ANALYSIS AND RESOLUTION OF EQUIPMENT WORKSPACE CONFLICTS IN INFRASTRUCTURE PROJECTS

By Amin Hammad¹, M.ASCE, Cheng Zhang², and Germain Cardinal³

¹ Assoc. Prof., Concordia Institute for Information Systems Engineering, Concordia University
1425 René Lévesque Boulevard, Montreal, Quebec, H3G 1T7, Canada, E-mail hammad@ciise.concordia.ca

² Grad. Res. Asst., Department of Building, Civil and Environmental Engineering, Concordia University
1425 René Lévesque Boulevard, Montreal, Quebec H3G 1T7, Canada, E-mail zha_che@encs.concordia.ca

³ Construction Project Manager, SNC Lavalin
2601, Principal, St-Joseph-du-Lac, Quebec, J0N 1M0, Canada, E-mail germaincardinal@sympatico.ca

Abstract

Workspace conflicts are one of the important problems that can delay construction activities, reduce productivity, or cause accidents that threaten the safety of workers. Workspace planning is particularly important in the case of large infrastructure projects, such as bridge construction and rehabilitation projects where heavy equipment is required. This paper aims to extend the previous research on workspace analysis and conflict resolution in the case of large infrastructure projects focusing on the following issues: (1) Specific representation of workspaces related to heavy construction equipment taking cranes as an example; (2) More realistic workspace definition using composite shapes based on Constructive Solid Geometry; (3) Semi-automatic conflict resolution based on a decision-support expert sub-system; and (4) Development of a CAD-independent system that can automatically generate workspaces, detect spatio-temporal conflicts, and support the decision-making process of resolving them in an interactive 4D environment. The computational aspects of the proposed approach are discussed and demonstrated by developing a prototype system and applying it in a case study about deck replacement of Jacques Cartier Bridge in Montreal.

Keywords: Workspace Analysis, Spatio-temporal Conflict Resolution, Construction Equipment, Infrastructure Projects, Bridge Re-decking, Constructive Solid Geometry
Introduction

Workspace conflicts are one of the important 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%. Early researches in this area focused on work patterns, which are important for space planning. In order to better understand workspaces, Riley and Sanvido (1995) defined repeatable patterns that describe how typical activities use space over time. They also presented a planning method, which is represented by a process model defining a logical order and priorities for decisions about construction space plans (Riley and Sanvido 1997). The development of 3D visualization techniques in the construction industry has greatly improved the efficiency of space planning. However, 3D models lack the temporal information needed for scheduling. On the other hand, scheduling software lacks the 3D geometric information to represent workspaces. 4D models include both the temporal and the 3D geometric information necessary to display when and where the activities are going to occur. 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. Although this approach would find the exact locations of collisions between objects based on the small time step used in the simulation, it does not provide a comprehensive method for solving the conflicts because the detected collisions are based on instantaneous situations (in contrast with the range of mobility situations represented by a workspace). Akinci et. al. (2002b) worked on the automation of time-space conflict analysis using 4D models. They have developed a prototype system – 4D WorkPlanner Time-Space Conflict Analyzer (4D TSConAn) using 4D models and classified spaces into three categories: macrolevel spaces, microlevel spaces, and paths. 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, such as workspaces for crews, equipment, and hazardous and protected areas.

Workspace conflicts have three characteristics that differentiate them from design 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. The challenges in spatio-
temporal analysis of these conflicts involve their detection, categorization and prioritization (Akinci et al. 2002b).

For example, conflicts between two labor crews are categorized as congestion, and conflicts between a protected space and an equipment space is defined as damage conflict. Most of the previous research work related to workspaces focused on the conflicts among workspaces without considering the conflicts that could happen between workspaces and the spaces occupied by physical components. This could be explained based on the assumption that the workspaces are designed in such a way that avoids those conflicts. However, this assumption is difficult to maintain in certain sites because of the complex geometry of the existing structures, as in the case of replacing the deck of a through truss bridge using large prefabricated panels. This example will be used as a case study in this research and will be explained in detail in a later section of this paper.

Workspace planning is particularly important in the case of large infrastructure projects, such as bridge construction and rehabilitation projects where heavy equipment is required. In these projects, selecting the wrong type of equipment would result in large losses because of the high cost of renting or purchasing the equipment. Several studies are available to help in selecting adequate equipment that satisfies both the requirements of the construction tasks and the spatial constraints of the site. For example, Al-Hussein (1999) developed a crane selection system that considers several technical, contractual and economical factors. The technical factors address the suitability of the selected crane to perform the task at hand considering site and lift conditions. Site conditions are mainly related to site layout and topography, presence of adjacent buildings and power supply cables, and availability of sufficient space for erecting and maneuvering the crane. Lift conditions include the weight, shape, and size of the planned lifts during construction (Construction Safety Association of Ontario 2005).

In the case of mobile cranes, the crane mounting configuration (i.e., all terrain, rough terrain, crawler-mounted, or truck-mounted), the boom type (i.e., lattice or telescopic), and the jib configuration should be considered.

The ultimate goal of workspace conflict analysis is to resolve the detected conflicts by changing the location, shape, or size of at least one of the workspaces that caused the conflict, or by changing its start and end time. Guo (2002) integrated CAD and schedule information for the identification and resolution of workspace conflicts. He defined several variables for subsequent analysis including interference space size, interference space percentage, interference duration, and interference duration percentage. A series of criteria is developed for analyzing conflict characteristics and assisting in deciding which activity requires adjustment. These criteria
include: changing the logical sequence of activities, changing the time of activities that are not on the critical path, considering workspace divisibility, changing the location, space size, start time of conflicting space occupation, or length of occupancy time. Mallasi and Dawood (2004) provided a multi-criteria weighting approach for critical space-time analysis. Zouein et al. (2002) used genetic algorithm for solving site layout problems, which only needs an objective function with no specific knowledge about the problem space. Chevallier and Russell (2001) created templates from previous experience to develop draft schedule using a rule-based expert system, which can merge different templates to represent a complex project. Although several methods have been proposed in the literature for resolving workspace conflicts, there is no detailed discussion on how to apply these methods automatically in a decision-support system.

This paper aims to extend the previous research on workspace analysis and conflict resolution in the case of large infrastructure projects focusing on the following issues: (1) Specific representation of workspaces related to heavy construction equipment taking cranes as an example; (2) More realistic workspace definition using composite shapes based on Constructive Solid Geometry (CSG); (3) Semi-automatic conflict resolution based on a decision-support expert sub-system; and (4) Development of a CAD-independent system that can automatically generate workspaces, detect spatio-temporal conflicts, and support the decision-making process of resolving them in an interactive 4D environment. The next section of the paper is about the proposed approach of this research including a detailed discussion of the above-mentioned issues. This is followed by a discussion of the computational aspects of the proposed approach. Details about a prototype system and a case study to demonstrate the approach are explained in the subsequent sections. Finally, the conclusions of the paper are summarized along with recommendations for future work.

**Proposed Approach**

**Specific representation of workspaces related to cranes**

As discussed in the Introduction Section, one of the main criteria in selecting cranes in a certain project is to satisfy site conditions. However, the shape and size of the workspace of a crane may change depending on the specific activity. For example, the location and shape of the lift will define the required lifting zone that can be covered by changing the length and angle of the boom of the crane. On the other hand, spatial constraints may put
severe limitations on the length and angle of the boom, thus reducing the lifting capacity of the crane. In many cases, these constraints impose a certain construction method that would not have been used otherwise, such as using two cooperative telescopic cranes instead of one larger straddle crane (Ali et al. 2002). 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. Another important issue when considering conflicts of equipment workspaces is the temporal Levels of Details (LoDs) used in analyzing the conflicts. Most previous research focused on crew workspaces where activities can be packaged in units that take several days or weeks to be done. For example, Akinci et al. (2002a) used three-week look-ahead schedule while Heesom et al. (2003) analyzed a weekly spatial layout. However, a more detailed temporal representation is needed for highly mobile resources, such as cranes utilized in dynamic environments with many concurrent activities.

More realistic workspace definition using composite shapes based on CSG

Previous researches simplified the shape of workspaces by assuming simple box shapes (rectangular prisms). For example, Akinci et al. (2002a) suggested a generic representation of workspaces using a reference object, orientation, and volumetric parameters. However, this simplification is not applicable in the case of cranes where the workspace should be defined based on the range of the dimensions of a crane occurring with the dynamic changes of its different components. In order to represent more complex workspaces, it is proposed in this research to use shapes other than boxes, e.g., cylinders, cones, and spheres, or a combination of several shapes using 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. An object representation is stored as an attributed tree. The leaves contain simple primitives and the nodes store Boolean operators or linear transformations. An object is built up by adding primitives and combining them with existing ones. Using CSG, complex shapes can be created to represent more realistic workspaces, such as the workspace of a telescopic crane shown in Fig. 1. In this example, the composite shape of the crane workspace is created by computing the union of a box representing the workspace for the crane body (including the outriggers) and the workspace of the boom with partial lifting zone. The workspace necessary for the boom is computed by taking the intersection of the complete lifting zone (cylinder) and an intermediate shape representing the angle of the boom’s
rotation around a vertical axis.

**Semi-automatic conflict resolution based on a decision-support expert sub-system**

In previous researches, conflict resolution was given little discussion. Conflicts detected in a plan can be resolved manually by changing the shape or location of one or more workspaces, or changing the work schedule to eliminate the time conflict. However, it is necessary to analyze the result after these changes to verify that they do not create new conflicts. This could necessitate repeating this process of detecting and resolving conflicts several times before a conflict-free plan is found. In some cases, a feasible solution may require changing the construction method. Research in Artificial Intelligent (AI) discussed algorithms for solving planning problems involving spatio-temporal conflicts (Russell and Norvig 2003). Furthermore, the development of AI techniques makes it possible to store the expertise and knowledge of construction managers into the knowledge base of an expert system to facilitate the automatic generation of construction schedules (Wang 2001). An expert system is suited for complex decision-making, therefore extending computing power beyond the mathematical and statistical constructs of simulation and conventional programming (Allen et al. 1996). However, the application of AI techniques in engineering problems has found limited success so far because of the complexity of these problems. Therefore, a fully automated approach is unlikely to give satisfactory solutions for problems related to workspace conflicts. It is proposed in this research to develop a semi-automatic conflict resolution method based on a decision-support expert sub-system that will compare the attributes of the detected conflicts against a set of predefined rules, and suggest some solutions to the user of the system.

**Development of CAD-independent system for workspace management**

Most of the previous research works are demonstrated through the development of prototype systems that are based on CAD software. Although this approach effectively uses available CAD drawings for generating the workspaces exploiting the functionalities of the CAD software, it limits the possibilities of generating and analyzing workspaces to the framework of that software. In spite of the many possibilities that exist for customizing CAD software and linking them with external applications, this approach does not provide the flexibility and portability available when developing software with a standard programming language based only
on Application Programming Interfaces (API). Therefore, this research proposes the development of a CAD-independent system that can automatically generate workspaces, detect spatio-temporal conflicts, and support the decision-making process of resolving them in an integrated, interactive 4D environment. In the following sections, the main computational aspects required in this system are discussed and detailed discussion is given about a prototype system that has been developed in this study.

Computational Aspects of the Proposed Approach

Specifications for workspace management system for infrastructure projects

(1) 4D Visualization and interaction

The advantage of visualization is that the user can simulate and check the interferences that may happen in reality between the 3D physical elements and virtual workspaces or among virtual workspaces. In many infrastructure projects, such as the case study discussed in a later section of this paper, a physical model of the project is built to check workspace interferences. The proposed system would provide a digital 4D model to facilitate spatio-temporal analysis instead of the more costly method of building physical models. The system should have an advanced user interface to help the user in defining complex workspaces. For example, the user can pick an element of the structure model using the pointing device to edit the location and orientation information of workspaces relative to the picked surface of that element. Then, the composite shape of the workspace is automatically created based on parametric equations. For example, as shown in Fig.1(b), the workspace of a telescopic crane has a cylindrical part representing the workspace of the boom. The radius ($r$) and the rotation angle of the boom about a vertical axis ($\theta$) can be specified by the user interactively. Furthermore, information about workspaces and conflicts can be shown on the model using different colors and transparency levels. Elements of the structure can be shown as solid shapes with opaque colors while workspaces can be shown as transparent shapes with different colors to represent different types of workspaces. Then, conflicts can be shown as shapes with faces bearing the colors of the respective conflicting objects.

(2) Usability throughout project lifecycle

Workspace management in infrastructure projects is a task that is required throughout the lifecycle of these
projects. Although previous research put more emphasis on workspaces related to construction activities, maintenance activities (e.g., repair, rehabilitation, and replacement) have similar requirements with respect to workspaces with additional spatial constraints resulting from the fact that maintenance activities are very often executed under operational conditions of the infrastructure. For example, road maintenance activities are done while closing a certain number of lanes and allowing the traffic on other lanes (Karim and Adeli 2003; Chien et al. 2002).

(3) Linking 3D models of structures and workspaces to actual geographical spaces

In large-scale infrastructure projects, Geographic Information Systems (GIS) are inevitably needed for generating information that relates to locations. Spatial conflicts would not be understood fully if they were not linked to geographical locations as perceived in the real world (Zlatanova et al. 2002). This requirement is important because it adds the possibility of monitoring the execution of the work in real time using tracking techniques, such as the Global Positioning System (GPS), while comparing the location of the workers and equipment with the corresponding workspaces as planned in the construction schedule (Navon and Goldschmidt 2003). The monitoring could be used to measure the efficiency of the work, check safety requirements, or control the equipment to automate the construction work. This requirement can be achieved by integrating the CAD models with GIS, so that the results of workspace analysis would be computed using geographic coordinates that can be related to actual locations using digital maps.

(4) Building 4D models based on standard data structures

Because of the need to exchange information in infrastructure projects, using standard data structures to represent workspaces is highly desirable. Akinci (2002c) explored the potential of using Industrial Foundation Classes (IFC) space representations to represent workspaces. IFC is an open international standard managed by the International Alliance of Interoperability (IAI 2004). In IFC2x2 the concept of visual presentation of geometric items has been added to the IFC model. However, none of the space representations within IFC properly represents micro-level activity space requirements. In the proposed approach, formal definitions of workspaces and conflicts are suggested and can be used as a base for extending IFC space definitions as shown in Fig. 2. The *Workspace* class
defines the basic geometric and temporal information, such as location, dimensions, time, etc. Functions for creating and displaying a workspace as well as for Boolean operations (e.g., intersection) are also defined in this class. Conflict class has a similar structure but has additional attributes to calculate spatial and temporal interference ratios.

(5) Database and knowledge base design

The proposed system should have a database that combines the information of the structure’s model, the related activities during all the stages of the lifecycle, and the workspaces definitions based on related physical objects (elements of the structure and equipment) and activities. Knowledge related to conflict resolution should be organized in the knowledge base of a rule-based expert system. However, the knowledge base should have a mechanism to access and update information in the database.

Fig. 3 shows the integrated structure of the proposed system based on the above requirements.

Workspace generation and analysis

Fig. 4 shows the flowchart of the workspace analysis in the proposed approach. The analysis is done to detect spatio-temporal conflicts related to construction activities during a specific period of time. All the corresponding activities are retrieved by querying a database, and the information about the related physical objects \(\{O\}\) (structural elements, equipment, etc.) are found and used to initialize the attributes of the workspaces, such as the start time and the duration of a workspace. Furthermore, geometric attributes about the physical objects (e.g., transformations, normal vectors, etc.) are computed based on information extracted directly from the scene graph. This information is used to find the location of a workspace relative to a physical object. The normal vectors of the surfaces of the objects are used to represent the orientation of the workspace, and offset distances along those vectors are used to define its relative location. For example, Fig. 5 shows a simplified 2D example for locating a workspace above and to the left of a reference object with offset distances of \(d\) and zero in the directions of the normal vectors \(N_1\) and \(N_2\), respectively.

After all the workspaces \(\{WS\}\) are created based on the above information, conflict detection is applied on pairs of workspaces (or a workspace and a physical object) that have temporal overlap. Two cases are considered
in this step: the simple case of parallel boxes (two rectangular prisms with parallel faces) and the general case where one or two of the workspaces have a composite shape or a shape that is not a box. CSG is a powerful method for representing workspaces and detecting conflicts between them. However, CSG is computationally expensive when considering the very large number of objects (workspaces and physical objects) for which interference has to be checked. A special, albeit very common, case is the case of a pair of objects where the shapes of both objects can be approximated to simple rectangular prisms and where the objects have parallel faces (Fig. 6(a)). Examples of this case are the crew workspace used when fixing windows into walls. In this case, 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, a conflict box is created, its attributes are calculated, and the conflict information is added to the database. This information is used to help in resolving the conflict using a rule-based expert sub-system. The following two paragraphs explain about the conflict detection algorithms used in the cases of parallel boxes and complex shapes:

(1) **Collision detection algorithm in the case of parallel boxes**: To simplify the analysis of two parallel boxes, the inverse transformation of one of the workspaces is applied to both of them so that the spatial relationship between them is maintained. This will result in the first box being transformed to the origin (i.e., its center point is at the origin) and both boxes having their edges parallel to the axes of the coordinate system (Fig. 6(a)). The distance between the center points are calculated in three dimensions ($\triangle x$, $\triangle y$, and $\triangle z$). If $\triangle x < (a_1+a_2)/2$ and $\triangle y < (b_1+b_2)/2$ and $\triangle z < (c_1+c_2)/2$ (where $a_1$, $b_1$, $c_1$ and $a_2$, $b_2$, $c_2$ are the dimensions of the two boxes) then there is overlapping between the two boxes and a conflict exists. For the purpose of simplicity, the 2D cases of intersection and containment are shown in Figs. 6(b) and (c), respectively. For example, in Fig. 6(b), $\triangle x > abs((a_1-a_2)/2)$ and therefore, the dimension of the conflict box along the $X$ axis is $a_c = (a_1 + a_2)/2 - \triangle x$. Fig. 6(c) shows that $\triangle x \leq abs((a_1-a_2)/2)$ and therefore $a_c = min(a_1,a_2) = a_2$.

(2) **Collision detection algorithm in the case of complex shapes**: For complex shapes created using CSG operators, a common exact collision detection algorithm is used (Watt 2000). Three tests are applied and the success of any of them implies that a collision has occurred. For the case of the two convex polyhedra $P$ and
shown in Fig. 7, the first test is to check if any of the vertices of \( Q \) is contained in \( P \) and vice versa (Fig. 7 (a)). Each vertex of \( Q \) has to be checked against every face of \( P \), and a collision is detected if any vertex is on the inward side of all the faces of \( P \). Thus for each vertex \( v_i \) of \( Q \) and for each face \( j \) of \( P \) the dot product \((v_i - u_j) \cdot N_j\) is evaluated, where \( u_j \) is any vertex of face \( j \) and \( N_j \) is its outward normal (Fig. 7 (c)). If this dot product is negative then the vertex \( v_i \) is on the inward side of face \( j \). In the second test, the edges of \( Q \) are tested for penetration against the faces of \( P \) and vice versa (Fig. 7(b)). The intersection of an edge \((v_i, v_j)\) of \( Q \) with the planes containing the faces of \( P \) is calculated. For any plane \( k \) of \( P \), an edge intersects it if the perpendicular distance from each vertex to the plane changes sign. The intersection point \( x \) can then be calculated as follows:

\[
\begin{align*}
  d_i &= (v_i - u_k) \cdot N_k \\
  d_j &= (v_j - u_k) \cdot N_k \\
  t &= |d_i|/(|d_i| + |d_j|) \\
  x &= v_i + t(v_j - v_i)
\end{align*}
\]

Equations (1)

This gives, in general, a number of intersection points along the edge. Those for which \( t \notin [0, 1] \) are discarded and the remaining points are sorted in order of their \( t \) values. These form a sequence of potential intersections from one vertex to the other (Fig. 7 (d)). Finally, to check for intersection, the midpoint of each pair can be substituted into the first test. The third test is to check the infrequent case of two identical polyhedra with faces perfectly aligned.

**Conflict Resolution Using a Ruled-Based Expert Sub-System**

Three resolution strategies can be considered to resolve the detected conflicts (Guo, 2002): (1) Adjust space demand by changing the location of the space or dividing the original space into several smaller volumes to eliminate space conflicts; (2) Adjust the planned schedule to avoid space conflicts. Typical solutions for this strategy include adjusting the starting time of an activity, reducing the period for space requirements, or splitting the working period; (3) The third strategy is a hybrid approach, which adjusts the space demand and scheduling sequence simultaneously. In some cases, these changes may result in changing the construction method and using equipment different than those selected in the original plan. The proposed approach to resolve conflicts is a semi-automatic method where the user interacts with the system to make modifications and resolve the conflicts based
on the suggestions given by an expert sub-system, which is dynamically linked with the database and the workspace simulation. After conflict detection, the type of the physical objects and workspaces causing the conflict are checked. If the conflict is between a physical element and a workspace, then the workspace must be changed. If the conflict is between two workspaces, then each of them is checked to see whether it can be changed in time or space. At present only basic rules are defined based on the assumption that the database of the system has enough information about the possibilities to modify workspaces. More detailed knowledge should be added to the knowledge base to facilitate the automatic analysis of the workspaces (e.g., the possibility to change location, size, start time, duration, etc.).

Prototype System

The prototype system integrates a 4D model of a bridge with an object-relational database and GIS (Hammad et al. 2004). Using the 4D model, the user can directly interact with the system to get information on a certain stage of the lifecycle of a bridge. Java programming language is used to build the system and Java 3D is used to implement the 3D graphics of the system (Walesh and Gehringer 2001). Java 3D is a runtime API for developing portable applications and applets that can run on multiple platforms and multiple display environments. The 4D model is built using Java 3D based on CAD drawings and other data about construction and maintenance schedules. Virtual universes in Java-3D can be created from scene graphs. Scene graphs are assembled from objects to define the geometry, location, orientation, and appearance of objects. Java 3D scene graphs are constructed from node objects forming a tree structure in parent-child relationships. BranchGroup objects are used to form scene graphs. TransformGroup objects can be constructed by applying Transform3D objects, which represent transformations of 3D geometry such as translations and rotations. Java Database Connectivity (JDBC) is the programming framework used to access information stored in databases. The commands to be executed on a database are based on SQL (Structured Query Language). The database of the 4D model is designed with Microsoft Access XP to represent the information of the structural components. The temporal information associated with each activity and related objects are also stored in the database. Also, for each activity, different types of workspaces are defined in the database. The name, type, dimensions, location, properties, and the starting and ending dates of the construction or maintenance activities of each member are defined in the corresponding
tables. The database has also information about a limited number of construction equipment (e.g., cranes and trailers) that is necessary for realizing the case study and demonstrating the proposed approach. The expert subsystem for conflict resolution is developed using Java Expert System Shell (JESS). JESS is a rule-based expert system shell written entirely in Java language (Friedman-Hill 2003). Therefore, it is possible to call Java functions from JESS to extend its functionalities, and to embed JESS in Java applications. JESS uses the Rete algorithm to process rules, which is an efficient mechanism for solving many-to-many matching problems. A JESS expert system has a knowledge base that maintains a collection of knowledge called facts, and a collection of rules that are executed whenever their if parts are satisfied.

**Case Study**

Jacques Cartier Bridge in Montreal is chosen as the subject of the case study. Jacques Cartier Bridge is a five-lane bridge with steel truss frame of about 2.7 km in length. Inaugurated in 1930, this bridge carries about 43 million vehicles per year with an annual increase rate of 2.4%. Over the last 70 years, the old reinforced concrete bridge deck had suffered seriously from the increase of the number and load of trucks and the de-icing salts used extensively since the 1960s. Consequently, the deck has been replaced in 2001-2002. The third author of this paper was the manager of this project. 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. Due to the spatial and temporal constraints, deck replacement had to be done during the night of weekdays from 8:30 PM to 5:30 AM. The deck replacement involved six principal types of construction activities (Zaki and Mailhot 2003): (1) Steel work that included floor beam repair, strengthening work, and installation of new bearing assemblies to support the panels; (2) Precasting of new deck panels; (3) Removal of existing deck sections; (4) Installation of new panels; (5) Joint mortar placement and post-tensioning; and (6) Installation of expansion joint armors, cast-in-place expansion joint dams, and waterproofing and paving work. A total of 1680 precast deck panels were installed, including 410 panels for the main span. The rest of 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, each having an average period of about 15 min., 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, which included the slab, steel stringers, barriers and railings, was removed and a new panel (weighing between 22 and 42 tons) was lifted from a flat-bed semi-trailer truck and lowered onto the new bearing assemblies, which were installed by other crews working in advance during the day. At peak production, the contractor was able to replace eight panels per crew per night.

In the initial plan for replacing the deck panels, the general contractor company contemplated the usage of an industrial straddle crane (Shuttlelift SL80 Gantry Crane) with maximum lifting capacity of 80 tons and overall height, width and length of 8.13 m (26' 8''), 9.14 m (30') and 9.14 m (30'), respectively (Fig. 8(a)). The contractor built a physical model of the bridge to check the conflicts that could appear when using different crane models (Fig. 8 (c) and (d)). It was found that two straddle cranes (used by two crews) cannot meet at the same location on the bridge because of the limited road width. In addition, a straddle crane would block the emergency lane, which is necessary at all times. Because of these spatial conflicts, the contractor decided to use a pair of 60.5-ton self-propelled telescopic cranes (Grove TR 700E Crane) placed at opposite ends of a panel instead of the straddle cranes (Fig. 8(b)). The other reasons for this selection are that telescopic cranes are more available, easier to operate and to mobilize at the beginning and end of a shift. Erection equipment used for the installation of panels along the main span was the same as that used for the approach spans despite major differences in the geometry of the panels and the configuration of steel supporting members. However, low clearance below the cross-frames of the through trusses made the operation more delicate.

Fig. 9(a) shows the work pattern of two crews working together during the period of one week (Day-1 (D1) to Day-5 (D5), excluding Saturday and Sunday) with the productivity of six panels per crew per night. Fig. 9(b) shows details about the positions of the cranes and the trailers serving each crew during the night shift of Day-1 (D1). For each crew, two telescopic cranes are positioned on both sides of the panel to be replaced. Two trailers (one empty and the other loaded with a new panel) are in a stand-by state in between the two crews. These trailers are assigned to serve crew-1 and are waiting for crew-1 to finish cutting the old section of the deck. This figure also shows that a minimum distance (greater than double the length of the trailer) is required between the two crews working simultaneously to allow for the stand-by trailers. This requirement is important for maximizing productivity by assuring that the trailers serving one crew will not block the bridge for the trailers.
serving the other crew.

The prototype system was applied in the above case study. The bridge data were acquired from the bridge management authority. The data include CAD drawings, deck rehabilitation schedules and inspection and maintenance records. The bridge model and the deck panels are created as 3D prismatic elements. The model of the bridge is integrated with GIS data (2D maps and Digital Elevation Model (DEM)) to consider the geography and topology of the whole area where the project is located. The database was built to include data about construction, rehabilitation, and inspection. Furthermore, a number of simulations were developed to demonstrate the usefulness of the 4D approach, such as displaying elements with different colors according to construction, painting, or rehabilitation periods.

Workspaces are generated automatically based on the data stored in the database. The workspaces for re-decking include workspaces for cranes, trailers, and an emergency path. In the case of the straddle crane (Shuttlelift SL80 Gantry Crane), when an old section has been cut and removed by the crane, the empty area on the deck would become a safety area and the crane will move to the other side of the deck to load the old section on a trailer and then wait for unloading a new panel from another trailer (Fig. 8(c)). Therefore, the workspace of the straddle crane should cover the range of positions of the crane along the width of the bridge. The workspaces of telescopic cranes are represented by composite shapes as shown in Fig.1. Both conflicts among workspaces and between workspaces and physical elements are automatically detected and analyzed. Fig. 10(a) and (b) show different workspaces using one straddle crane and two telescopic cranes, respectively. In Fig.10(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, because of the low clearance of the main span (about 5.5 m), another conflict between the crane workspace and the cross truss elements is detected. These conflicts are resolved with the support of the rule-based expert sub-system integrated with the system to give recommendations based on the results of the analysis. The only rule in the expert system that could produce a feasible solution is the one suggesting the usage of smaller cranes. Because of practical reasons in this project, a telescopic crane (Grove TR 700E Crane) was selected by the user from the list of cranes available in the database. However, because of the low clearance problem, the crane had to work with a flat boom; therefore, decreasing its lifting capacity by more than 50%. Consequently, this resulted in using two telescopic cranes instead of one to match the lifting
requirements of the panels. Fig.10(b) shows the workspaces of the two telescopic cranes with flat booms on both sides of a panel, the trailer and the emergency path (viewed from the top of the bridge). Although it seems that there is overlapping parts between the workspaces of the cranes and the trailer, this overlap is not causing any conflict because the booms of the cranes are always moving above the trailer. No other conflicts are detected in this case between the workspaces and the physical elements.

Conclusions and Future Work
This paper extended the previous research on workspace analysis and conflict resolution in the case of large infrastructure projects focusing on the representation of workspaces related to cranes, and the computational method to define the composite shapes of these workspaces using CSG. The requirements of a CAD-independent system that can automatically generate workspaces, detect spatio-temporal conflicts in an interactive 4D environment, and support the decision-making process of resolving them using a semi-automatic strategy based on an expert sub-system were discussed. The computational aspects of the proposed approach were also discussed and demonstrated by developing a prototype system and applying it in a case study about the deck replacement of Jacques Cartier Bridge in Montreal. During the process of developing the rules of the expert sub-system, it was found that the rules about equipment selection would require adding many constraints that are usually given in the safety manuals. Therefore, future work will focus on further development of the rules of the expert sub-system by adding these constraints. Furthermore, additional development is needed to accommodate the automatic generation of the workspaces of equipment so that the system could be easily used in engineering practice. Another extension of the system would be to integrate it with discrete event simulation tools in order to create the workspaces automatically based on detailed simulation data.

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References


Captions of figures:

Fig. 1 Example of workspace of a telescopic crane:
(a) Workspace of a crane superimposed on a picture of construction site;
(b) Parameters used in generating the workspace;
(c) Generating the composite shape of the crane workspace using CSG

Fig. 2 (a) Definition of workspace class and (b) conflict class

Fig. 3 Proposed system structure

Fig. 4 Flowchart of workspace generation and analysis

Fig. 5 Translation distance for locating a workspace
(Simple case of above and left with offsets of zero and d, respectively)

Fig. 6 Collision detection between two parallel boxes:
(a) Distance between center points of two boxes;
(b) Intersection case; and (c) Containment case

Fig. 7 Collision detection tests for convex polyhedra.
(a) A vertex of Q contained in P;
(b) An edge of Q penetrates a face of P;
(c) A vertex of Q contained by P test;
(d) An edge of Q cutting a face of P

Fig. 8 (a) Straddle crane and (b) Telescopic cranes considered in the project,
(c) and (d) Partial models of the bridge with straddle and telescopic cranes, respectively

Fig. 9 Work pattern of replacing the deck panels by two crews
(a) Work pattern a period of five days; and
(b) Details about the locations of cranes and trailers

Fig. 10 Workspace conflicts detected in the case study:
(a) Case of straddle crane viewed from the road level;
(b) Case of two telescopic cranes viewed from the top of the bridge
Fig. 1 Example of workspace of a telescopic crane:
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Workspace center point $(x_2, y_2)$

Reference object center point $(x_1, y_1)$

$N_1 = \frac{y_1}{2}$

$N_2 = \frac{y_2}{2}$

$\frac{(x_1 + x_2)}{2} + d$
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Conflict between workspaces of crane and emergency path

Conflict between workspaces of crane and cross truss

Workspace of straddle crane

Emergency path

Panel to be replaced

Workspace of trailer

Workspaces of two telescopic cranes

Fig. 10 Workspace conflicts detected in the case study:
(a) Case of straddle crane viewed from the road level;
(b) Case of two telescopic cranes viewed from the top of the bridge