3. Cell Representation of the Bridge Model

Figure 4. Zone Division and the Rules for Changing Directions in Each Zone

Table 1. Codes Used in the Bridge Model

Layer	Code	Description
Occup-ancy	0	Empty cell
	1	An OS truck before loading old section
	2	Crane
	3	Old section
	4	An OS truck after loading old section
	5	Empty space after removing the old section
	6	New installed panel
	8	An NP truck before unloading
	9	An NP truck after unloading
	10	For temporary use
	11	For temporary use
Control	0	Empty cell
	1	Truck moves north
	2	Truck moves south
	4	Truck moves west
	5	Static object
	6	Truck temporarily stops – waiting delay
ID	0	Empty cell
	1- 40	OS Truck
	41 - 80	NP Truck
	91 - 99	Work team
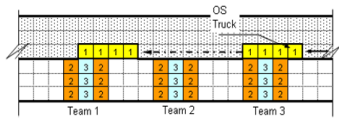
(a) Teams on One Side in Ascending Order
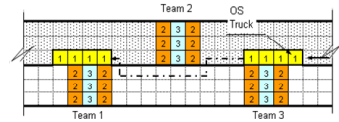
(b) Teams on Both Sides in Ascending Order
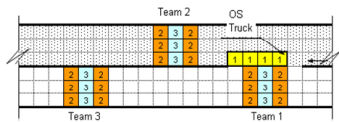
(c) Teams on Both Sides in Descending Order

Figure 5. Examples of site Layouts

(6) Define zones for Cell-DEVS models. A zone defines a region of the cellular space that will use a different local computing function or condition. In this case study, the cell space is divided into two zones as shown in Figure 4. The difference of the rules in the two zones is that a truck takes different moving directions when it meets an obstacle.

(7) Develop rules for each Cell-DEVS model. Rules are applied to each layer to control the movement of objects. The user can define his/her own rules to detect and give possible solution to the spatial conflicts.

(8) Develop DEVS models. External events are collected through input ports and the *external transition function* defines how to react to such inputs. At the moment the duration for the present state expires, desired results are spread through output ports by activating the *output function*, which will trigger the *internal transition function*, causing a state change (Wainer 2002). These functions are defined for each DEVS model.

Main-Processing. Because the worksite is explicitly represented by cells, the objects can be controlled by rules and each object can be identified by its ID. Consequently, the resource allocation and site layout can be considered. Figure 5 shows three patterns of site layouts. In pattern A, teams are on one side of the bridge and their ID numbers are in ascending order; in pattern B, teams are on both sides of the bridge in ascending order, while in pattern C, teams are on both sides of the bridge in descending order. When a truck is moving from west to east, it checks if it is passing a team and if this team is its corresponding team. If the truck finds its corresponding team, i.e., the truck's ID number matches that of the team, it will stop for loading old sections or unloading new panels; otherwise, it will move on. In this way, the team layout and the order of the team's ID numbers determine where the trucks should stop. Thus, the results of different worksite layouts can be compared. Resource

combination is also determined in this phase. The acronym TSON is used to indicate resource combinations, e.g., TSON 5235 means a combination of 5 *Teams*, 2 *Saws*, 3 *OS Trucks* and 5 *NP Trucks*.

Post-Processing

(1) Delays resulting from spatial conflicts: As presented in Table 1, we use codes to indicate spatial conflicts on the *Control* layer. If all the trucks always move straight on an east-west axis, there will be no spatial conflicts or delays. However, trucks may change directions to turn around obstacles such as cranes or other trucks, which results in changing direction delays. In other cases, a truck has to stop temporarily and give the priority to another one, which results in waiting delays. Assuming that trucks always move on the bridge at a constant speed of 10 km/h, it takes about one second for a truck to go from one cell to the next. Thus, we can calculate the delays resulting from spatial conflicts. Occasionally, two or more trucks may get onto the bridge at the same time and one of them has to wait for a short while. We counted all of the three types of delays based on 45 combinations of TSON. As shown in Figure 6, we found that the changing direction delays are the major reason for the delay and Pattern A always has a significantly less delays than the other two patterns.

(2) Sensitivity Analysis: Sensitivity analysis is done by changing the number of each resource for each site layout pattern. The results for patterns and resources (Figure 6) show that the productivity is very sensitive when the number of NP trucks is less than 5, the number of teams less than 5, the number of OS trucks less than 3, and the number of saws less than 2. Thus, the TSON 5235 is the optimum combination from the productivity perspective, which consists with the results of MicroCYCLONE. The productivity results between MicroCYCLONE (Zhang et al. 2007) and Cell-DEVS are compared (Figure 7). Based on the 45 combinations of three site layout patterns, we found that: (1) The results from both modeling techniques are similar; (2) In most combinations, the productivity of Pattern A is a little higher than the other two patterns;   (3) In most combinations, the productivity of MicroCYCLONE is higher by about 5% (1-2 panels) when the speed of trucks is constant (10 km/h). The reason for this is that the delays are very short (Figure 8), compared with the simulation time (9 hours). However, when a truck is changing direction, it will slow down and longer delays should be taken into account. To make the model more realistic, we slowed down the truck's turning speed and kept the other conditions to compare the effect of turning delays on the productivity using combination TSON 5235 and pattern B (Fig. 5(b)). Table 2 shows that the productivity dropped to 89% when the turning speed changed from 10 km/h to 1 km/h.

Table 2. Effect of Turning Speed on Productivity (TSON 5235 Pattern B)

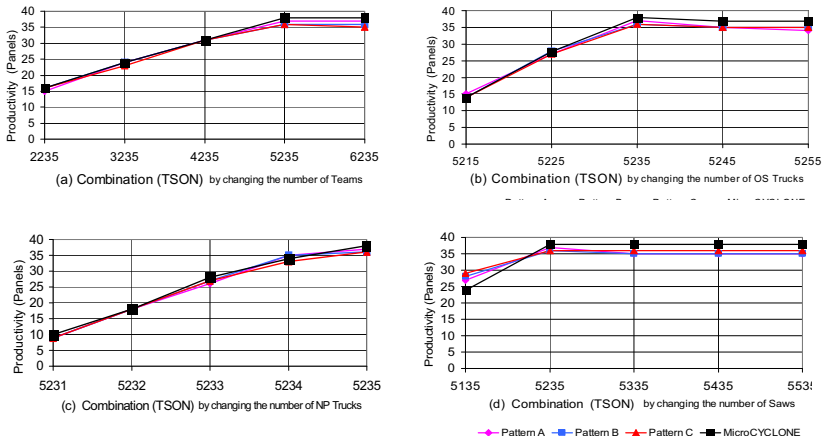| Turning Speed (km/h)	Productivity (Panels/9h)	Rate
10	36	100%
2	34	94%
1	32	89%

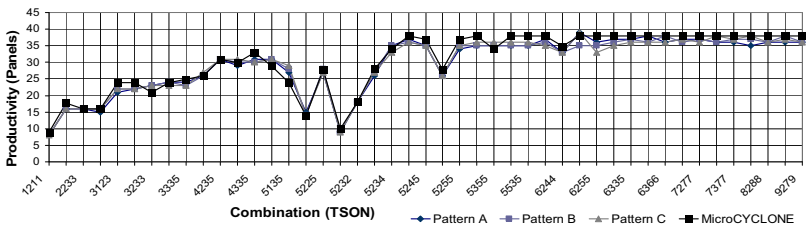Figure 6. Sensitivity Analysis Using MircoCYCLONE and Cell-DEVS

Figure 7. Comparisons of Productivity between MicroCYCLONE and Cell-DEVS
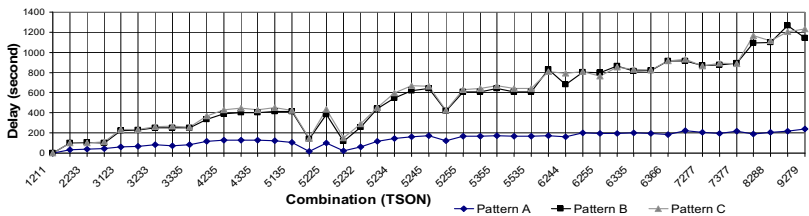

Figure 8. Comparisons of Delays in Different Patterns

Conclusions and Future Work

Cell-DEVS simulation is a general-purpose simulation tool for broad domains and can be used to simulate complex construction operations, especially when spatial constraints are crucial to the project. The proposed Cell-DEVS system integrates three phases, which facilitates arranging worksite layouts, visualizing recourse allocation, controlling the movement of objects and animating the simulation results. More information (occupancy, moving direction and ID, etc.) is integrated in the Cell-DEVS model, which makes it possible to identify and trace a specific object.

The programmability and the capability of defining rules make the Cell-DEVS system more flexible and capable of detecting and resolving spatial conflicts during the simulation. The simulation results of Cell-DEVS show that spatial conflicts can be decreased by selecting appropriate patterns and combinations. The difference between the results of MicroCYCLONE and Cell-DEVS illustrates that in some cases the impact of spatial constraints on productivity is significant and should not be neglected. Based on the present study, it has been found that Cell-DEVS simulation is an effective tool for space-related analysis in construction project.

Future work will include the following: (1) Investigating more case studies to further validate the Cell-DEVS approach in construction modeling; (2) Investigating new features of CD++, such as parallel processing and dynamic features for contingencies and dynamic releasing/allocating recourses; and (3) Exploring 3D visualization of simulation results (Khan et al. 2005).

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