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FORMALIZATION AND AUTOMATION OF TIME-SPACE CONFLICT ANALYSIS

Burcu Akinci[1], Martin Fischer[2], Raymond Levitt[3], Robert Carlson[4]

ABSTRACT

With increasing pressure for shorter delivery schedules, space is a critical resource at construction sites. Current industry practice lacks a formalized approach or a tool to help project managers analyze spatial conflicts between activities prior to construction. Consequently, time-space conflicts occur frequently and significantly impact construction processes. Time-space conflicts have three characteristics which impede the detection and analysis of time-space conflicts prior to construction: (1) They have a temporal aspect, (2) They have different forms creating different problems, (3) Multiple types of spatial conflicts can exist between a pair of conflicting activities. This research formalizes time-space conflict analysis as a classification task and addresses these challenges by automatically (1) detecting conflicts in four dimensions, (2) categorizing the conflicts according to a taxonomy of time-space conflicts developed, and (3) prioritizing the multiple types of conflicts between the same pair of conflicting activities. This research extends previous research on construction space management by developing a taxonomy of time-space conflicts and by defining an approach for the analysis of time-space conflicts prior to construction.

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1. INTRODUCTION

Subject to increasing pressure for time to market, general contractors must increase the amount of work done per time unit by increasing the resources utilized by activities, and by scheduling more activities concurrently. Both of these strategies increase the demand for space per time unit. Since space is limited at many construction sites, an increase in space per unit time can result in *time-space conflicts*, in which an activity's space requirements interfere with another activity's space requirements, or with work-in-place.

Current industry practice lacks a formalized approach and tools to help project managers detect, analyze and manage the time-space conflicts between the construction activities in a given schedule prior to construction. Consequently, time-space conflicts occur frequently at construction sites. For example, (Riley and Sanvido 1997) observed 71 cases of spatial conflicts between only four trades at a job site during a two-month study period.

Time-space conflicts also significantly hinder the performance of interfering activities. In fact, many research studies cite time-space conflicts among the major causes of productivity loss in construction (e.g., Rad 1980; Ahuja and Nandakumar 1984; Oglesby et al. 1989; Sanders et al. 1989; Muehlhausen 1991; Howell and Ballard 1995).

Time-space conflicts have three characteristics that differentiate them from design conflicts: (1) they have temporal aspects, i.e., they occur only during certain periods of times, (2) they exist in different forms, and (3) they create different types of problems on site. Therefore, the challenges in time-space conflict analysis involve the detection of spatial conflicts in x, y, z, and time dimensions, the categorization of the conflicts detected, and the prioritization of the conflicts categorized.

Currently, there are static and dynamic conflict detection applications, e.g., PlantSpace (Jacobus 1997) and Plant Design System (Intergraph 1999), available to the construction industry. These applications predominantly detect geometric clashes between permanent building components. Typically, the user can also define an envelope around the building components by defining clearance requirements needed during installation. Accordingly, these applications can distinguish the "soft" interferences, which are the interferences between different clearance volumes, from the "hard" ones, which are the interferences between physical components. However, these applications do not fully address the challenges associated with time-space conflict analysis, since they do not represent all of the different space requirements associated with performing construction activities. Consequently they do not represent and reason about the different types of time-space conflicts.

Previous research studies on construction space management (Tommelein et al. 1993; Thabet and Beliveau 1994; Zouein and Tommelein 1994; Riley 1994) focused on generating a schedule free of conflicts. They developed space-scheduling strategies to eliminate spatial conflicts between activities. However, they did not represent and reason about multiple types of spatial conflicts between activities. Hence, they did not formalize the analysis of time-space conflicts. Therefore, the space-scheduling strategies are not tailored to the different types of time-space conflicts. Consequently, the space-scheduling strategies developed and implemented in those research studies are mostly ad-hoc.

In the research presented in this paper, we formalized time-space conflict analysis as a classification task and developed a taxonomy of time-space conflicts to be used in categorizing and prioritizing the spatial conflicts detected. We implemented these formalisms in a prototype system, 4D WorkPlanner Time-Space Conflict Analyzer (4D TSConAn). This system automatically detects and analyzes time-space conflicts existing in a given space-loaded production model – an integrated product and process model with explicit work space requirement representations (Akinci and Fischer 2000).

In the next section we describe a motivating case illustrating the impacts of time-space conflicts at construction sites and the benefits of proactive time-space conflict management. From that case, we identify the challenges associated with time-space conflict analysis. The following sections describe the 4D TSConAn system and the time-space conflict analysis formalism that we developed to address these challenges.

2. MOTIVATING CASE

The motivating case described below combines and simplifies some of the time-space conflicts observed at three construction sites: (1) Haas School of Business project in Berkeley (O'Brien 1998), (2) Portside Housing Project at San Francisco (Akinci and Fischer 1998), and (3) Boarding Area A Terminal Extension Project at San Francisco

International Airport (Akinci and Fischer 2000). For the discussion of this combined case, we adopted the design of a portion of the terminal building in the third case. Figure 1a shows graphically the building used in the motivating case. The schedule discussed in this case is an aggregation and simplification of different activities observed at these three job sites.

The case focuses on eight different activities on one section of the building. The contractor was under substantial time constraints and scheduled many activities concurrently (Figure 1b). The target duration for executing all five activities was 11 days.

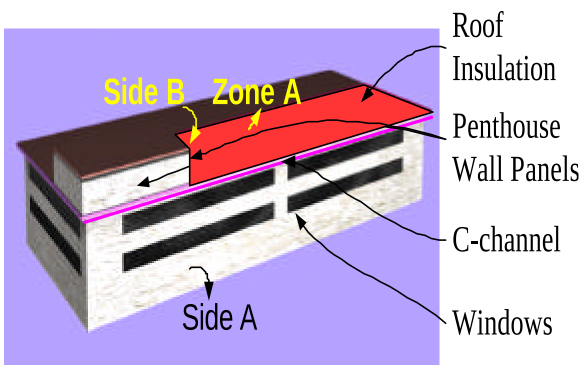

Figure 1a. 3D Representation of the building

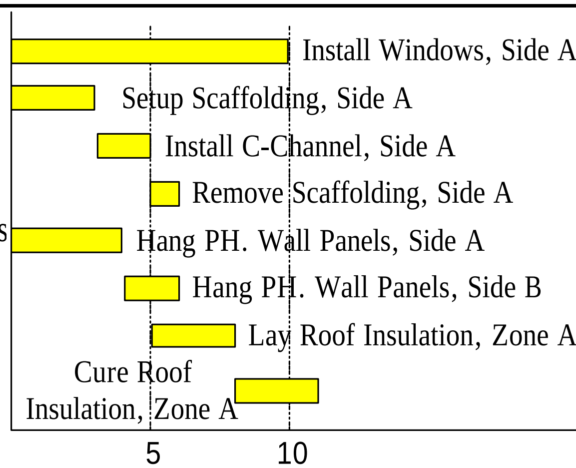

Figure 1b. The initial schedule developed

Figure 1. Overview of the motivating case

This schedule, however could not be executed as planned due to three major time-space conflicts between activities (Figure 2):

(1) *Time-space conflict between the installation of windows and the installation of c-channel on Side A* (Figure 2a): The construction method used for installing windows required the labor crew to install the components from the outside using a scissor lift. Similarly, the construction method used for c-channel installation required the labor crew to install the c-channel using scaffolding. The time-space conflict occurred because the labor crew spaces and the equipment spaces for the window installation conflicted with the scaffolding space for the c-channel installation. This created a severe congestion situation at the site, and resulted in a constructability problem, in which the activities could not be performed concurrently as scheduled.

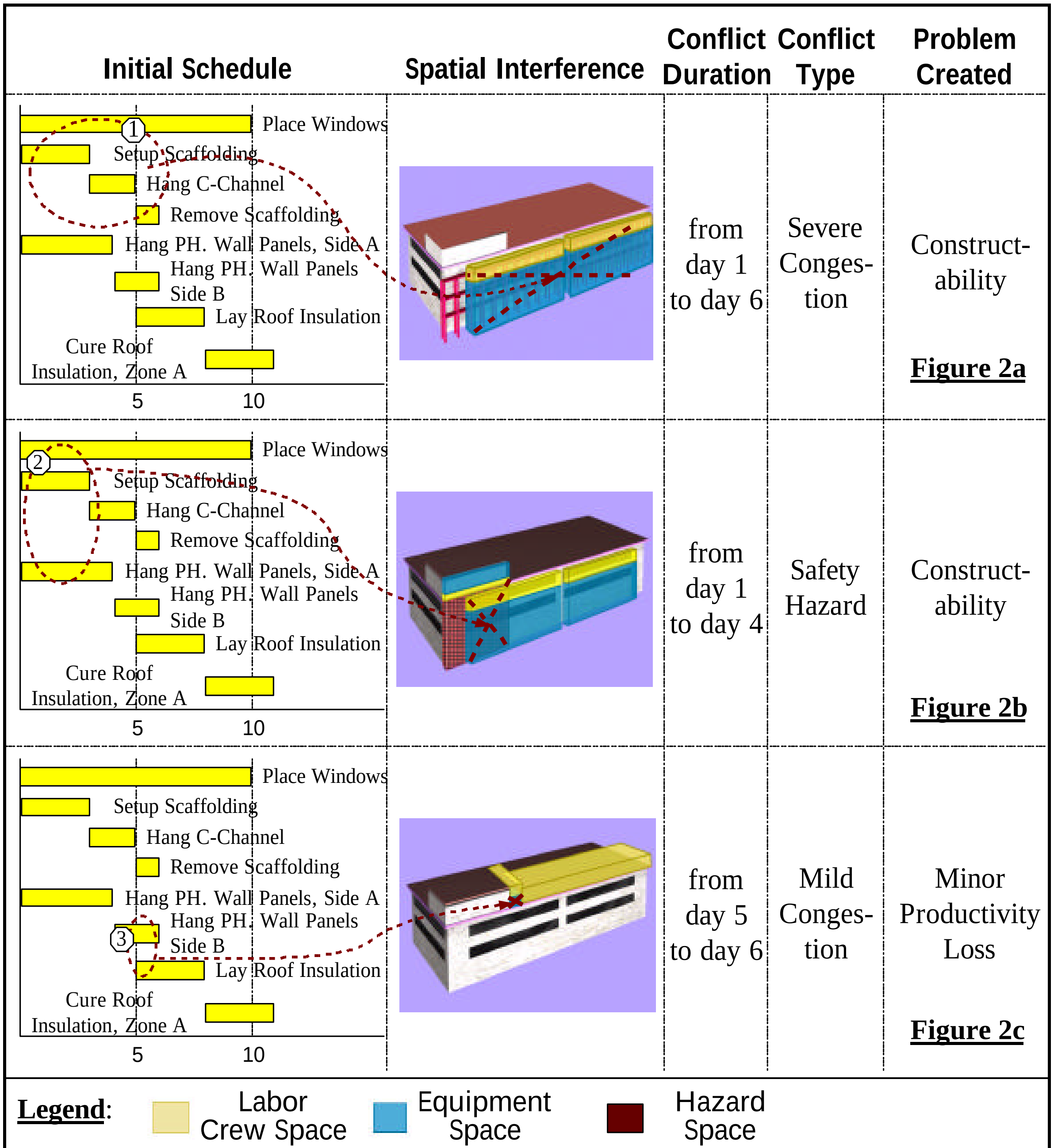

Figure 2. Different types of time-space conflicts existing in the schedule

(2) *Time-space conflict between the hanging of penthouse wall panels on side A and the window installation, the scaffolding setup and removal, and the c-channel installation activities on Side A* (Figure 2b shows the conflict between the installation of the penthouse wall panels on Side A and the installation of windows on Side A as an example): The construction method used for wall panel installation required the wall panel labor crew to install the wall panels from the outside using a swing stage that is hung from the roof top. This operation created a hazard space below the labor crew

installing the wall panels. This hazard space conflicts with the labor crew spaces occupied during the setting up of the scaffolding, the hanging of the c-channel, and the installation of the windows on Side A. This time-space conflict created a safety hazard situation at the site, and it resulted in a constructability problem in which the installation of penthouse wall panels on Side A could not be performed concurrently with the setting up of the scaffolding, the hanging of c-channel, and the installation of windows on the same side.

(3) *Time-space conflict between the installation of penthouse wall panels on Side B and the laying of roof insulation in Zone A* (Figure 2c): The wall panel crew was installing the wall panels on Side B from the outside using a rolling scaffolding. The space required by the rolling scaffolding interfered with the labor crew space required for laying of roof insulation. This conflict created minor congestion at the site and resulted in a minor productivity loss during the execution of both activities.

The contractor, in this case, realized these spatial conflicts only when they occurred at the site. With no time to explore options, the contractor delayed the window and wall panel installation activities (Figure 3a). This resulted in a nine-day delay from the original project duration.

Had the contractor identified and analyzed time-space conflicts prior to construction, he could have explored different options to manage these conflicts since he would not yet have been committed to a certain set of construction methods and sequencing decisions. For example, he could have changed the construction method of installing windows from installing windows from the outside using a scissor lift to installing windows from the inside. Figure 3b shows the CPM chart of an alternative schedule incorporating this change in the construction method for window installation. This alternative schedule eliminates the spatial conflicts in the original schedule without significantly delaying the construction process. The total duration of the alternative schedule is less than the total duration of the realized schedule. This difference represents the potential benefit of proactive time-space conflict management.

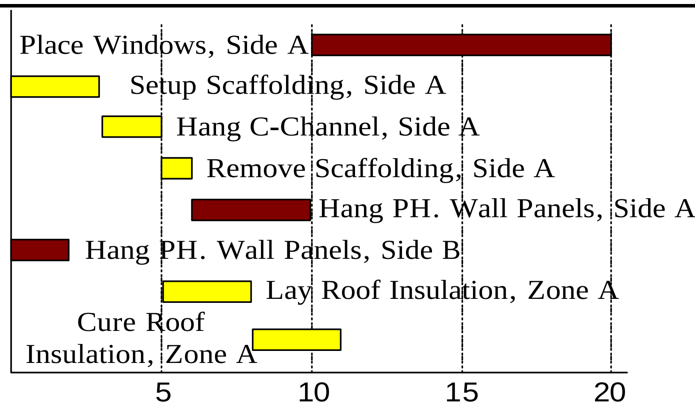

Figure 3a. Actual Schedule (Reactive)

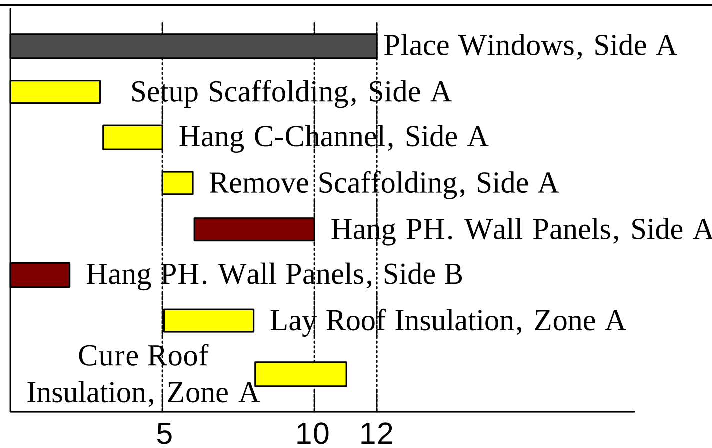

Figure 3b. Alternative Schedule (Proactive)

Legend:

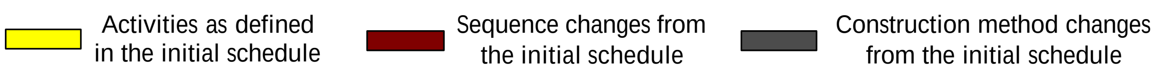

Figure 3. Comparison of the schedules developed as a result of reactive and proactive time-space conflict management

3. CHARACTERISTICS OF TIME-SPACE CONFLICTS

Time-space conflicts have three characteristics that make difficult for project managers to identify, analyze, and manage spatial conflicts without the help of a computer system. These characteristics are:

(1) *Temporal aspects of time-space conflicts*: Since activity space requirements change over time (Zouein and Tommelein 1993; Thabet and Beliveau 1994; Akinci et al. 2000a), time-space conflicts between activities only occur for certain periods of time. For example, in the case described above, the time-space conflict between the window installation and the penthouse wall panel installation occurs only between

day 1 and day 4. Similarly, the time-space conflict between the hanging of wall panels on Side B and the laying of roof insulation in Zone A occurs only between day 5 and day 6. This temporal aspect of time-space conflicts suggests that the detection of spatial conflicts between activities must include reasoning not only about three-dimensional geometric clashes, but also about temporal clashes.

(2) *Multiple types of time-space conflicts*: Depending on the types of spaces conflicting and the ratio of the volumes of the conflicts to the volumes of the required spaces, time-space conflicts can have many types. The case described above exemplified some of the different types of conflicts, such as severe congestion, mild congestion and safety hazard (Figure 2). Project managers need to understand the different types of conflicts existing in a schedule to develop a customized solution for each case and to prioritize the management of the conflicts detected.

(3) *Multiple conflicts existing between a pair of conflicting activities*: In some cases, multiple types of spaces required by an activity conflict with multiple types of spaces required by another activity. This could result in multiple types of conflicts existing between the same pair of conflicting activities. For example, during the time-space conflict between the window installation and the wall panel installation on Side A (Figure 2b), both the labor crew spaces and the equipment spaces required for the window installation conflicted with the hazard space generated by the wall panel installation. The conflict between the labor crew spaces that is required for the window installation and the hazard space that is generated during the wall panel installation created a safety hazard situation at the site. On the other hand, the conflict between the equipment space that is required for the window installation and the hazard space that is generated during the wall panel installation did not create problem. Consequently, between these two types of conflicts, the conflict that created a safety hazard had a higher priority because of the severity of the problem it created. This suggests that in cases where multiple types of conflicts exist between activities, the time-space conflicts need to be prioritized according to the severity of the problems they can create. As a result, a project manager can focus on managing the conflict that has the potential of most severely impacting construction.

In our research, we addressed these challenges associated with the time-space conflict analysis by automating

- the detection of spatial conflicts in all x, y, z and time dimensions,
- the categorization of the conflicts detected according to a taxonomy of time-space conflicts we developed, and
- the prioritization of the conflicts categorized in cases where multiple types of conflicts exist between the same activities.

The next section overviews the prototype system implemented and the following sections describe in detail the time-space conflict analysis formalism developed.

4. 4D WORKPLANNER TIME-SPACE CONFLICT ANALYZER

We developed a prototype system, 4D WorkPlanner Time-Space Conflict Analyzer (4D TSConAn) (Figure 4) to automate the time-space conflict analysis process. This system is implemented in Powermodel™, which is an object-oriented programming language developed by Intellicorp of Mountain View, CA.

4D WorkPlanner Time-Space Conflict Analyzer is linked to another system, 4D WorkPlanner Space Generator, which automates the generation of work space requirements of activities (Akinci et al. 2000a). The output of 4D WorkPlanner Space Generator is a space-loaded production model, which is an integrated product, process, and work space model. Space-loaded production models represent the different types of space requirements of activities as intelligent objects knowing *when* and *where* they exist, and *how much volume* they occupy.

In this research, we represented and developed the mechanisms to reason about six types of spaces required by construction activities. These are:

(1) Building component space; the physical space occupied by the building component to be installed.

(2) Labor crew space; the space used by a labor crew installing the components.

(3) Equipment space; the space used by the equipment supporting a labor crew or a component during installation.

(4) Hazard space; the space generated when an activity creates a hazardous situation.

(5) Protected space; the space required to protect a component from possible damage for a certain period of time.

(6) Temporary structure space; the physical space occupied by temporary structures, such as scaffolding and shoring. Temporary structures are modeled like permanent building components.

Hence, the space-loaded production model, which provides the input to 4D TS ConAn includes these six types of spaces required by activities. The input box in Figure 4 shows the contents of space-loaded production models.

Using this input, 4D TSConAn first detects spatial conflicts between activities by simulating the construction process while checking for possible three-dimensional geometric clashes between the different types of spaces required by activities. When time-space conflicts are detected, 4D TSConAn categorizes them according to a taxonomy of time-space conflicts we developed. In cases where multiple types of time-space conflicts exist between the same pair of conflicting activities, 4D TSConAn prioritizes these conflicts according to the severity of the problems they can create. Hence, it identifies the primary conflict, if any, between each pair of activities.

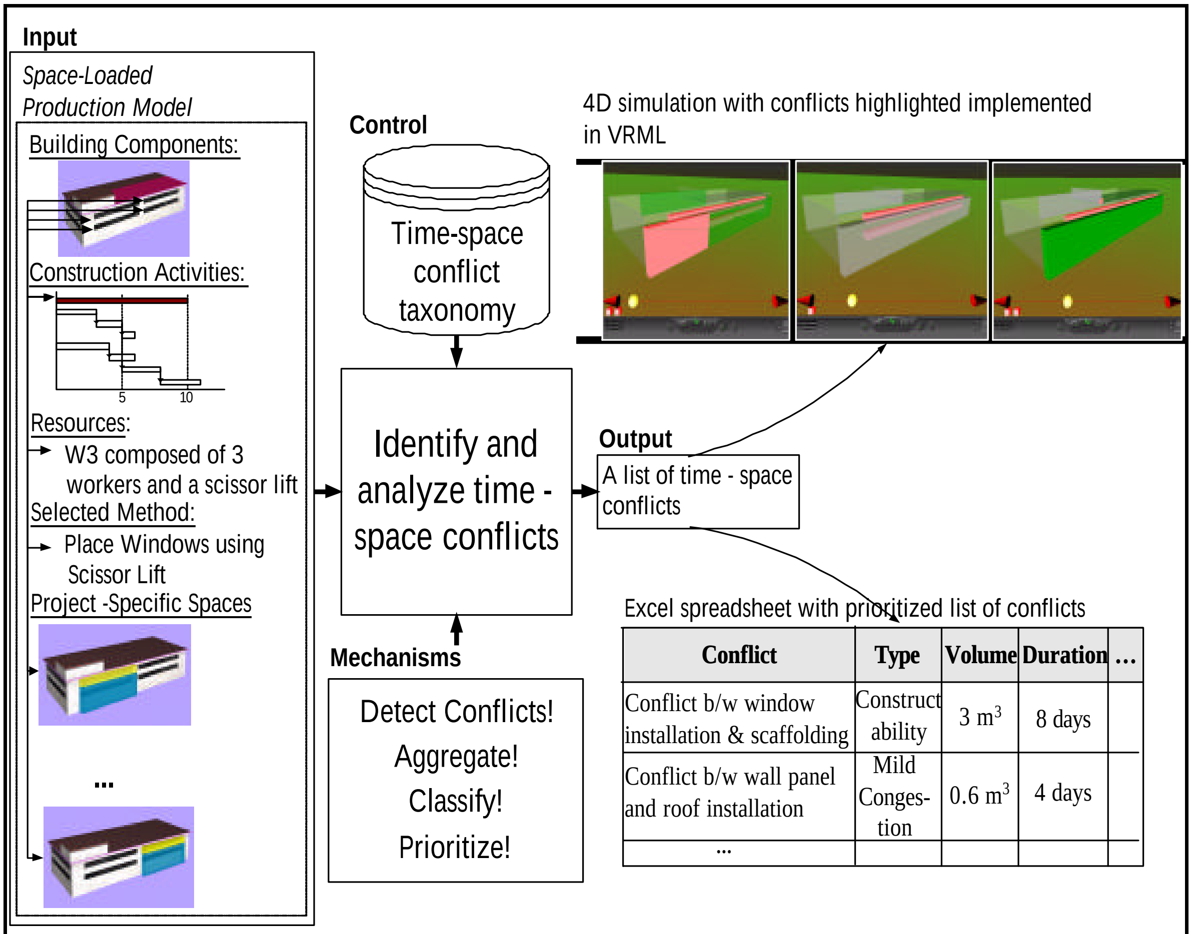

Figure 4. 4D WorkPlanner Time-Space Conflict Analyzer

The output of 4D TSConAn is a list of categorized and prioritized time-space conflicts. This output can be viewed in two ways:

(1) Within a 4D CAD simulation implemented in VRML 2.0 (Hartman and Wernecke 1996), in which the conflicts detected are highlighted in red color,

(2) Within an Excel spreadsheet that documents all of the information about the conflicts detected, e.g., their types, volumes, durations, etc.

Project managers can use this information about the different types of time-space conflicts to modify their production models by changing construction methods, sequences, etc. to minimize problems related to time-space conflicts prior to construction. Hence, using 4D WorkPlanner Time-Space Conflict Analyzer project managers can perform what-if analyses and can implement different time-space conflict management strategies to proactively manage time-space conflicts. Exploration of different alternatives for managing spatial conflicts prior to construction could reduce time-space conflicts that contribute to productivity, constructability, safety and quality problems, and consequently, can reduce project delays and enhance safety performance on sites.

The next section describes the time-space conflict analysis formalism developed and implemented in 4D TSConAn.

5. FORMALIZATION OF TIME-SPACE CONFLICT ANALYSIS AS A CLASSIFICATION TASK

Since time-space conflicts have multiple types, the analysis of time-space conflicts involves not only the detection of spatial conflicts, but also the categorization of the conflicts. Therefore, we modeled the time-space conflict analysis as a classification problem.

Clancey (1985) formalized the classification task as the process of matching specific data to a fixed set of known possible solution classes. Clancey's (1985) heuristic classification model includes abstracting detailed problem data to a class of typical problems, matching the abstracted problem class to its generic class of solutions, and refining the generic class of solutions by using the detailed data about the problem. Figure 5 shows the different components of heuristic classification as modeled by Clancey.

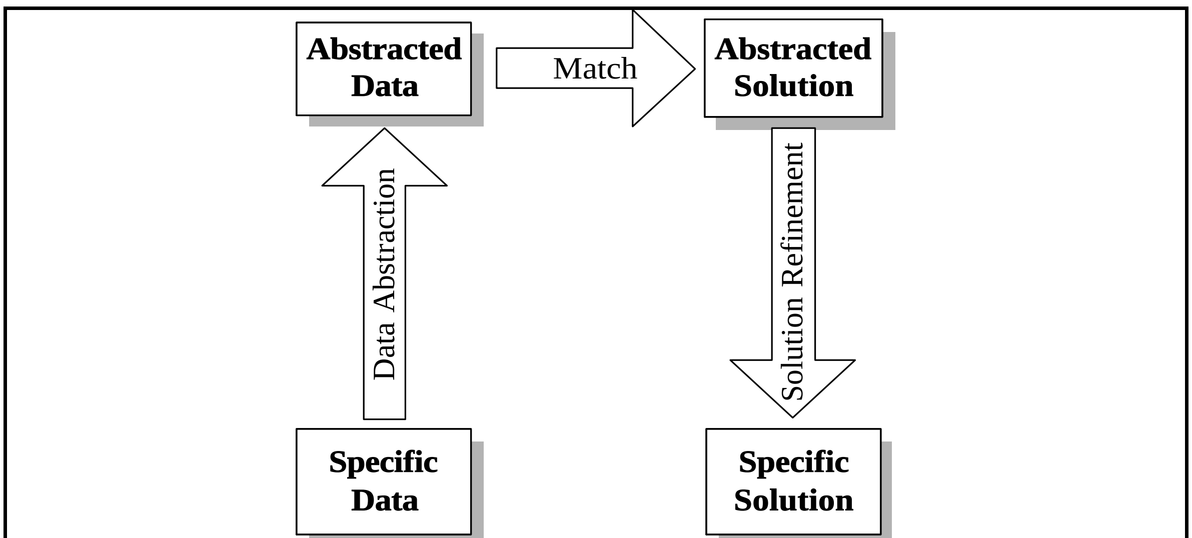

Figure 5. Heuristic Classification

In formalizing time-space conflict analysis, we applied Clancey's classification model. Time-space conflict analysis includes two levels of abstraction and two levels of refinement (Figure 6). The initial data in time-space conflict analysis is a space-loaded production model, in which activity space requirements are represented as intelligent objects, and they are linked to an intelligent product and process model (the input box in Figure 3 shows the data included in the space-loaded production model).

The steps of this time-space conflict analysis formalism are:

(1) Detection of spatial conflicts in a given space-loaded production model

(2) Aggregation of the conflicts detected

(3) Categorization of the conflicts aggregated

(4) Prioritization of the conflicts categorized

(5) Managing the conflicts prioritized

The research presented in this paper focuses on formalizing the first four steps. We developed and implemented mechanisms to automate each of these four steps in 4D TSConAn. Instead of automating the management of the conflicts prioritized – the fifth step – we require the user to define specific strategies for managing the time-space conflicts.

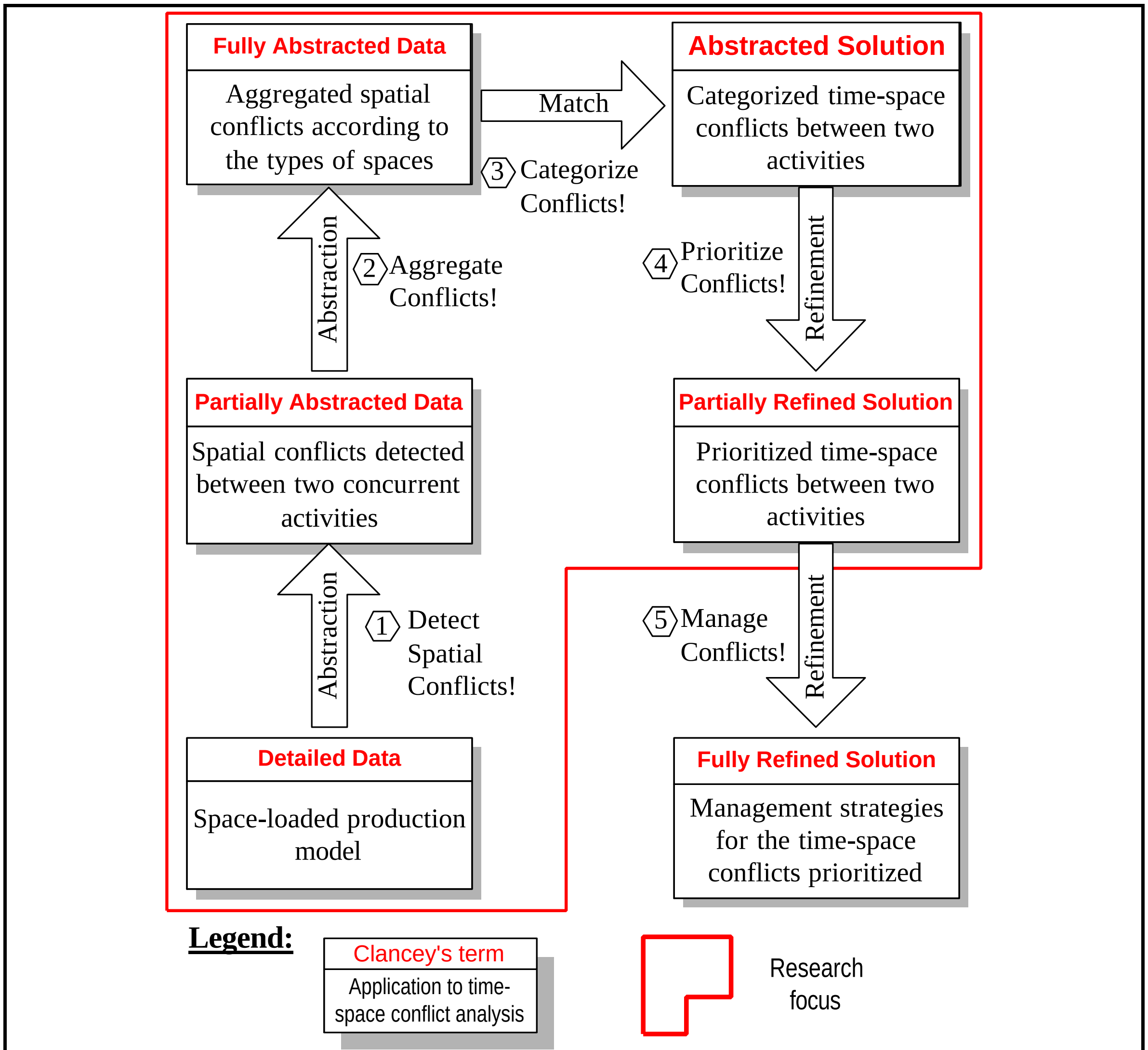

Figure 6. Formalization of time-space conflict analysis as a classification task

Previous research studies on construction space scheduling (Tommelein et al. 1993; Thabet and Beliveau 1994; Zouein and Tommelein 1994) focused on formalizing and automating the strategies necessary to automate the management of time-space conflicts. The space scheduling formalisms developed in those research studies directly relate the first step to the fifth step without formally categorizing the conflicts detected. Hence, the strategies implemented in the space-scheduling systems are mostly ad-hoc and do not address the particular types of time-space conflicts. Moreover, the strategies implemented in those systems do not cover all of the possible ways of managing time-space conflicts. For example, they do not reason about alternative construction methods of installing the same component as a possible time-space conflict management strategy.

As the case discussed above exemplified, a change in construction method can be a very effective way to eliminate time-space conflicts between activities.

Our research complements the previous research on space-scheduling by developing a taxonomy of time-space conflicts and by formalizing time-space conflict analysis as a classification task. Hence, our research provides the missing link for developing space-scheduling strategies to improve the management of time-space conflicts.

The next four sections describe the first four steps of time-space conflict analysis.

5.1. Detection of Time-Space Conflicts

As described above, time-space conflicts have temporal properties, i.e., they occur only during a certain period of time. Therefore, the detection of time-space conflicts needs to identify clashes not only within three-dimensional geometric space, but also across time.

The time-space conflict detection algorithm that we implemented combines basic three-dimensional geometric clash detection algorithms (Lin and Gottschalk 1998) with discrete event simulation mechanisms (Law and Kelton 1991). In 4D TSConAn, spaces are represented as rectangular prisms in parallel to the orthogonal planes. We found the rectangular prism to be an acceptable approximation for the four types of work spaces that we represented (Akinci et al. 2000a; Akinci et al. 2000b). Consequently, the time-space conflict detection algorithms implemented in 4D TSConAn apply only to rectangular prism shapes.

4D TSConAn simulates the construction process according to the schedule developed by the user. The simulation starts by identifying the set of activities that do not have any predecessor, and can thus occur concurrently. It sets the completion of an activity with the shortest duration as the first event of the simulation. The simulation continues by adding the successors of the activities completed to the list of concurrent activities and assigning the completions of the activities with the earliest finish dates as the events of the simulation.

During each event period, 4D TSConAn selects a pair of activities from the list of concurrent activities, which can be executed during that period. It checks for possible geometric clashes among the different instances of spaces required by these two activities. This process continues until all of the concurrent activities have been paired up and checked for possible spatial conflicts. In addition, during each simulation period, 4D TSConAn checks for possible geometric clashes between the spaces required by activities and the work-in-place and temporary structures-in-place. The simulation continues until all of the activities have been executed.

The detection of time-space conflicts creates a list of spatial conflicts between the different spaces required by concurrent activities, and between the different spaces required by activities and the work-in-place. This list of spatial conflicts might include more than one instance of spatial conflicts between two activities. For example, in the case described above, all four of the labor crew space instances and all four of the equipment space instances required to install four windows on Side A conflict with the scaffolding space used for c-channel installation. Consequently, the time-space conflict detection stage identifies eight instances of time-space conflicts between the window installation and the c-channel installation activities. These geometric conflicts need to be further aggregated such that the time-space conflict analysis becomes manageable for the project managers. The next section describes how we implemented the aggregation of time-space conflicts detected in this way.

5.2. Aggregation of the Time-Space Conflicts Detected

The second step in time-space conflict analysis is the aggregation of the time-space conflicts. During the aggregation of time-space conflicts, 4D TSConAn selects a pair of activities that conflict with each other, and aggregates the conflicts detected between those two activities by following three steps:

(1) It adds the volumes of the *same types of spaces required* by each of the activities in the conflicting activity pair. 4D TSConAn calculates the total volumes of each type of space required by a conflicting activity. For example, the window installation activity described in the case requires four instances of labor crew spaces in installing four windows on Side A of the building (for the ease of discussion we exclude the four instances of equipment spaces required by the window installation). Each labor crew space requires 75 m^3 of volume. During the aggregation of time-space conflicts, 4D TSConAn adds the volumes of the four instances of the labor crew spaces to calculate the

total volume of the labor crew space occupied during the window installation as 300 m^3 (Figure 7).

(2) It adds the volumes of the *conflicts detected*. Once a time-space conflict is detected, 4D TSConAn calculates the volume of the conflict. 4D TSConAn adds the volumes of the time-space conflicts detected between the same pair of interfering spaces. For example, as Figure 7 shows, during the time-space conflict between the window installation and the c-channel installation, 40% of all four labor crew spaces occupied during the window installation conflict with the scaffolding space of the c-channel installation. Each of these conflicting spaces occupies 30 m^3 (0.40 * 75 m^3) volume. Since there are four instances of conflicts between the labor crew spaces occupied during the window installation and the scaffolding space occupied during the c-channel installation, the aggregated volume of spatial conflicts adds up to 120 m^3.

(3) It calculates the *conflict ratios*. 4D TSConAn calculates the conflict ratios for each type of space required by the conflicting activities by using the following equation:

$$ConflictRatio = \frac{\Sigma ConflictingVolume}{\Sigma VolumeofSpace\mathrm{Re}quired} * 100\%$$

This conflict ratio is similar to Thabet and Beliveau’s (1994) Space Capacity Factor, which is described as the ratio of space demand required by the activity to the current space availability. Thabet and Beliveau use the space capacity factor to measure the degree of congestion in an area and to assess the corresponding productivity impacts of that congestion. Similarly, we use the conflict ratio in determining the different levels of congestion. The next section describes how the conflict ratio is used in categorizing time-space conflicts.

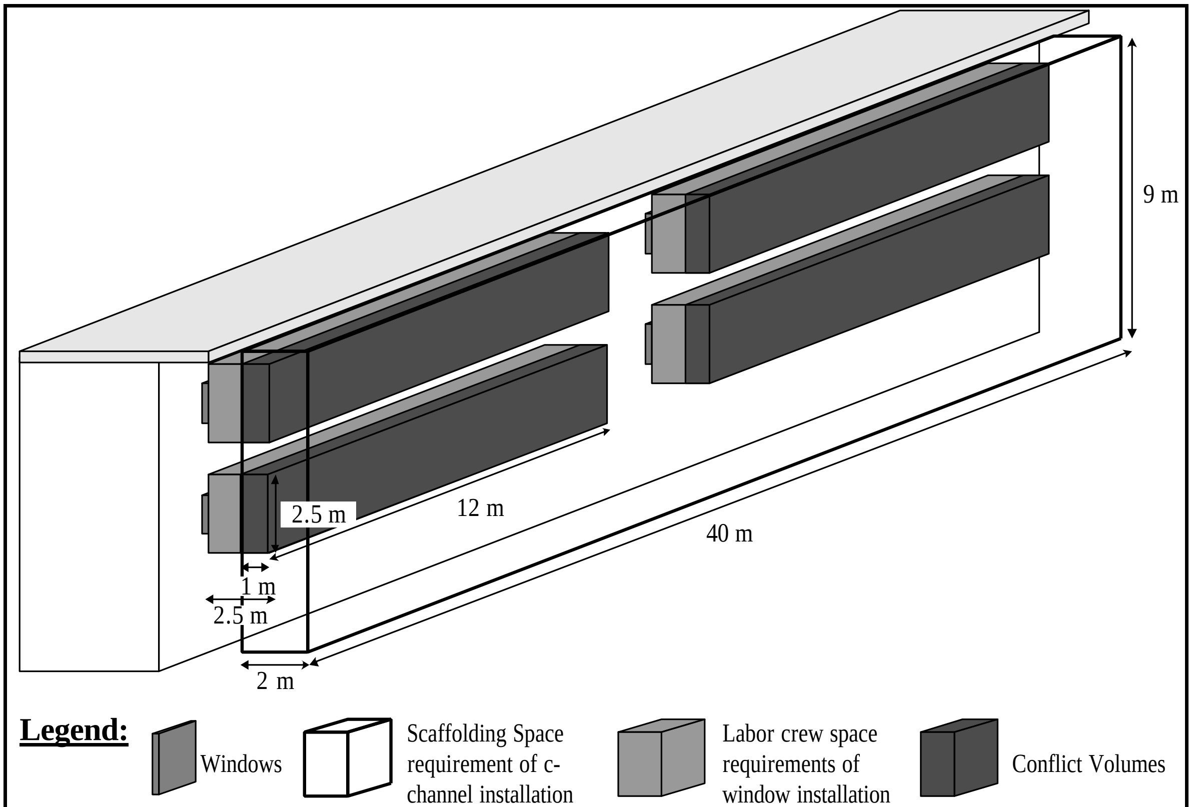

Figure 7. The aggregation of the time-space conflict between the labor crew spaces required for window installation and the scaffolding space required for c-channel installation.

Table 1 shows the output of the aggregation step using the time-space conflict between the window installation and the c-channel installation case as an example. At the end of the aggregation stage, 4D TSConAn reduces eight conflicts detected between the window installation and the c-channel installation at the time-space conflict detection stage to two instances of aggregated conflicts.

However, at the end of this aggregation, the system still does not know what types of conflicts exist between these two activities. The next section describes the categorization of time-space conflicts aggregated according to a taxonomy of time-space conflicts that we developed.

	Conflicting Space Types	Aggregated Volume of the Space Required	Aggregated Conflicting Volume	Aggregated Conflict Ratio (%)
1.	Labor crew space for the window installation	300 m^3	120 m^3	40%
	Scaffolding space for the c-channel installation	800 m^3	120 m^3	15%
2.	Equipment space for the window installation	660 m^3	264 m^3	40%
	Scaffolding space for the c-channel installation	800 m^3	264 m^3	33%

Table 1. Aggregated time-space conflicts between the window installation and the c-channel installation.

5.3. Categorization of the Aggregated Time-Space Conflicts

A project manager needs to understand the different types of conflicts in a schedule to develop customized solutions for managing the conflicts. We categorized conflicts according to the types of spaces conflicting and according to the conflict ratio. Table 2 shows the taxonomy of time-space conflicts we developed by performing case studies at four different construction sites.

The columns and the rows of the table represent the different types of spaces required by construction activities. The spaces represented in this taxonomy include the micro-level activity space requirements (Akinci et al. 2000a; Akinci et al. 2000b). These spaces are located within the proximity of the components being installed and are required by the direct installation activities. In this research, we chose to focus on micro-level spaces since any time-space conflict associated with micro-level activity space requirements directly impacts the installation. A future research project could extend the time-space conflict taxonomy developed to include other types of spaces, such as paths (e.g., material transportation paths, debris paths, crew paths, etc.) and macro-level spaces (e.g., storage areas, staging areas, etc.).

		Activity 1					
		Building Component	*Work space*	*Equipment Space*	*Hazard Space*	*Protected Space*	*Temporary Structure Space*
Activity 2	*Building Component*	**Design Conflict**	**Congestion**	**Congestion**	**No Impact**	**No Impact**	**Severe Congestion**
	Work Space		**Congestion**	**Congestion**	**Safety Hazard**	**Damage Conflict**	**Congestion**
	Equipment Space			**Severe Congestion**	**Safety Hazard**	**Damage Conflict**	**Congestion**
	Hazard Space				**No Impact**	**Damage Conflict**	**No Impact**
	Protected Space					**No Impact**	**Damage**
	Temporary Structure Space						**Severe Congestion**

Table 2. Time-Space Conflict Taxonomy

Since the table is symmetrical, the lower-left portion of the taxonomy shown in Table 2 is left empty for ease of reading.

As Table 2 shows, we identified five major types of conflicts:

1) *Design conflict:* A design conflict occurs when a building component conflicts with another building component. Hence, the causes of these conflicts are not construction related, but rather design related.
2) *Safety hazard:* A safety hazard conflict occurs when a hazard space generated by an activity conflicts with a labor crew space required by another activity. A hazard space is generated when an activity creates a hazardous situation, e.g., falling objects, fire sparks, etc. Therefore, when a hazard space conflicts with a labor crew space it creates a safety hazard situation for the labor crew.
3) *Damage conflict:* A damage conflict occurs when a labor crew space, or an equipment space, or a hazard space required by an activity, conflicts with the protected space required by another activity. A protected space is required to protect a component from damages for a certain period of time. For example, a protected space is needed around the component during the curing of concrete or drying of paint. Therefore, when a labor crew or an equipment is assigned to the same area where the protected space is needed, it may damage the component that is being protected.

   In cases where there is a spatial conflict between the hazard space of an activity and the protected space of another activity, one needs to compare the content of the hazard space generated to the function of the protected space to assess whether the contents of the hazard space can actually damage the component that the protected space is protecting. For example, if a hazard space generated due to the risk of falling objects conflicts with the protected space required during the curing of a concrete, it might damage the concrete. However, if a hazard space generated due to fire sparks during a welding operation conflicts with the same protected space required during the curing of a concrete, it might not create any damage at all. Therefore, to find out whether a conflict between a hazard space and a protected space results in a damage situation, 4D TSConAn compares the functions of the hazard and the protected spaces.

4) *Congestion:* A congestion time-space conflict occurs when a labor crew space or an equipment space required by an activity conflicts with another labor crew space, or an equipment space, or a temporary structure space or a building component space required by another activity. As the case showed, there are different levels of congestion. Some congestion cases create a constructability problem, in which the conflicting activities could not be performed concurrently as planned (Figure 2a). Some congestion cases create a minor productivity loss for both of the conflicting activities (Figure 2c).

In this research, we modeled three levels of congestion:

4a) *Mild congestion:* A mild congestion occurs when only a small portion of a labor crew space conflicts with another space (Figure 2c). Mild congestion cases create a *minimal productivity loss problem* at the site, where both of the activities can be performed concurrently, but with a lesser productivity rate.

4b) *Medium congestion:* A medium congestion occurs when a sizable portion of a labor crew space conflicts with another space. A medium congestion *significantly reduces the production rates* of the conflicting activities if they are executed concurrently as planned.

4c) *Severe congestion:* A severe congestion occurs when a significant portion of a labor crew space or an equipment space conflicts with another space. A severe congestion creates a *constructability problem*, where both of the conflicting activities cannot be executed concurrently as planned.

In all of the congestion cases involving labor crew space, the conflict ratio of a labor crew space determines the degree of the conflict. For example, during the time-space conflict between the window installation and the scaffolding setup described in the case (Figure 2a), 40% of the labor crew space required for window installation conflicts with 15% of the scaffolding space resulting in medium congestion. On the other hand, during the time-space conflict between the wall panel installation and the roof insulation installation described in the case (Figure 2b), only 10% of the labor crew space required for roof insulation installation conflicts with the 100% of the space for rolling scaffolding for wall panel installation, resulting in a mild congestion. In congestion cases where an equipment space conflicts with a building component or a temporary structure space, the conflict ratio of the equipment space determines the level of congestion.

In time-space conflict cases where a labor crew space conflicts with another labor crew space, the conflict ratio with the lower percentage determines the "level of congestion". For example, in the case described above, 100% of the labor crew space required during the installation of the first layer of wall panels on Side B conflicts with 10% of the labor crew space required for roof insulation installation, resulting in a mild congestion.

To differentiate the different levels of congestion, 4D TSConAn considers the conflict ratios calculated in the aggregation step. Currently, conflicts with a conflict ratio lower than 30% are categorized as mild congestion; conflicts with a conflict ratio higher than 30% and lower than 60% are categorized as medium congestion; and conflicts with a conflict ratio higher than 60% are categorized as severe congestion. These limits are assigned roughly based on our experiences and interviews with different subcontractors. More case studies on identifying the productivity impacts of congestion would establish more precise limits for the different levels of congestion.

5) *No impact*: In some cases, the spatial overlaps between two different spaces do not create any problem at construction sites. For example, if a hazard space generated due to the risk of falling objects overlaps with a temporary structure space, such as scaffolding, it does not hamper the execution of any of the conflicting activities. We call these kinds of spatial overlaps that do not create any problem on sites "No Impact" conflicts.

By using the taxonomy of time-space conflicts developed, 4D TSConAn categorizes the spatial conflicts aggregated between activities. In certain conflicting situations, such as a temporary space conflicting with another temporary structure, 4D TSConAn checks for resource sharing between activities. If both of the activities are using the same resource at the same time, it does not consider the geometric overlaps of the same resource as a conflict.

The categorization of time-space conflicts provides the necessary information to prioritize the conflicts detected. The next section describes the prioritization of time-space conflicts.

5.4. Prioritization of the Time-Space Conflicts Categorized

In some time-space conflict situations, multiple types of spaces required by an activity conflict with multiple types of spaces required by another activity, resulting in multiple types of conflicts between the same pair conflicting activities. In those cases, the different types of conflicts need to be prioritized to identify the conflict having the potential of creating the most severe problem as the main conflict.

For example, during the time-space conflict between the window installation and the c-channel installation (Figure 2a), the labor crew spaces and the equipment spaces required for the window installation conflicted with the scaffolding space required for the c-channel installation. The conflict between the labor crew space required by the window installation and the scaffolding used for the c-channel installation is of type medium congestion, and it reduces the production rates of the conflicting activities significantly. On the other hand, the conflict between the equipment spaces required by the window installation and the scaffolding used for the c-channel installation is of type severe congestion, and it prohibits the concurrent execution of the conflicting activities. Among these two conflicts between the same pair of activities, the conflict of type severe congestion has a higher priority since it creates a more severe problem than the conflict of type medium congestion. Hence, in this case, the main conflict between the window installation and the c-channel installation is of type severe congestion, which results in a constructability problem at the site.

In prioritizing time-space conflicts, we analyzed the different problems each time-space conflict type can create. We ranked the different conflict types according to the severity of the corresponding problems they can create. Table 3 shows the different types of time-space conflicts, the corresponding problems they can create and their priority rankings.

Priority Rank	Conflict Type	Problem Created
1	Design Conflict	Design related constructability problem
2	Safety Hazard	Construction related constructability problem
3	Severe Congestion	Construction related constructability problem
4	Damage	Construction related quality problem
5	Medium Congestion	Significant productivity loss problem
6	Mild Congestion	Minimal productivity loss problem
7	No Impact	No problem created

Table 3. Prioritization of the different types of time-space conflicts according to the problems they create.

We ranked design conflicts as the highest priority since to solve that problem, project managers need to coordinate not only with different crews, but also with different designers. Moreover, if there is a design conflict, there is likely to be no way of installing the related components as planned.

Safety hazard and severe congestion are ranked second and third since they create construction related constructability problems where the conflicting activities cannot be executed concurrently as planned. In these cases, project managers need to either change the construction methods or change the sequences of the conflicting activities.

The damage conflict is ranked fourth since it results in a construction related quality problem which requires rework on the damaged components. The medium and mild congestion are ranked fifth and sixth since they create two different levels of productivity problems at construction sites. Finally, the “No Impact” conflict is ranked as the lowest priority since it does not create any problem on site.

4D TSConAn uses this ranking of conflict types to prioritize the conflicts in cases where multiple types of conflicts exist between two interfering activities. Currently, in 4D TSConAn, a user cannot override this ranking of conflicts. A future extension of 4D TSConAn should allow users to rank the different types of conflicts according to their preferences. Moreover, currently the prioritization is done only among the conflicts within the same pair of conflicting activities. These prioritization algorithms can also be extended to prioritize the different types of time-space conflicts existing throughout the whole project. Research in this direction would identify different characteristics of time-space conflicts – in addition to the ones that we specified – and different preferences of contractors to be used for prioritizing all of the conflicts in a project.

6. VALIDATION

We validated the time-space conflict taxonomy and the time-space conflict analysis formalism developed in this research and implemented in 4D TSConAn by comparing retrospectively the time-space conflicts identified and analyzed in our system with those observed at four construction sites: (1) Haas School of Business (O'Brien 1998), (2) Portside Housing (Akinci and Fischer 1998), (3) San Francisco International Airport Boarding Area A Terminal Extension project (Akinci and Fischer 2000), (4) Palo Alto Medical Foundation (Katz 1998). Table 4 annotates the time-space conflict taxonomy with the specific instances of conflicts observed at these three sites and the instances of conflicts identified and analyzed in our system.

The time-space conflict analysis mechanisms implemented in 4D TSConAn successfully identified and categorized all the conflicts observed in these three cases. 4DTSConAn did not identify any other conflicts for these three cases. Hence, there were neither false positives nor false negatives among the conflicts detected by 4D TSConAn.

		Activity 1					
		Building Component	*Labor crew space*	*Equipment Space*	*Hazard Space*	*Protected Space*	*Temporary Structure*
Activity 2	*Building Component*	**Design conflict**	**Congestion**	**Congestion** Q	**No Impact**	**No Impact**	**Severe Congestion**
	Labor Crew Space		**Congestion**	**Congestion**	**Safety Hazard**	**Damage**	**Congestion**
	Equipment Space			**Severe Congestion**	**Safety Hazard**	**Damage** Q	**Congestion**
	Hazard Space				**No Impact**	**Damage**	**No Impact**
	Protected Space					**No Impact**	**Damage**
	Temporary Structure						**Severe Congestion**

Legend:

Observations made at Haas School of Business — Modeled as a test case — Predicted retrospectively

Observations made at SFO Boarding Area A — Modeled as a test case — Predicted retrospectively

Observations made at Portside Housing — Modeled as a test case — Predicted retrospectively

Q Observations made at Palo Alto Medical Foundation

Table 4. 4D WorkPlanner predicted 10 time-space conflicts in the three test cases modeled retrospectively, and the predictions were the same as those observed at the three construction sites

We also validated the taxonomy developed against the observations made at the Palo Alto Medical Foundation site by Katz (1998). These spatial conflicts were categorized manually using the time-space conflict taxonomy developed. The conflicts categorized using the time-space conflict taxonomy were the same as those observed at that construction site.

These validation studies provide initial evidence of the generality and applicability of the time-space conflict analysis taxonomy and of the time-space conflict analysis formalism that we implemented.

7. CONCLUSIONS AND FUTURE WORK

This research has shown that time-space conflict analysis can be formalized as a classification task. This time-space conflict analysis formalism involves: (1) detecting spatial conflicts in all four dimensions using three-dimensional geometric clash detection and discrete event simulation mechanisms, (2) aggregating conflicts detected according to the types of spaces conflicting, (3) categorizing conflicts aggregated according to a taxonomy of time-space conflicts, and (4) prioritizing conflicts categorized according to the problems they can create on site.

The time-space conflict analysis formalism developed in this research can be used in identifying conflicts prior to construction. Consequently, it can enable proactive time-space conflict management.

The time-space conflict analysis formalism presented in this paper has the following limitations: (1) The detection of time-space conflicts is limited to rectangular prisms located parallel to orthogonal planes, (2) Time-space conflict taxonomy includes only micro-level activity space requirements, and (3) Prioritization of time-space conflicts only ranks conflicts between pairs of conflicting activities.

Our research study can be further extended by: (1) representing and reasoning about complex geometric shapes; (2) including the reasoning about macro-level spaces and paths required by construction activities; and (3) developing mechanisms to prioritize among conflicts identified throughout the whole project. Research studies in these directions would result in a more comprehensive time-space conflict analysis formalism.

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