

SENSITIVITY ANALYSIS OF CONSTRUCTION SIMULATION USING CELL-DEVS AND MICROCYCLONE

Hong Pang

Dept. of Building, Civil & Environmental Engineering
Concordia University
Montreal, QC, CANADA

Cheng Zhang

Dept. of Building, Civil & Environmental Engineering
Concordia University
Montreal, QC, CANADA

Amin Hammad

Concordia Institute for Information Systems Engineering
Concordia University
Montreal, QC, CANADA

ABSTRACT

Simulation has been widely used in the construction industry to optimize productivity and resource allocation. However, simulation research that provides an explicit method to investigate possible space conflicts is still limited. This paper suggests a cell-based modeling approach to represent space resources in construction simulation, which enables spatial conflict analysis and visualization of the worksite and of the occupation of spaces. Comparison between the cell-based modeling approach and MicroCYCLONE approach is done to investigate the validity of the new proposed approach. Sensitivity analysis is applied to both methods to find the optimal resource combination.

1 INTRODUCTION

Discrete event simulation has been widely used in the construction industry in order to plan processes, allocate resources, and detect conflicts. The objective of simulation is usually to determine the impact of a change of an input on the whole system or on local parts of the system. Different simulation techniques have been developed to model and analyze construction processes and to help decision-makers. CYCLONE (Halpin 1977), Symphony (Hajjar and AbouRizk 1999), and Stroboscope (Martinez 1998) are popular software systems used in the construction industry. They have proven to be effective and efficient in simulating various construction projects. Recently, researchers have been more concerned about workspace conflict detection using simulation. Kamat (2003) has proposed detecting conflicts between any pair of mobile or static objects on a construction site based on collision detection methods implemented within visualization tools of discrete event simulators. However, this approach is based on visualizing the results of the simulation rather than considering spatial issues in the simulation itself.

Cell-based modeling has been investigated in construction simulation (Zhang et al. 2005, Zhang et al. 2006). Spatial conflict detection is applied in cell-based modeling, and is based on an explicit representation of the worksite which is not available using MicroCYCLONE. Comparison between cell-based modeling and MicroCYCLONE has been made to show the feasibility of Cell-DEVS (Wainer 2002; Wainer and Giambiasi 2002). This paper focuses on investigating the usefulness of Cell-DEVS in sensitivity analysis considering different worksite layouts. The Cell-DEVS model has been improved by incorporating more complex rules to detect and solve spatial conflicts, and to calculate delays. Sensitivity analysis is applied to Cell-DEVS and MicroCYCLONE models to further investigate the possibility of using cell-based modeling in resource optimization.

2 SIMULATION MODELS USING MICROCYCLONE AND CELL-DEVS

The Jacques Cartier Bridge re-decking project is used as a case study to develop the simulation models using both MicroCYCLONE and Cell-DEVS methods. The deck of this bridge was replaced in 2001-2002. The case study focuses on the two activities of removing existing deck sections and installing new panels on the main span of the bridge. The existing deck was removed by saw-cutting the deck into sections similar in dimensions to the new panels. The existing deck sections were removed, and replaced, by two telescopic cranes. The old sections were transported to the dumping area near the bridge, and the new panels were transported from the plant located at the south end of the bridge. More details can be found in Zhang et al. (2006).

2.1 MicroCYCLONE Model

Figure 1 shows the simulation model for the re-decking project using MicroCYCLONE. Active-state rectangular nodes represent tasks; idle-state circles represent delays or

waiting positions for resource entities; and directional flow arrows represent the path of resource entities as they move between idle and active states. Tasks can be executed only when all the required resources are available. For example, the task “Dumping” (node 13) is the task of dumping an old section of the deck in the dump area. It takes a mean time of 5 minutes and needs two resources: “Truck waiting for dump” (node 11) and “Forklift waiting” (node 12). After the dumping of one section is finished, these two resources are released: the truck will return to the bridge (node 14) and the forklift will go back to idle state (node 12).

Resources required in this project include: teams (two cranes and crews), saws (including operators), trucks (including the drivers) for carrying old sections (OS), trucks (including the drivers) for carrying new panels (NP), small crane for loading new panels in the plant, forklift for dumping the old sections in the dump area, empty deck space of the removed section, truck working space, etc. The developed model consists of several cycles; the three main cycles are described as follows:

1. Old section cycle: The existing deck is cut by saw into sections. Empty trucks are waiting for

the team to load the old section. After loading, the truck transports the old section to dump area. After dumping, the truck goes back to the bridge for loading the next old section.

2. New panel cycle: New panels are transported from the plant to the bridge. The same team for removing the old sections also installs the new panels. After installation, the truck goes to the plant to load another new panel.
3. Team cycle: Teams are located at different locations on the bridge for removing old sections and installing new panels. They move to the next location on the bridge after they finish the installation of each new panel.

When one team, one truck for carrying new panels (NP), one truck for carrying old sections (OS), and a cutting saw are used, the resulting productivity is 0.89 panels/hr. This will generate 8 panels/day during 9 working hours (8:30 p.m. to 5:30 a.m.). The worksite layout on the bridge’s main span is shown in Figure 2. The length of the main span is 600 m. The required length for each rehabilitation team is 60 m based upon the project manager’s experience to avoid spatial conflicts. Therefore, the

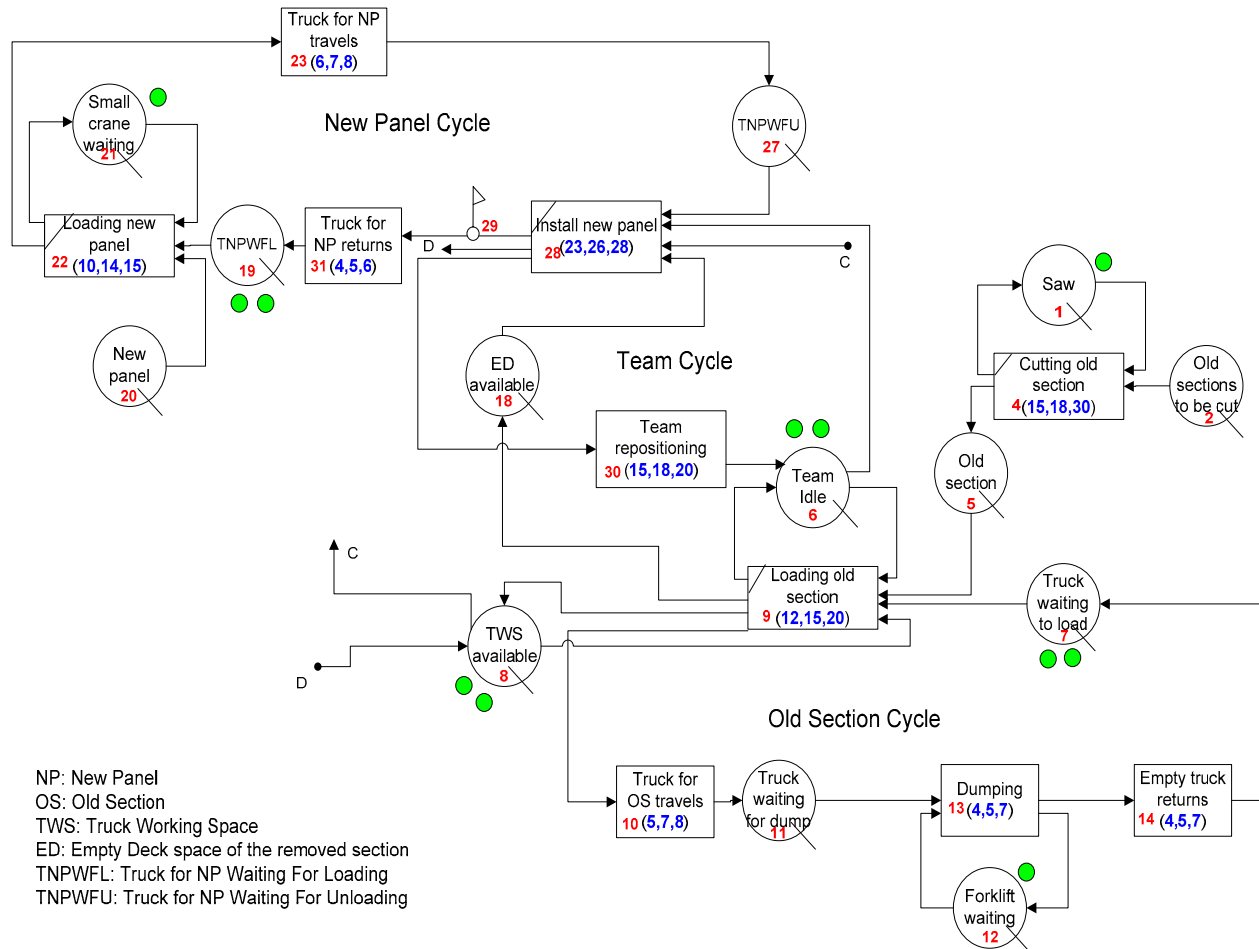


Figure 1: MicroCYCLONE model of Jacques Cartier bridge re-decking project

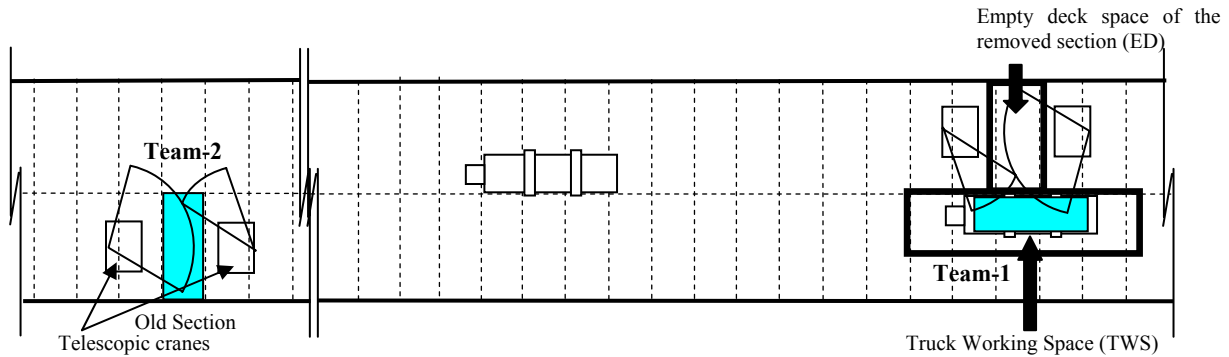


Figure 2: Worksite layout of the bridge re-decking project

maximum number of teams that can work simultaneously without major conflicts is ten teams. Sensitivity analysis is performed to select the optimum fleet of teams that generate higher productivity with lower expenses and conflicts as is explained in Section 3.1.

2.2 Cell-DEVS Model

Figure 3 shows the structure of the cell-based simulation model for the re-decking project of Jacques Cartier Bridge. This model is a combination of Cell-DEVS and DEVS models (Wainer and Giambiasi 2002). Arrows show the input and output information flow between different models through ports. *Bridge*, *Plant*, and *Dump Area* are Cell-DEVS models.

The following DEVS models are built to facilitate communications between these Cell-DEVS models: *Control Unit* model, *Reposition* model, and *Transport (T)* and *Queue (Q)* models. For example, the *T-Plant-Bridge* is a *Transport* model representing the transportation of a panel from the plant to the bridge, and the *Q-Old* is a *Queue* model representing the queue of trucks that carry the old sections. The *Control Unit* model is built to provide overall control of the system, such as permitting a queue to send a truck to the bridge when a truck is needed and a space on the bridge is available.

The discussion about building Cell-DEVS models has been explained in our previous paper (Zhang et al. 2005). The *Bridge* model is introduced briefly:

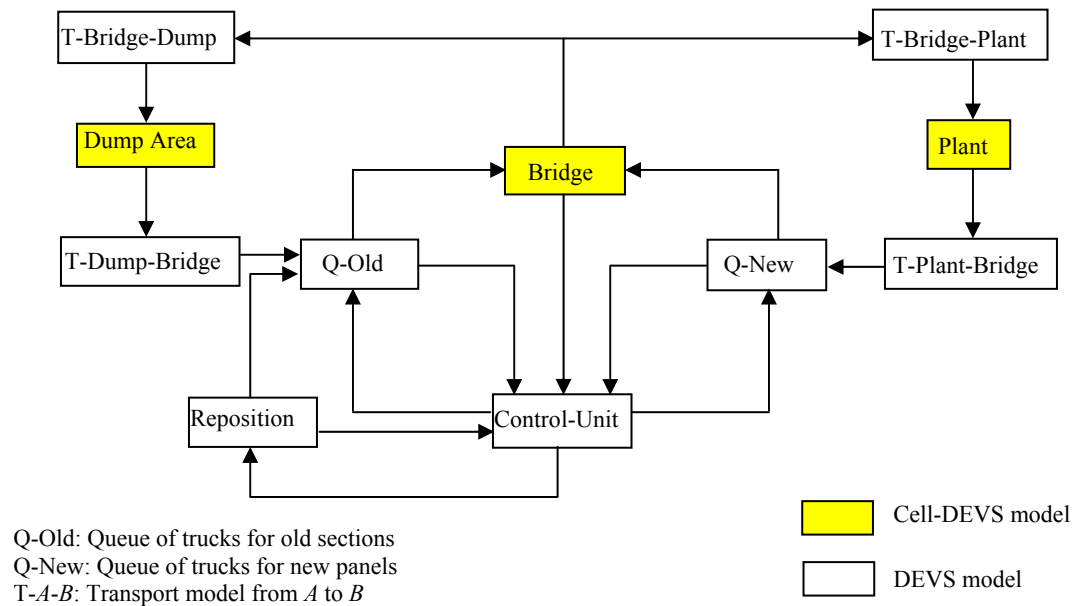
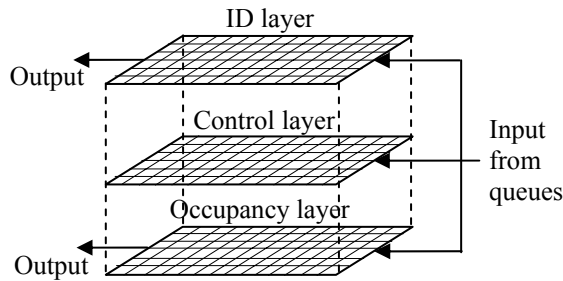
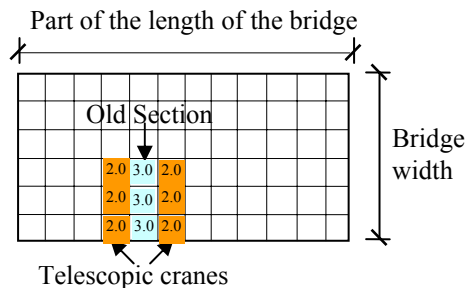


Figure 3: Structure of the cell-based model for Jacques Cartier Bridge re-decking project



(a) the Three layers used to model occupancy, control, and ID information



(b) Cell representation of the occupancy layer

Figure 4: Cell representation of the bridge model

There are two input ports of the *Bridge*: *in-old* and *in-new*. The queues will send the ID number of each truck to the *Bridge* through the respective input port. The output port of the *Q-Old* is linked with the *in-old* port, while the *Q-New* is linked with the *in-new* port. Different layers act differently when receiving an ID number of a truck from a queue. The *occupancy layer* generates trucks; the *control layer* generates the directions; and the *ID layer* keeps the received value as it is and moves it with the truck (Figure 4(a)).

There is one output port of the bridge, which is linked with *T-Bridge-Dump*, *T-Bridge-Plant*, and *Control-Unit* models to send the ID number of each truck. The ID numbers are initialized in the *Dump Area* and in the *Plant* models. The technique used in implementing the *Dump Area* and the *Plant* models is similar to that used in the *Bridge* model.

In the Cell-DEVS model, the cell size is assumed to be 3*3 meters. The main span of the bridge is approximately represented by 200*6 cells. As shown in Figure 4(b), the old section and the telescopic crane are represented by three cells in size. Cells communicate with each other through rules which govern the interactions between layers, control the movement of trucks and detect and solve conflicts. About 200 rules are applied to implement all the functions of the Cell-DEVS models. In general, rules in a Cell-DEVS model are applied on all the cells of

that model. However, in many cases, it is necessary to specify a part of the model as a zone in order to define local rules that apply only within that zone. In the *Bridge* model, both the *Occupancy* and *Control* layers should be divided into two zones to define different moving directions when a conflict is detected (Figure 5). The main difference between the rules of these two zones is that a truck has to take a different direction when it meets an obstacle. For example, when the control layer detects a conflict between a truck and a crane, the direction of the truck is changed to south or north to avoid the obstacle depending on whether the crane is in Zone-1 or Zone-2, respectively.

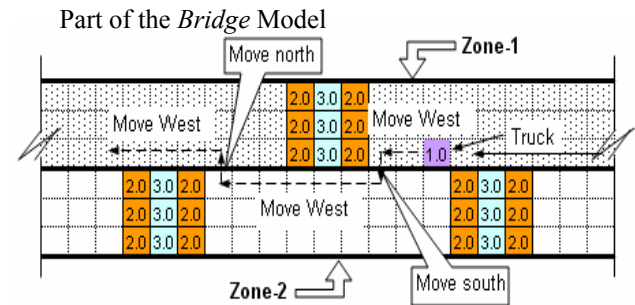


Figure 5: Zone division and the rules for changing directions in each zone

Table 1 shows the rules that control the actions on the bridge (*Bridge* Model, Zone-1). The “Layer” column shows the three layers in the *Bridge* model. The “Functions” and the “Number of Rules” explain how many rules are applied to realize the specific function. In the “Dependency” column, the rules with the same letter indicate that they work together to perform the same functions in different layers. The symbol * indicates that this rule is the controlling rule and the other rules with the same letter are dependent on it.

Before running the simulation, the trucks and their locations in the *Dump Area* and the *Plant* are initialized and the teams are located on the bridge. The ID number for each truck and team are assigned. Simultaneously, the rules control the trucks to move from east to west on the bridge.

Since Cell-DEVS provides the representation of physical spaces, in addition to the task durations and resource allocations, the patterns of teams’ order and layout should be also considered (Figure 6). When a truck is moving west, 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 a while for loading or unloading panels; otherwise, it will move on. In this way, the team layout and the order of the team’s ID number determine where the trucks should stop. Thus, the results of different worksite layouts can be compared.

Table 1: Rules defined for the bridge model (zone-1)

Table of rules on the bridge			
Layer	Functions	Number of Rules	Dependency
Occupancy layer	Truck moves west before loading or unloading if the cells to the south of the reference cell are not occupied by a workteam	2	A
	Truck moves west after loading or unloading without waiting delays	1	B
	After loading / unloading procedures, the truck changes its status (OS truck changes from empty to loaded, while NP truck changes from loaded to empty)	2	C,D
	After loading / unloading procedures, a truck changes its status and begins to move west	1	E
	Remove the duplicated truck's Occupancy code after the truck moves	1	F
	Solutions to waiting delays	1	G
	Truck moves north to get around obstacles	1	H
	Truck moves south to get around obstacles	1	I
	Workteam moves west and keeps its position	9	K*
	Reset "O" to all unoccupied cells	1	L
	If a truck is static, keep its status	2	M
	An OS truck is loading old section	2	O
	A NP truck is unloading new panel	2	P
	Keep the empty deck spaces before the corresponding NP truck comes	2	Q
Control layer	Truck moves west before loading or unloading if the cells to the south of the reference cell are not occupied by a workteam	6	A*
	Truck moves west after loading or unloading without waiting delays	1	B*
	After loading / unloading procedures, a truck changes its status and begins to move west	2	E*
	Remove the duplicated truck's Control code after the truck moves	1	F*
	Solutions to waiting delays	8	G*
	Truck moves north to get around obstacles	2	H*
	Truck moves south to get around obstacles	2	I*
	Truck changes direction from south or north to west	2	J*
	Workteam moves west and keeps its position	2	K
	Reset "O" to all unoccupied cells	1	L*
	If a truck finds its corresponding workteam, it stops	6	M*
ID Layer	Truck moves west before loading or unloading if the cells to the south of the reference cell are not occupied by a workteam	4	A
	Truck moves west after loading or unloading without waiting delays	2	B
	After loading / unloading procedures, a truck changes its status and begins to move west	2	E
	Remove the duplicated truck's ID code after the truck moves	2	F
	Solutions to waiting delays	1	G
	Truck moves north to get around obstacles	1	H
	Truck moves south to get around obstacles	1	I
	Workteam moves west and keeps its position	2	K
	Reset "O" to all unoccupied cells	1	L
	If a truck is static, keep its status	3	M
	Remove the duplicated workteam's ID code after it moves west	1	N

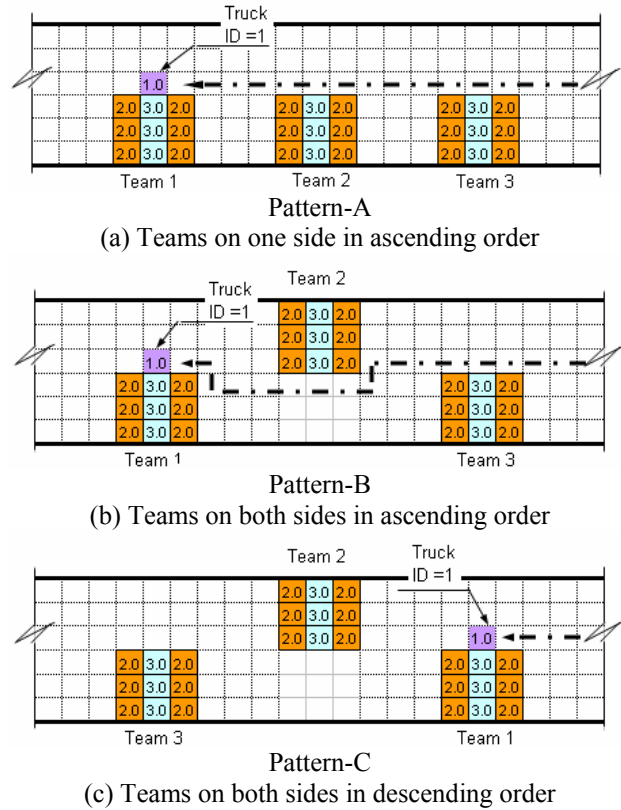


Figure 6: Possible patterns of teams' order and layout

If all the trucks always move straight on an east-west axis, there will be no spatial conflicts. However, trucks on the bridge may encounter various spatial conflicts. They may change directions to get around obstacles such as cranes or other trucks, which results in some small delays. Besides the “Changing Direction Delay”, another kind of delay – “Waiting Delay” results from spatial conflicts when a truck stops temporarily waiting for another truck. For example, when the model detects that two trucks will occupy the same cell at the next step, it will give priority to one of them, making the other one wait until the first truck passes. Figure 7 shows an example of “Waiting Delay”. At time t_1 , there are two trucks for carrying new panels in Figure 7(a). To get around the team, Truck 1 (ID = 1) has to go south, while Truck 2 (ID = 2) is going west since there is no obstacle ahead of it. At the next time-step, the two trucks will try to occupy the same cell, and a spatial conflict occurs. Therefore, some rules are defined to avoid this situation. As Figure 7(b) and 7(c) show, Truck 1 is given the priority of passing. Truck 2 has to stop waiting for Truck 1 and then continues to move west as shown in Figure 7(d).

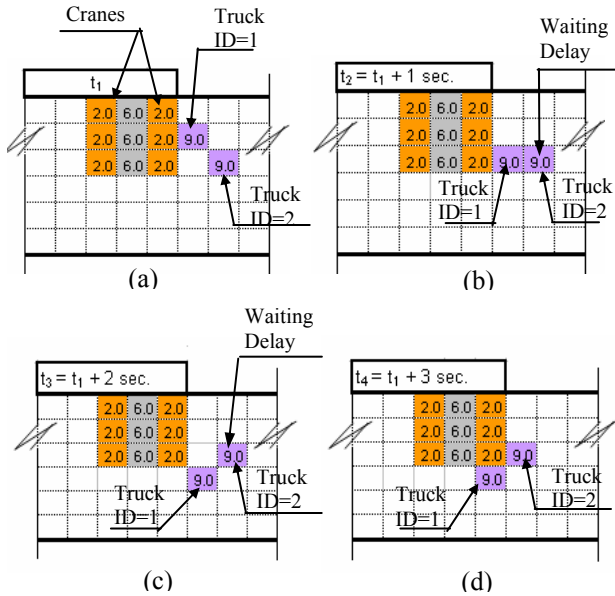


Figure 7: Example of waiting delay

3 SENSITIVITY ANALYSIS AND RESOURCE OPTIMIZATION

Sensitivity analysis is applied to both methods to find the optimal resource combination for teams, saws for carrying Old Sections (OS) and trucks for carrying New Panels (NP).

3.1 Sensitivity Analysis in MicroCYCLONE

In MicroCYCLONE, the generated number of combinations is 1296 to change the number of teams from 1 to 6 with 1 team increment; saws from 1 to 6 with 1 saw increment; OS trucks from 1 to 6 with 1 truck increment; and NP trucks from 1 to 6 with 1 truck increment. More combinations were tried to check the increase in productivity and decrease in cost. Therefore, the number of teams was increased to 7, 8, 9, and 10 but productivity did not increase beyond what was achieved using 5 teams. The results of sensitivity analysis are analyzed to select the optimal combination of resources. The combinations that have higher productivity and lower cost are selected because they dominate the other combinations that have similar or lower productivity and higher cost. The index method that is developed by Zayed and Halpin (2001) is used to select the optimal combinations that cannot be dominated. Table 2 shows the results of sensitivity analysis for the optimal combinations that have the lowest unit cost in terms of different teams. The “Case” column shows different combinations of teams, saws, OS trucks, and NP trucks. For example, “TSO1211” means the combination of 1 team, 2 saws, 1 OS truck, and 1 NP

truck. The “MC” columns show the results obtained from MicroCYCLONE. It is found that the lowest unit cost of all the combinations is \$747, which involves 5 teams, 2 saws, 3 OS trucks, and 5 NP trucks.

Table 2: Results of the sensitivity analysis

Case	Teams	Saws	OP Trucks	NP Trucks	Total Panels Replaced		Productivity (panel/hr)		Unit cost (\$/panel)		Panels/team	
					MC	CD	MC	CD	MC	CD	MC	CD
TSO1211	1	2	1	1	9	8	1.00	0.89	1055	1181	9.0	8.0
TSO2223	2	2	2	3	17	16	1.97	1.78	838	928	8.9	8.0
TSO3123	3	1	2	3	23	23	2.66	2.56	751	783	8.0	7.7
TSO4335	4	3	3	5	32	31	3.66	3.44	765	813	8.2	7.8
TSO5235	5	2	3	5	38	37	4.22	4.11	747	766	7.6	7.4

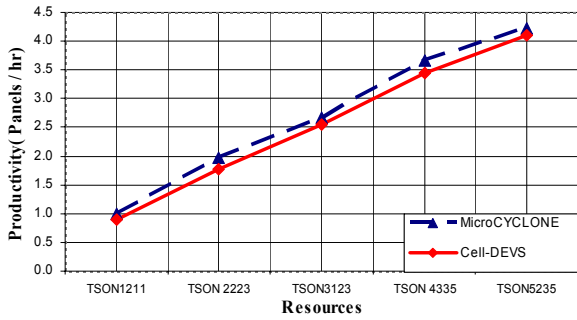
(MC: MicroCYCLONE CD: Cell-DEVS)

3.2 Sensitivity Analysis in Cell-DEVS

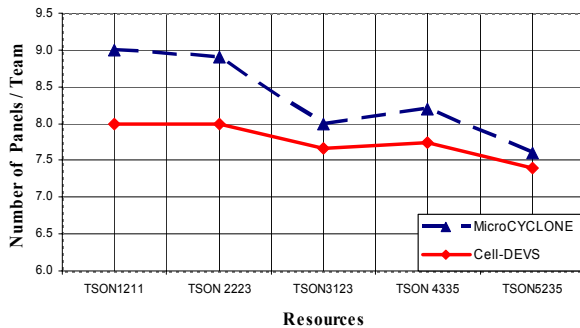
Based on the cases simulated in MicroCYCLONE, thirty combinations are selected for simulation using the Cell-DEVS method. The sensitivity analysis is based on the following assumptions: (1) the teams are located following Pattern-B; (2) The space between teams is 40 cells (120 m); (3) The simulation time is 9 hours; and (4) The number of saws is sufficient not to cause any delays. The “CD” columns in Table 2 show the results of five typical combinations. As the case of MicroCYCLONE simulation, the same optimal combination is found using Cell-DEVS from both productivity and economy aspects. The three patterns of team layouts shown in Figure 6 for each combination have subtle differences in productivity but have evident distinctions in spatial delays. Of the three patterns, Pattern-A has the minimum spatial delays; Pattern-B has medium delays; and Pattern-C leads to the maximum delays. This result indicates that the spatial delays can be decreased by properly arranging the teams and choosing resource combinations.

3.3 Comparison

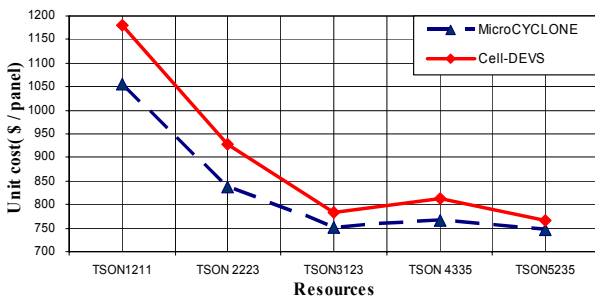
Figure 8 shows the comparison of the sensitivity analysis results between MicroCYCLONE and Cell-DEVS. The x-axis represents different resource combinations, while the y-axis represents Productivity [panels/hr], Productivity [panels/Team] and Unit Cost [\$/panel], respectively. The results of Cell-DEVS have the same trend as those of MicroCYCLONE with a lower productivity and a higher unit cost. Although the difference in productivity is no more than one panel per shift, the results show the influence of the spatial constraints concerned in the Cell-DEVS model. This indicates that the effect of spatial conflicts on productivity is small in this case study.



(a) Productivity [panels/hr]



(b) Productivity [panels/team]



(c) Unit cost [\$/panel]

Figure 8: Productivity and unit cost trends in different cases

Furthermore, the number of spatial delays occurring on the bridge can be calculated based on the results of Cell-DEVS simulation. Cell-DEVS visualizes the construction operations and occupation situations on the bridge, so every detail including the potential spatial conflicts can be detected and the solutions to the conflicts can be checked. Most of the spatial conflicts occur on the bridge since the *Dump Area* and the *Plant* have enough space. Figure 9 shows the number of spatial conflicts of some selected combinations. Notice that the spatial conflicts are very sensitive to the number of teams and the number of trucks. With the increase of number of teams, the spatial conflicts increase sharply. The numbers of OS

trucks and NP trucks also influence the spatial conflicts. The “Changing Direction Delay” is the major reason for delays while the “Waiting Delay” is the minor one.

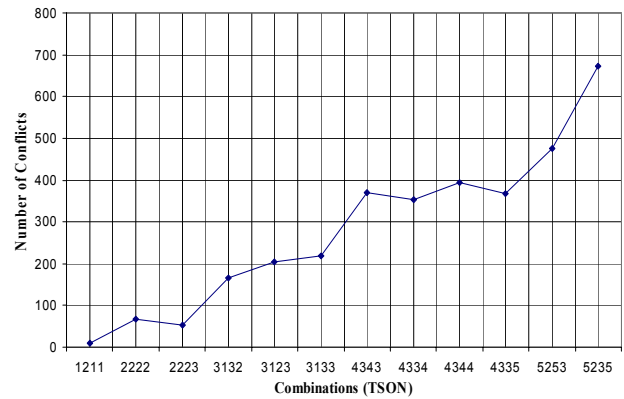


Figure 9: Number of spatial conflicts of combinations

4 CONCLUSIONS

Following up our previous results about the feasibility of applying Cell-DEVS as a simulation method in construction (Zhang et al. 2006), this paper aimed to compare its results with those of MicroCYCLONE while considering spatial delays. This paper analyzed different resource combinations for a bridge rehabilitation project using MicroCYCLONE and Cell-DEVS. The optimal combinations are selected based on productivity and cost. The following conclusions can be drawn: (1) Unlike MicroCYCLONE, Cell-DEVS explicitly represents spatial resource allocation, worksite layout, as well as the movement of mobile equipment, which makes it possible to consider how to arrange resources on worksite before construction. Users can try different resource allocations and worksite layouts to find the optimal combination and layout pattern; (2) Different worksite layouts can be compared through assigning a truck to its corresponding team. The number of spatial conflicts and their accumulative effect on productivity can be calculated; (3) The result shows that spatial delays can be decreased by properly arranging the teams and choosing resource combinations; and (4) The difference between the results of MicroCYCLONE and Cell-DEVS indicates that the impact of spatial conflicts on productivity is small in this case study. Future work will consider a more accurate spatial representation of the mobile equipment, such as representing the trucks with a block of cells. In addition, more detailed sensitivity analysis is needed to investigate the differences between worksite layout patterns.

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AUTHOR BIOGRAPHIES

HONG PANG is currently pursuing his Master of Science degree at the Department of Building, Civil and Environmental Engineering at Concordia University. His research interests are focused on construction simulation. His email address is [<hong_pan@encs.concordia.ca>](mailto:hong_pan@encs.concordia.ca).

CHENG ZHANG is currently a Ph.D. student at the Department of Building, Civil and Environmental Engineering at Concordia University. Her research interests are focused on spatio-temporal issues in infrastructure management systems. Her email address is [<zha_che@encs.concordia.ca>](mailto:zha_che@encs.concordia.ca).

AMIN HAMMAD is currently working as Associate Professor at Concordia Institute for Information Systems Engineering. His research interests are mainly focused on telegeoinformatics, infrastructure and urban management systems. His email and web addresses are [<hammad@ciise.concordia.ca>](mailto:hammad@ciise.concordia.ca) and [<www.ciise.concordia.ca/~hammad>](http://www.ciise.concordia.ca/~hammad).