SPATIO-TEMPORAL REPRESENTATION AND ANALYSIS IN INFRASTRUCTURE SYSTEMS

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ABSTRACT

Much information is needed to manage the activities and events that occur throughout the lifecycle of an infrastructure system. Conventional Infrastructure Management Systems provide only limited support for representing, visualizing and analyzing the spatio-temporal relationships throughout the lifecycle of the infrastructure. This paper proposes a method that integrates 4D modeling with several information technologies to facilitate space and time visualization and analysis. Based on a 4D model of a bridge, two approaches are investigated for spatio-temporal conflict detection and analysis. The first approach focuses on workspace conflicts. Combinations of different 3D shapes are used to represent the workspaces, which is more accurate than the simple prismatic element that was used in previous research. The second approach dynamically detects spatio-temporal conflicts during construction using cell-based modeling techniques. Detailed procedures for each modeling method are discussed. Both methods enable conflict analysis and visualization of the worksite and the occupation of spaces.

KEY WORDS

4D modeling, infrastructure management systems, lifecycle, visualization, spatial analysis, workspace conflicts, cell-based modeling, construction simulation.

INTRODUCTION

Infrastructure systems are usually large and have long life. During the lifecycle, many changes occur and it is important to get information about these changes and represent them with respect to the infrastructure model. The traditional way of representing the information is to build data-bases about the infrastructure, including drawings of the infrastructure, inspection database, images, and documentations related to the design, construction and maintenance. However, these methods are not enough to create a visual model to demonstrate the changes that take place during the lifecycle of the infrastructure. Therefore, the spatio-temporal data should be explicitly added to the existing databases and the model of the infrastructure. The spatio-temporal data include spatial data about present shape and past changes and the time of these changes. It should be linked to the 3D model to create a 4D space (including time) and to show the changes as they happen over time. Both physical (e.g., structural) and virtual (e.g., work-related) spaces should be visually represented in the

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4D model to extend the spatial representation concept. Spatio-temporal analysis can help construction managers find spatio-temporal conflicts, and thus to avoid these conflicts or resolve them by taking suitable measures. Workspace conflicts are serious problems that can delay construction activities, reduce productivity, or cause accidents that threaten the safety of workers. Akinci et al. (2002) worked on the automation of time-space conflict analysis using 4D models. Heesom et al. (2003) developed a dynamic virtual reality system for visualizing construction space usage focusing on the workspaces required within the proximity of the components being installed. However, in previous research, simplified shapes (rectangular prisms) were used to represent different workspaces. This simplification has limitations in representing heavy equipment workspaces, such as cranes.

Simulation has been used in construction for process planning and resource allocation. However, due to the specific characteristics of workspaces, it is not easy to detect spatial conflicts without an explicit representation of space in the construction simulation. In MicroCYCLONE (Halpin 1992), space is represented by using abstract symbols. Zhang et al. (2002) have 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. 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.

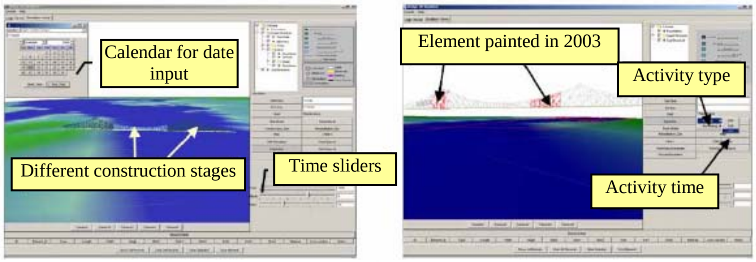
In the present paper, we choose Bridge Management Systems (BMSs) as an example of infrastructure management systems. Based on the 4D model of a bridge, two approaches are investigated for spatio-temporal conflict detection and analysis. The first approach focuses on workspace conflicts. The second approach dynamically detects spatio-temporal conflicts during construction using cell-based modeling techniques. Detailed procedures for each modeling method are discussed. Both methods enable conflict analysis and visualization of the worksite and the occupation of spaces.

PROPOSED APPROACH

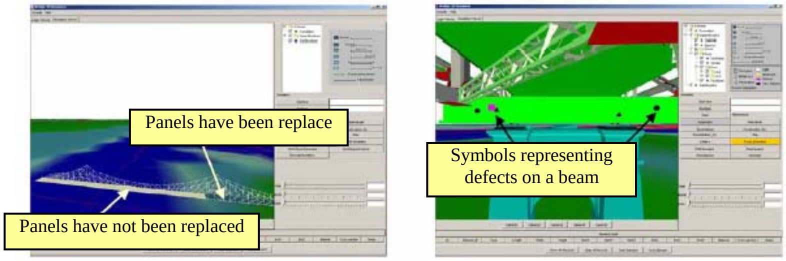
Details about the 4D model development can be found in the paper of Hammad et al. (2005). The information about the lifecycle of a bridge can be integrated with the 3D model of the bridge, resulting in 4D models which can display the changes on the 3D model at a specific time or during a specific period of the lifecycle (Figure 1). Based on the spatio-temporal information, analysis can be applied to help decision-making, such as selecting appropriate equipment according to the spatial constraints, or finding the conflicts between workspaces during construction.

WORKSPACE REPRESENTATION AND CONFLICT DETECTION

The workspace of equipment is more complex than other types because the shape and size of the workspace of equipment may change depending on the specific activity. Cranes are used as an example of equipment in the rest of the present paper. Spatial constraints may put limitations on the length and angle of the boom of a crane, thus reducing the lifting capacity



(a) Construction Stages (b) Painting History



(c) Deck Replacement (d) Defects on a beam

Figure 1: 4D Visualization of Lifecycle Information

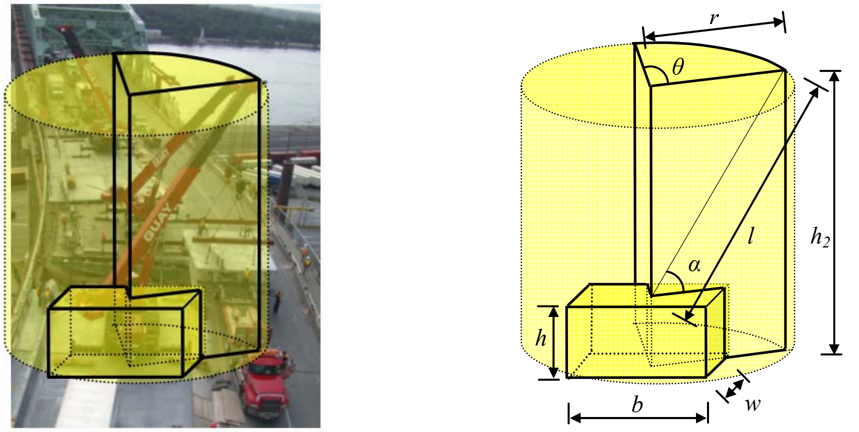
of the crane. These complex relationships between the lifting capacity of a crane and its dimensions necessitate careful consideration of the workspaces used in the spatial analysis of projects involving cranes.

Pepresentation of equipment workspaces using composite shapes

In order to represent more complex workspaces, we propose to use shapes other than boxes, e.g., cylinders, cones, or a combination of these shapes to represent more realistic workspaces, such as the workspace of the telescopic crane shown in Figure 2. In this example, the composite shape of the crane workspace is created using *Constructive Solid Geometry* (CSG) (Watt 2000) by computing the union of a box representing the workspace for the crane base (including the outriggers) and the workspace of the boom with partial lifting zone. The workspace of the boom is computed as the intersection of the complete lifting zone (cylinder) and an intermediate shape representing the angle of the boom's horizontal swinging. This method requires several parameters to define the workspace. As shown in Figure 2(b), the workspace of the telescopic crane is represented according to the dimensions of the base (h, b and w), the length (l), the angle to the ground (α), and the horizontal swinging angle (θ) of the boom.

General procedure for workspace analysis

The general procedure for workspace analysis described in this section identifies the main steps needed in a computerized system for the generation and analysis of equipment workspaces. This system integrates information from, and adds information to, the following databases and models: (1) Activity database: this database includes information about all the activities in the construction project, such as the start and finish times of each activity, the target physical components and their attributes (e.g., the deck section to be replaced), and the



(a)Workspace of a crane superimposed on a picture of construction site

(b) Parameters used in generating the workspace

Figure 2: Example of Workspace of a Telescopic Crane

types of equipment required in that activity. (2) Equipment databases: Equipment manufacturers and large construction companies usually have databases of the various equipment used in their work. These databases include the specifications about the different models of a certain type of equipment. D-Crane is a good example of such databases (Al-Hussein 1999). (3) Workspace and conflict database: This database has the schemata representing the attributes of workspaces and spatio-temporal conflicts. (4) 3D model of the site: This model integrates the digital terrain model of the construction site and the 3D CAD models of the surrounding structures. In addition, 3D shapes representing the workspaces are generated and added to this 3D model. These shapes are used to visualize and detect conflicts between the 3D elements representing the structures and the workspaces, or among the workspaces themselves, using the conflict detection algorithm. Using the above databases and the 3D model, the following procedure is applied for workspace analysis (Zhang 2005):

(1) The user starts by selecting the main activity to be considered in the workspace analysis.

(2) The system retrieves the information about this activity and all other overlapping activities from the activity database. The information includes the related objects and the required equipment types.

(3) Then, feasible equipment is selected for each required type from the corresponding equipment database. At the same time, the basic equipment parameters necessary to define their workspaces are retrieved. For example, in Figure 2(b), the following parameters should be retrieved from the crane database: b, w, h, l, and α.

(4) Other parameters that are necessary for creating workspaces and that are related to the specific site layout are input manually using the user interface of the system. For example, in Figure 2(b), the boom horizontal swinging angle (θ) can be specified by the user interactively. In addition, the relative location of equipment on site can be defined with respect to the reference object that was retrieved from the activity database, such as the section of the bridge deck to be replaced. The parameters include the orientations and the offset distances between the workspace and the object.

(5) Then, workspaces are generated using these parameters. To locate a workspace in the 3D model, the absolute location of the reference object is retrieved and combined with the relative location of the workspace to generate the absolute location of the workspace.

(6) After all the workspaces have been generated and located in the 3D model, the conflict detection algorithm is applied on each pair of workspaces, or on a workspace vs. a physical component of the structure. The conflict is also represented as a 3D shape in the 3D model. In addition, the dimensions of the conflict and other related information are saved in the workspace and conflict database.

Workspace conflict detection

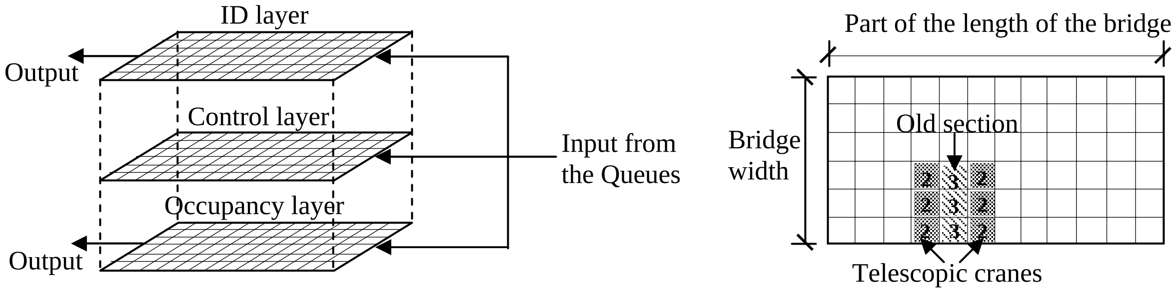
Two types of test are applied to detection conflicts between workspaces: (1) the test of the intersection of the bounding boxes of the workspaces (BWS_i and BWS_j), which are two rectangular prisms with parallel faces, and (2) the general intersection test using CSG. The reason for this is that CSG is computationally intensive when considering the very large number of objects (workspaces and physical components) for which interference may have to be checked. In the first test, a conflict can be detected simply by comparing the distance between the center points of the two rectangular prisms with the dimensions of the prisms. If a conflict exists, the CSG test is applied to confirm the existence of the conflict based on the detailed representations of the workspaces and to find the accurate shape of the intersection. Details about the algorithem can be found in Zhang (2005).

CELL-BASED SIMULATION MODELING

To further investigate the spatio-temporal conflict in a dynamic way, we propose to use cell-based modeling to simulate the construction processes. In 1948, John Von Neumann and Stephan Ulam introduced a modeling formalism, called Cellular Automata (CA), suitable for defining spatial systems and to 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 those of its nearby neighbors. In the 1970s, Bernard Zeigler (1976) defined a theory for Discrete-EVent systems Specification (DEVS). It is a formal method for building models using a hierarchical and modular approach. Zeigler also defined a cell space model that 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. Based on the concept of cell space and DEVS formalism, Wainer (1998) developed an approach called Cell-DEVS, which describes cell spaces as discrete event models using the DEVS formalism, including delay functions to have a simple definition of the timing of the cell. This section investigates the possibility of a cell-based approach for the representation and analysis of spatial resources in construction simulation.

General procedure of applying cell-based modeling in construction

The following procedure shows the specific steps that can be used in simulating construction activities using Cell-DEVS approach (Zhang et al. 2005):



(a) The three layers used to model occupancy, direction, and ID information

(b) Cell representation of the *occupancy layer*

Figure 3: Cell Representation of the *Bridge* Model

(1) **Identify Cell-DEVS and DEVS models.** Cell-DEVS models are used where the spatial representation is important; while the DEVS models are used to simulate the parts that do not need spatial representation or could not be represented using cells. For example, in our case study that is described in a later section, three main working areas are represented as Cell-DEVS models: *Bridge, Plant* and *Dump Area.* DEVS models are used to build the models of queues and transports between these Cell-DEVS models.

(2) **Define the relationships and information exchange between models and connect them using input and output ports.** For example, whenever there is an old section to be replaced, a request for a truck to go to the *Bridge* model will be sent to the queue of waiting trucks.

(3) **Decide the suitable size of cells and the dimensions of each Cell-DEVS model.** For example, the cell size of the bridge model is assumed to be 3*3 meters.

(4) **Define the layers of each model.** Based on our experience in cell-based modeling, three layers should be created for the *Bridge* model to represent the occupancy, mobility conditions and IDs of the objects occupying the cells (Figure 3(a)). The first and main layer is the *occupancy layer*, which has the occupancy states of the cells (e.g., the type of equipment occupying a cell). The second layer is the *control layer*, which decides the mobility state and moving direction, detects conflicts between objects, and sets the priority of moving depending on the types of objects as defined in the *occupancy layer*. The *ID layer* contains the ID numbers of each piece of equipment.

(5) **Identify the resources needed and define the codes that will be used in Cell-DEVS models.** Different encodings can be used to represent equipment states, the occupancy of cells, and the IDs of equipment. For example, Figure 3(b) shows an old section (2) and two cranes (3) beside it, which occupies 3 cells each.

(6) **Analyze the activities and develop rules for each Cell-DEVS model.** Cells can communicate with each other through rules that detect the state changes of a cell's neighborhood and that change the cell's own state accordingly. There are several types of rules that could be applied for simulating construction activities, such as rules for moving trucks, conflict detection, truck generation, direction changes, etc. Each rule has a condition part, an action part, and a time delay.

(7) **Develop the DEVS models.** DEVS models can be developed based on the functions that they perform, such as queues or transport functions.

(8) **Initialize the resources and run the simulation.** The number of resources should be initialized before running the simulation. For example, the number of trucks can be initialized in the *Dump Area* and the *Plant* models. Then, the simulation tool generates the discrete changes of states in each model when running the simulation. The result of the simulation can be visualized as an animation that gives a quick method for checking the results.

PROTOTYPR SYSTEM AND CASE STUDY

The prototype system integrates a 3D model of a bridge with databases and a Geographic Information System (GIS) using Java language (Hammad et al. 2005). Java3D is used to implement the 3D graphics of the system. Java Database Connectivity (JDBC) is used to access information stored in the databases. The three databases (activities, cranes, and workspace and conflict databases) discussed above are developed with Microsoft Access. The Jacques Cartier Bridge in Montreal is chosen as the subject of the case study. The old reinforced concrete bridge deck had suffered seriously from the increase of the number and load of trucks and from the de-icing salts. Consequently, the deck was replaced in 2001-2002. The existing deck was removed by using a saw to cut the deck into sections with dimensions similar to those of the new panels being installed. Each existing deck section was removed and a new panel was lifted by two telescopic cranes 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 at the south end of the bridge. Figure 4 shows a schematic representation of the worksite layout during the deck replacement on the main span of the bridge. The low clearance below the cross-frame of the through truss was a major constraint in selecting the cranes. We used the workspace analysis approach to investigate the feasibility of two types of cranes: straddle crane and telescopic crane. In the case of a straddle crane, when an old section is cut and removed by the crane, the empty area on the deck becomes a safety area and the crane moves to the other side across the road to load the old sec tion on a trailer and then waits for unloading a new panel from another trailer. Therefore, the workspace of the straddle crane covers the range of positions of the crane along the width of the bridge. The workspaces of the telescopic cranes are represented

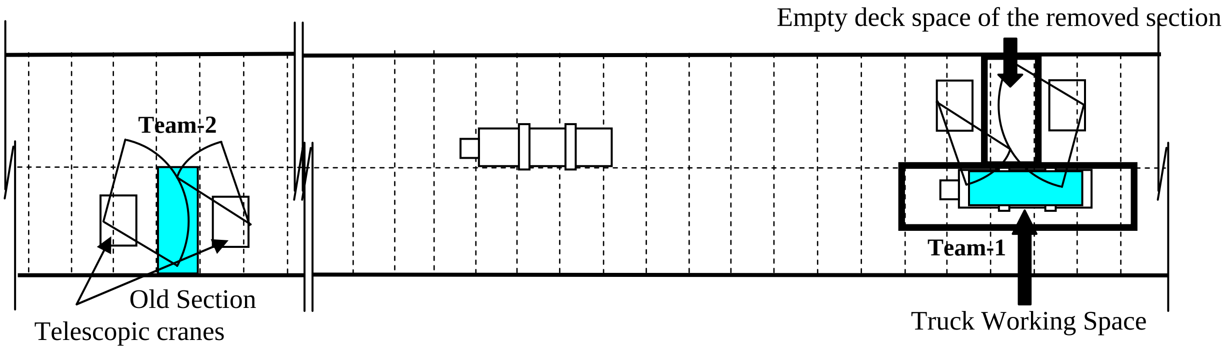
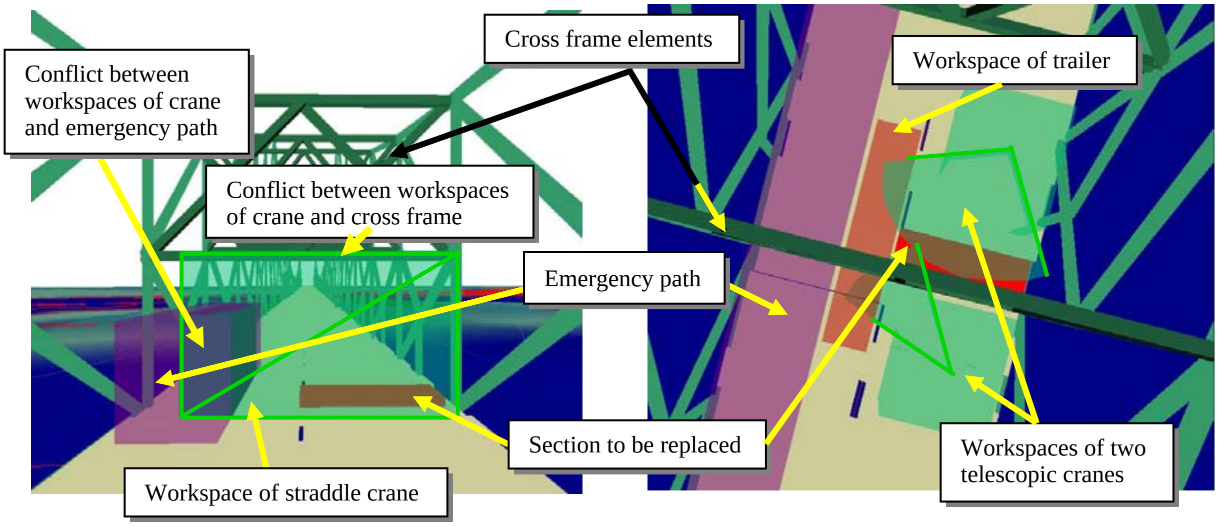


Figure 4: Worksite Layout on the Main Span of the Bridge



(a) Straddle crane viewed from the road level (b) Two telescopic cranes viewed from the top of the bridge

Figure 5: Workspace Conflicts Detected in the Case Study

by composite shapes as shown in Figure 2. Both conflicts among workspaces and between workspaces and the components of the truss are automatically detected and analyzed. Figures 5(a) and (b) show different workspaces in the case of using one straddle crane or two telescopic cranes, respectively. In Figure 5(a), the workspace of the straddle crane and the emergency path are represented by two transparent boxes, and a conflict between them is detected. In addition, another conflict between the crane workspace and the cross-frame is detected. Figure 5(b) shows a top view of the workspaces of the two telescopic cranes with near-flat booms on both sides of an old section, the trailer and the emergency path. Although there are overlapping parts between the workspaces of the cranes and the trailer, this overlap does not cause any real conflicts because the booms of the cranes always move above the trailer. No other conflicts are detected in this case between the workspaces and the components of the truss. In the actual re-decking project, the contractor built a physical model of the bridge to check the conflicts that could appear when using these two types of cranes. Because of the spatial conflicts, the contractor decided to use two telescopic cranes instead of the straddle crane.

To detect the conflicts in the worksite in a dynamic way, we applied the second approach to develop a cell-based simulation model for the re-decking project using CD++, a tool for cell-based discrete-event modeling and simulation (Wainer 2002). This model is a combination of Cell-DEVS and DEVS models. *Bridge*, *Plant*, and *Dump Area* are created as 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 will 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. We did the simulation of the Jacques Cartier Bridge re-decking case study using the following resources based on the data from the real project: two teams, two trucks for carrying old sections, and two trucks for carrying new panels. The construction time that has been simulated is 9 hours, which is the real construction period from 8:30 p.m. to 5:30 a.m. the next day. The result of the simulation shows that 18 panels have been installed during this period, a number which is the same as the result obtained from the simulation using MicroCYCLONE. The worksite layout can be displayed at every time step to show the space occupancy in the *Bridge* and other Cell-DEVS models. Figure 6 shows part of the occupancy layer of the *Bridge* model, where two teams are working on the bridge in parallel. Figure 6(a) shows that Truck-1 is loading an old section while Truck-2 is coming to unload a new panel at another location. Figure 6(b) shows Truck-1 finished work and is carrying the old section to the dump area, and Truck-2 is unloading a new panel. The advantages of using cell-based simulation are: (1) The space can be represented explicitly and the simulation models can be visualized so that the occupation of the workspace and other spatial information of the construction environment can be understood more easily than using conventional models; (2) The conflicts between spaces can be detected based on the site layout; and (3) The accuracy of the duration of activities is expected to improve, especially for situations where spatial conflicts are present.

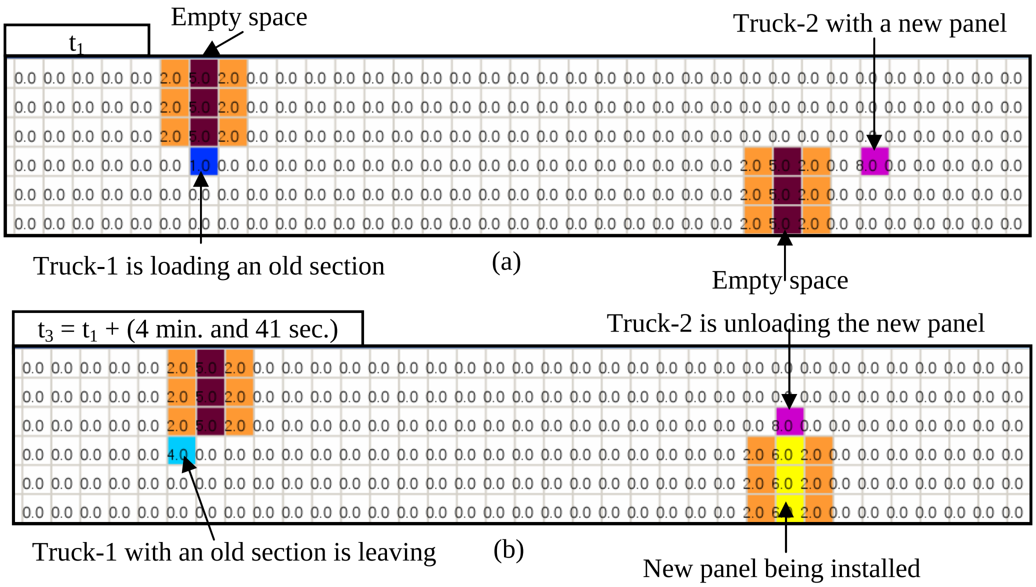


Figure 6: Snap Shot Showing Part of the *occupancy layer* of the *Bridge* Model

CONCLUSIONS

Two spatio-temporal analysis approaches are proposed in this paper: workspace analysis and cell-based simulation of construction processes. The first approach focuses on representing workspaces in a more realistic way. Composite shapes with different levels of complexity are used to represent workspaces of equipment using CSG techniques, which extends the workspace representation using simple shapes. The proposed procedure integrates the attributes of a construction activity, the attributes of the equipment, and the geometry information retrieved from a 3D model to generate the workspaces, and then to apply conflict detection algorithms on them. The developed prototype system was tested by several project managers and they gave positive evaluation. The second approach investigats the possibility of a cell-based simulation to further analyze the spatio-temporal conflicts in a dynamic way during construction. Based on the cell representation of the spatial model, the information of the construction environment can be understood more easily and the optimal resources combination can be found not only based on resource constraints, but also based on the availability of workspaces. Spatio-temporal conflicts can be avoided by applying rules to control the movement of equipment and other objects. The proposed general procedure of developing cell-based construction simulation models shows the specific steps that can be used in simulating construction activities. This procedure has several advantages over conventional simulation tools in representing spatial constraints and detecting spatio-temporal conflicts.

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