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# REPRESENTATION AND ANALYSIS OF SPATIAL RESOURCES IN CONSTRUCTION SIMULATION

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## ABSTRACT

Space is one of the resources that may cause crucial problems during construction. Discrete event simulation has been widely used in construction to allocate resources and improve productivity or mitigate conflicts. However, simulation research that provides an explicit method to investigate possible space conflicts is still limited. This paper suggests a cell-based method to represent space resources in construction simulation, which enables conflict analysis and visual display of the worksite and the occupation of spaces. Different simulation models are compared to identify their limitations in space representation.

## 1 INTRODUCTION

Workspace conflicts are serious problems that can delay construction activities, reduce productivity, or cause accidents that threaten the safety of workers (Guo 2002). Mallasi and Dawood (2004) discussed that workspace interference could result in decreasing work productivity by about 40%. Much research has been done to detect space conflicts during construction (Riley and Sanvido 1995, Akinci et. al. 2002, Guo 2002, Heesom et al. 2003, Mallasi and Dawood 2004). Workspace conflicts have three characteristics that differentiate them from other conflicts: (1) They have temporal aspects, i.e., they occur only during certain periods of time; (2) They exist in different forms that could change with the requirements of construction activities; and (3) They create different types of problems on site, e.g., compromising the safety of workers or reducing the productivity of equipment (Akinci et al. 2002). Due to these specific characteristics of workspace, it is not easy to detect space conflicts using static methods that focus on specific time points.

Simulation has been used in construction for process planning and resource allocation. Early in the research of Halpin, it was mentioned that location or space-type flow units usually constrain the access to certain work processed and thus constrain the movement of other type units. However, in MicroCYCLONE, space is represented as abstract symbols and it is limited to the operation spaces of equipment, excluding other workspaces, such as moving paths (Halpin 1992). Kamat (2003) 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.

Some research has been done to investigate the space visualization in construction simulation. Zhang et al. (2002) used 2D icons to represent the resources, which can move along the path between activities. However, this research did not clearly represent the spatial relationships between different activities although there are icons moving from one activity to another. It is difficult to understand the worksite situation with links between activities only. Zhong et al. (2004) developed the GIS-based Visual Simulation System (GVSS) to offer planning, visualizing, and querying capabilities of complex construction processes. However, workspace conflicts are not discussed in their research.

Space conflicts are not clearly represented in the previous simulation research. This could result in spatial constraints being ignored in the simulation, and the output may not reflect the real situation of the construction site. In addition, workspaces in a simulation model may change depending on the specific activity, such as the workspace of a crane. Spatial problems need to be studied in a general way that is easy to understand, and a model should be built in a way that the space can be represented explicitly.

## 2 CELL-BASED MODELING

In 1948, John Von Neumann and Stephan Ulam defined a modeling formalism, called Cellular Automata (CA), suited to define spatial systems, and allowing the description of cell-based models by using simple rules (Wolfram 1986). In CA, space is represented by a uniform grid, with each cell containing a few bits of data. At each step, each cell computes its new state from that of its close neighbors.

In the '70s, Bernard Zeigler defined a theory for Discrete-EVents systems Specification (DEVS). It is a formal approach to build models using a hierarchical and modular approach. Also, he defined a cell space model, which consists of an infinite set of geometrically defined cells, each cell containing the same computational apparatus as all other cells and connected to other cells in a uniform way. For a cell located at the origin (0,0), the nearest neighbors would be those located at: (0,0), which is the cell itself; (0,1) (1,0) (0,-1) (-1,0), which are at distance of one cell away orthogonally and (1,1) (-1,1) (-1,-1) (1,-1) which are at distance of one cell away diagonally (Zeigler, 1976). This paradigm allows the developer to build a Model Base permitting easy reuse of models that have been validated. A real system modeled with this paradigm can be described as several sub-models coupled into a hierarchy. Each model can be behavioral (atomic) or structural (coupled), consisting of a time base, inputs, states, outputs and functions to compute the next states and outputs. The basic idea is that each model uses input/output ports in the interface to communicate with other models.

Based on these ideas, Wainer (1998) developed an approach called Timed Cell-DEVS (2000). The proposal of the Cell-DEVS paradigm (Wainer and Giambiasi 2001) considers each cell of a CA as a hierarchical and modular discrete events model. In this way, complex models can be defined using a continuous time base. It also allows associating several kinds of delays for each cell, allowing the definition of complex models easily. The cell state changes according to a local function that uses the present cell state and a finite set of nearby cells. Many applications of Cell-DEVS have been developed including surface tension analysis, studies of ecological systems, and a specification language used to define traffic simulations.

Based on the cell representation of the spatial model, this paper tries to investigate the possibility of representing space explicitly when simulating construction processes. In the next section, limitations of space representation in conventional simulation models are discussed, and the usefulness of cell-based representation is also investigated in a bridge re-decking project. We apply the Cell-DEVS method in this project and try to link the simulation model with a 3D bridge model to show the space representation and space conflict detection during simulation.

## 3 LIMITATIONS OF AVAILABLE SIMULATION MODELS

### 3.1 Case Study: Jacques Cartier Bridge in Montreal

The deck of this bridge has been replaced in 2001-2002. The new deck is constructed of precast, prestressed and post-tensioned panels made of high performance concrete which were prefabricated in a temporary plant installed near the south end of the bridge. The case study will focus on the two activities of removing existing deck sections and installing new panels in the main span of the bridge. These two activities were critical for the success of the project from the point of view of spatial and temporal constraints. The existing deck was removed by saw-cutting the deck into sections similar in dimension to the new panels being installed. Each existing deck section was removed and a new panel was lifted from a truck and lowered onto the new bearing assemblies. Old sections were transported to a dumping area near the bridge. New panels were transported from the plant located in the south end of the bridge. Table 1 shows the tasks and their durations. In Figure 1, the worksite layout is shown when the bridge deck was replaced. Two teams worked in parallel in different parts of the bridge. However, in this study, only one team is considered. Different simulation models are built to investigate the space representation.

### 3.2 Simulation Model of the Re-decking Project Using MicroCYCLONE

A MicroCYCLONE model is built to demonstrate how space resources are represented. In Figure 2, spaces are represented as abstract symbols. There are four spaces explicitly represented in this model (see Figure 1): Waiting areas for the empty truck that will carry an old section (WST) and for the truck loaded with a new panel (WPT), empty deck space of the removed section (ED) and truck working space (TWS), which are represented as queues. Other spaces, such as the moving path of the truck, are considered as available all the time and not explicitly represented in this model. In addition, workspaces can change from one activity to another and it is the responsibility of the modeler to identify these spaces in MicroCYCLONE. Moreover, spatial conflicts are not discovered except by visualizing the results using post processing applications (Kamat 2001). In fact, our observation is that space resources are always attached to other resources (equipment, materials, etc.) and heavily depend on the site layout. Therefore, our proposed approach, which will be discussed in detail in Section 4, is based on defining spatial resources as attributes of other resources instead of as independent resources.

### 3.3 3D Workspace Conflict Analysis Model

A 3D bridge model is created using Java and Java3D (Zhang and Hammad 2005) to study the workspace conflicts. Workspaces are created using Constructive Solid Geometry (CSG) (Watt 2000). CSG is a solid modeling method that combines simple solid shapes called *primitives* to build more complex models using *Boolean operators,* such as *union*, *difference*, and *intersection*. The method of generating the workspace of a telescopic crane used in the re-decking project of Jacques Cartier Bridge is shown in Figure 3. Analysis of workspace conflicts can be done at a specific point of time using a common exact collision detection algorithm (Watt 2000), by which exact overlapped parts of different workspaces can be identified and directly shown on the bridge model (Figure 4). However, this method is not based on discrete event simulation and envelopes of the workspaces are generated for the whole period of the activities.

## 4 PROPOSED APPROACH: CELL-BASED MODEL

As discussed in Section 2, space can be divided into cells and every cell is a discrete event model, so it can change its state according to its own time delay and external events. A dynamic information exchange can be achieved during simulation period. Conflict detection can be simplified by checking the state of each cell and avoiding an occupied cell being used by other objects. Based on this idea, a cell-based model is built to investigate the space issues in construction simulation. In Figure 2, the site layout can be approximately divided into several areas according to the geographic locations, including Bridge, Plant, Dumping Area etc. Therefore, the cell-based space representation can be extended to cover the whole working area.

As shown in Figure 5, there are three main areas in the model: Bridge, Plant, and Dumping Area. The Bridge model combines waiting area for trucks transporting old sections (WST), waiting area for the truck loaded with a new panel (WPT), and the combined working area for one team (CWA) (Figure 1). To calculate productivity, counters are also created using cell models. Arrows show the input and output signals between different cell models. Each model is the combination of several cells, which can be occupied by different equipment and materials over time. Different numbers are used to represent different equipment states and the occupation of spaces. Details of the state numbering are shown in Figure 6. This figure also shows the graphical user interface of CD++, a tool for cell-based discrete-event modeling and simulation based on the DEVS formalism (Wainer et al. 2004). The description of each model and the rules are written and saved in a text file. After running the simulation, an output file (log file) is generated. Based on the log file, graphical animation can be created to show the simulation processes (Figure 7). A preliminary test of a simplified version of Jacques Cartier Bridge re-decking project is done using this approach. The simplified model does not reflect the topology of the places, and only part of the main span of the bridge is shown in this model. The cell dimensions are assumed to be 3*3 meters. The total length and the width of the main span are about 600 m and 20 m, respectively. The width of the approach part is 18 m. Therefore, the main span of the bridge can be approximately represented by 200*6 cells. It takes less than 1 minute to run the simulation for one panel and draw each of the five models.

Table 1: Task Durations

| Activity | Task ID | Task Description | Triangular Distribution of Durations (min) |
|---|---|---|---|
| Remove old sections | 4 | Cut old section | 15, 18, 30 |
| | 9 | Load old section | 12, 15, 20 |
| | 10 | Truck with old section travels to dumping area | 5, 7, 8 |
| | 13 | Dump old section | 4, 5, 7 |
| | 14 | Empty old-section truck returns to bridge | 4, 5, 7 |
| Install new panels | 22 | Load new panel | 10, 14, 15 |
| | 23 | Truck with new panel travels to bridge | 6, 7, 8 |
| | 28 | Install new panel | 23, 26, 28 |
| | 31 | New-panel truck returns to plant | 4, 5, 6 |
| | 30 | Team repositioning | 15, 18, 20 |

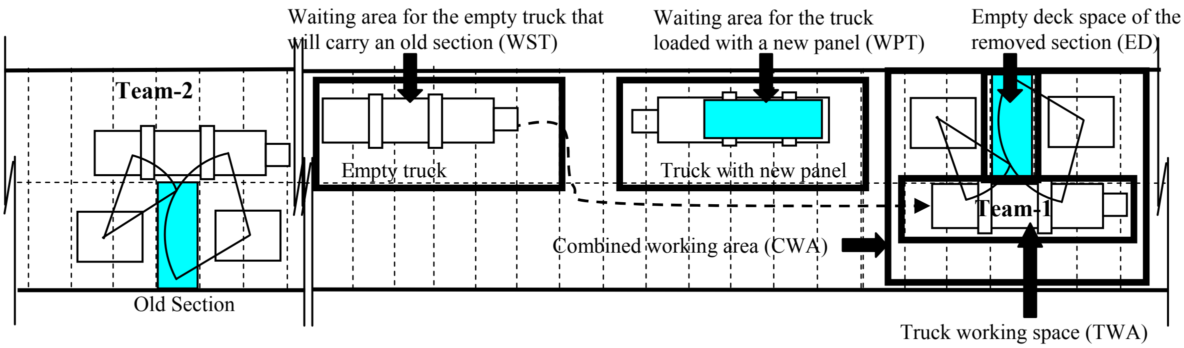



Figure 1: Worksite Layout of the Bridge Re-decking

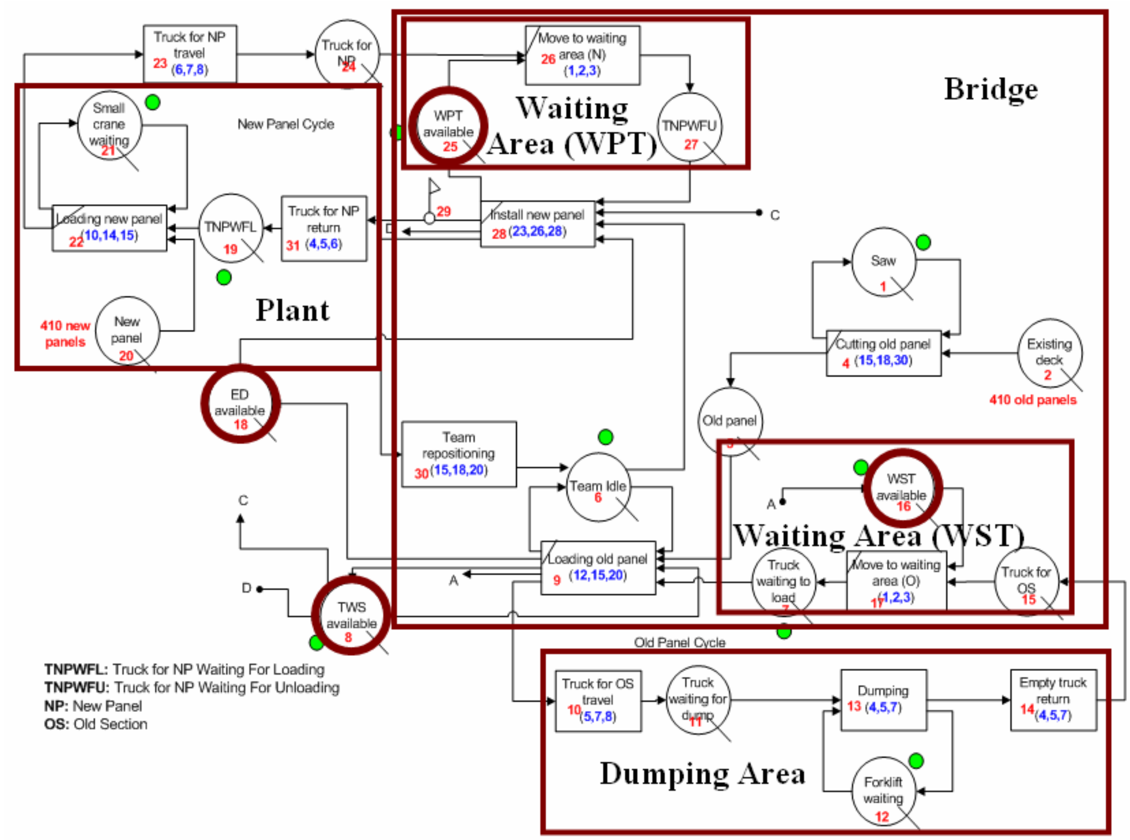
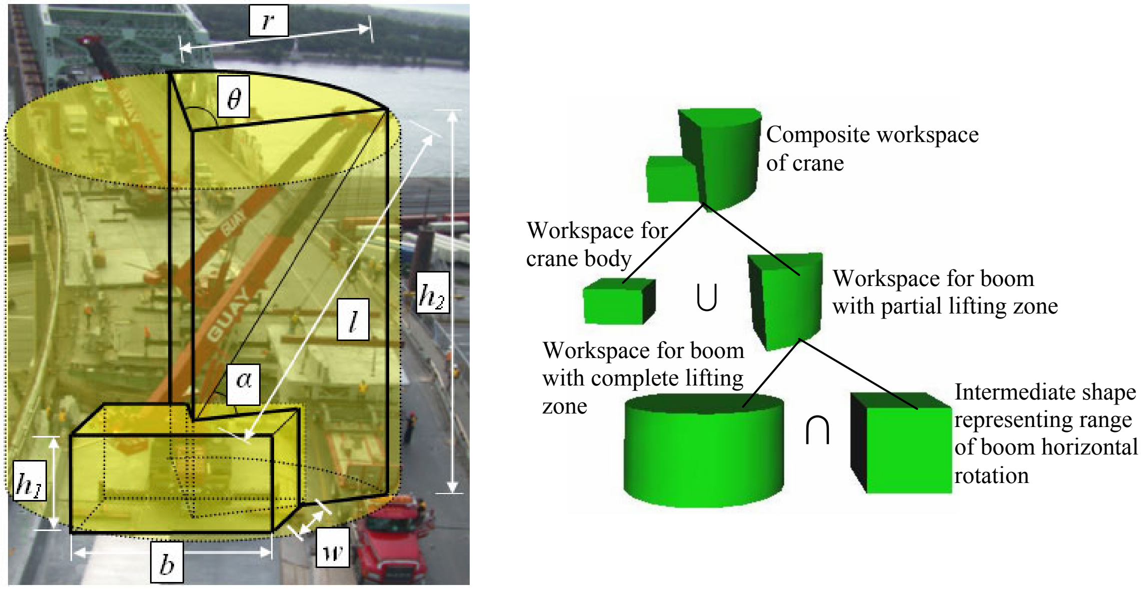



Figure 2: MicroCYCLONE Model of Jacques Cartier Bridge Re-decking Project




(a) Workspace of a Crane Superimposed on a Picture of the Construction Site

(b) Generating the Composite Shape of the Crane Workspace Using CSG

Figure 3: Example of Workspace of a Telescopic Crane

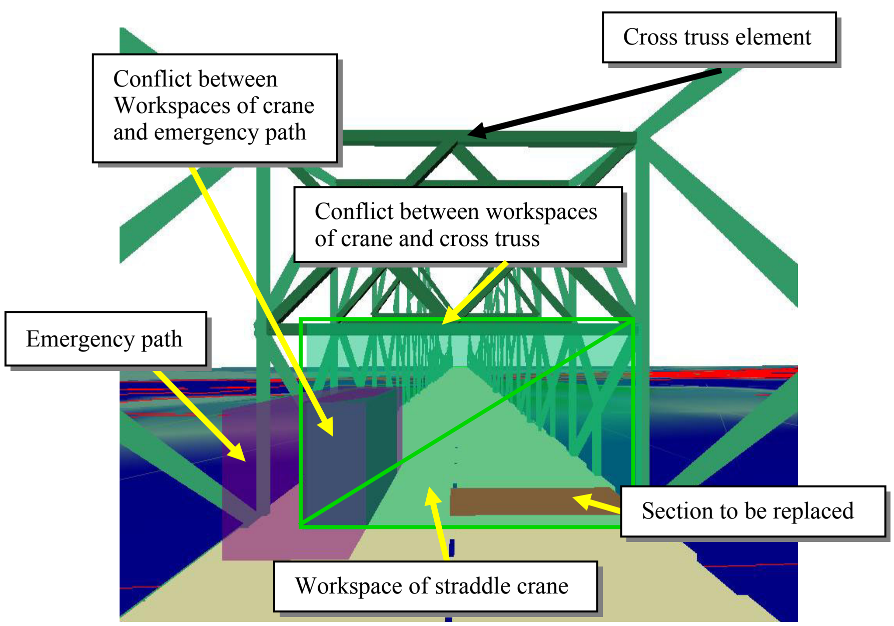



Figure 4: Conflict Detection in the Case of Straddle Crane

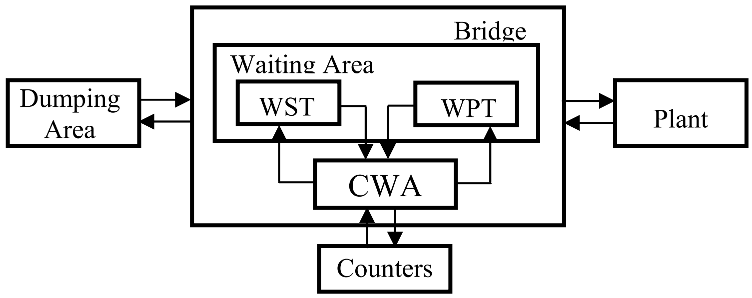



Figure 5: Interaction between Models

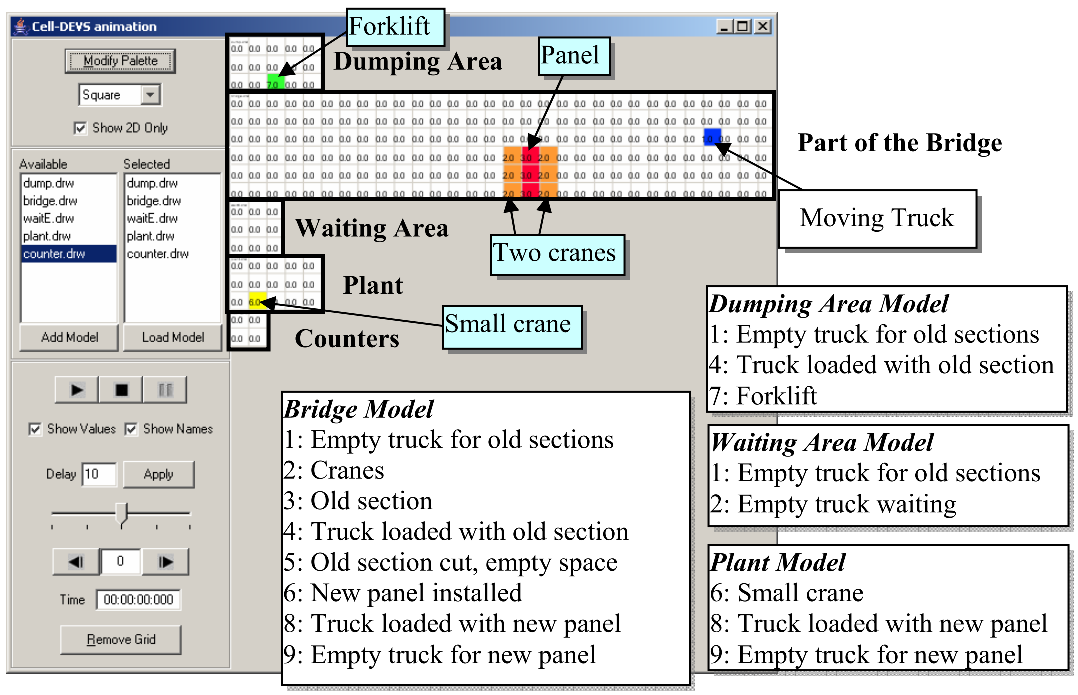



Figure 6: Graphical Display of the Cell-DEVS Model

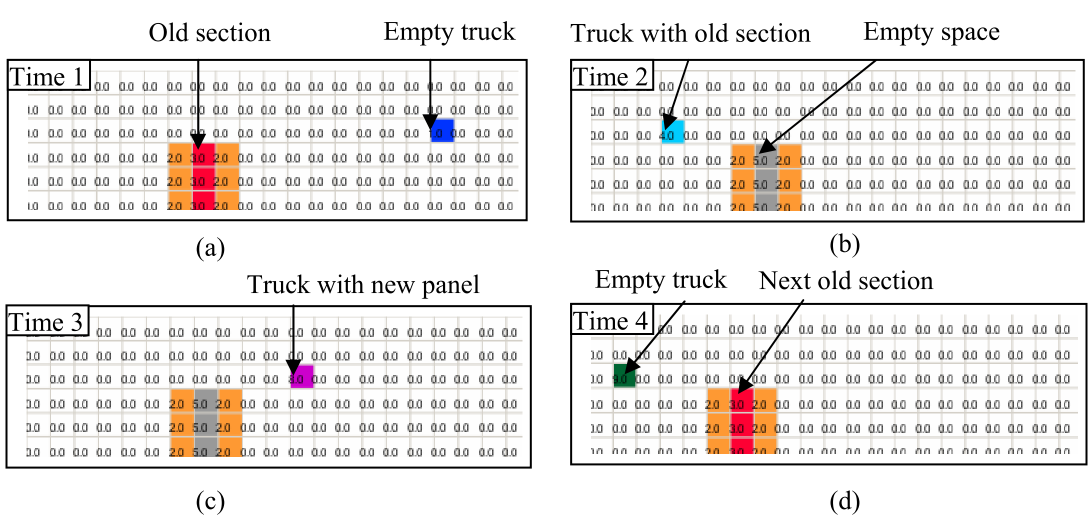



Figure 7: Part of the Bridge Model Showing the States of Each Cell

The behavior of the local computing functions is defined using a set of rules with the form: VALUE DELAY {CONDITION}. This format indicates that when the CONDITION is satisfied, the state of the cell changes to the designated VALUE, and it is DELAYed for the specified time. Each cell may have a number of states *i, j, …, n*. For example, one of the move rules on the bridge is *rule : 4 {round (normal(900000, 100))} { (0,0) = 0 and (0,1) = 1 and (1,0) = 3 and (0,-1) != 3}*, which means that when the empty truck (1) comes to the old section (3), the truck cell will change to state (4) and stay in that state for about 15 minutes following Normal distribution function based on the duration of each activity. The time delay values are given in millisecond.

***Bridge model***: Two cranes (2) and one old section (3) are initialized on the bridge. One empty truck (1) for loading old sections is also initialized at the right hand side of the bridge (Figure 7 (a)). It begins to move and reaches to the position of the section and changes its state to 4, which means that the truck is loaded with the old section. At the same time, the section changes from 3 to 5, which means the space is empty. The truck (4) continues moving to the left end of the bridge (Figure 7 (b)). The bridge model is linked with *Dumping Area*, *Waiting Area*, *Plant* and *Counters*.

***Plant model***: The signal 4 goes to *Plant*, indicating that an old section has already been cut, and a truck for transporting new panels (9) is generated at the plant and moves to the location of the small crane (6), where it changes to 8, which means that the truck is loaded with a new panel. It goes to the bridge and stops at the location of the empty space 5 (Figure 7 (c)). The space will change to 6, representing a new panel being installed (not shown in Figure 7), and after that the cranes move to the left and the next old section (3) appears in the corresponding position. At the same time, the truck state changes from 8 to 9, which means it is empty (Figure 7 (d)). The signal 9 goes to the *Waiting Area* model. If there is a waiting truck (2) there, it is activated and it changes to 1 then continues moving to the bridge and begins a new cycle.

***Dumping Area***: In *Dumping Area*, the truck (4) continues moving to the forklift (7) and unloads the old section, then changes to 1 and moves to *Waiting Area*.

***Waiting Area***: When *Waiting Area* receives signal 1, it means that one truck has unloaded an old section and is ready to go to the bridge for loading another old section. So the truck state changes from 1 to 2 and keeps in 2, waiting for a signal from the bridge (9), which indicates that the new panel is installed.

***Counters***: For the *Counters* model, when the signal 4 comes, the counter of the old sections will be incremented by one. The counter of new panels is also incremented when the signal 9 comes.

Conflict detection is controlled by another layer of cells, which matches the cells in the main layer. When different equipment try to occupy the same cell, the rules defined in the second layer will decide which equipment will occupy this cell, thus preventing collisions.

Using these interrelated cell models, the spatial relationships among construction processes can be shown explicitly. More complex models can be built by adding spatial constraints, such as adding an emergency path on the bridge, or adding another team. In addition, linking the cell space to the 3D environment discussed in Section 3.3 is also important to visualize events in 3D environment. The 3D workspace analysis model should be used to facilitate spatial analysis using cells.

To realize this idea, the whole space is divided into 3D cubic cells based on the world coordinate system to get uniformity of the representation. In addition, each cell has a unique ID. After dividing the space, occupied cells need to be identified. Based on the workspaces generated on the bridge model and using the collision detection algorithm, the cells that have been occupied at a specific time are identified (Figure 8).

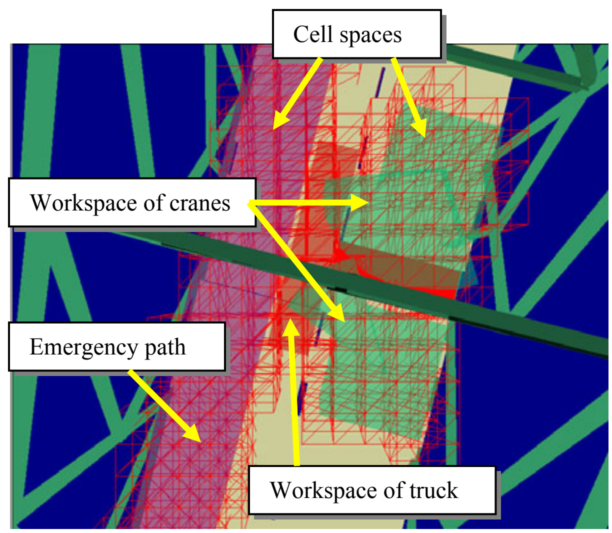



Figure 8: Occupied Cells by Different Workspaces (Top View of the Bridge)

## 5 CONCLUSION AND FUTURE WORK

This paper proposed analyzing spatial issues in construction sites using cell-based simulation. Different simulation models were built to investigate space representations and workspace conflicts analysis during construction. Dividing space into cells can be used as a general method to represent workspaces and facilitate workspace conflicts analysis. It is possible to simulate the real situation of the construction process using cell spaces. More realistic model should be developed and further study is needed to investigate the practical feasibility of cell-based models for conflict detection in 3D environments.

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