PROACTIVE APPROACH FOR REDUCING NON-VALUE ADDING ACTIVITIES DUE TO TIME-SPACE CONFLICTS

Burcu Akinci[1], Martin Fischer[2], and Todd Zabelle[3]

ABSTRACT

Time-space conflicts are one of the major causes of productivity losses at construction sites, and they are preventable and manageable if identified prior to construction. Current industry practice and project management tools and techniques do not support proactive time-space conflict management. Our research focuses on formalizing and automating time-space conflict analysis to assist construction managers to proactively manage spatial conflicts between activities at their sites. In this paper, we describe a case that highlights the challenges involved in time-space conflict analysis and discuss an initial framework showing the factors that determine the schedule impacts of spatial conflicts between activities. Using the presented framework, a construction manager can assess the type of a time-space conflict and predict the schedule impacts of spatial conflicts. Realizing the schedule impacts of time-space conflicts before they occur at a construction site, s/he can proactively manage spatial conflicts between activities and eliminate non-value adding activities that occur at construction sites due to time-space conflicts.

KEY WORDS

Time-space conflicts, space management at construction sites, work space requirements of activities, schedule analysis.

---

[1] Graduate Res. Assistant, Dept. of Civil and Environmental Engineering, Stanford University, CA 94305-4020, USA, akinci@leland.stanford.edu.

[2] Assistant Professor, Dept. of Civil and Environmental Engineering, Stanford University, CA 94305-4020, USA, fischer@cive.stanford.edu.

[3] President of Pacific Contracting Engineers, Inc., 221 Main Street, Suite 1560, San Francisco, CA 94105-1934, trz@pacificcontracting.com.

INTRODUCTION

There is increasing pressure to build faster and cheaper in the construction industry. To address this demand for building faster, contractors are scheduling more activities concurrently and increasing the resources utilized by the activities. Both of these strategies increase the space demand for each unit of time. Since space is limited at construction sites, the increase in demand for space can lead to time-space conflicts between trades.

A time-space conflict occurs when an activity's space requirements interfere with another activity's space requirements or with work-in-place, and it affects the performances of interfering activities. Time-space conflicts have been identified as one of the major causes of productivity loss in construction (Ahuja and Nandakumar 1984, Kuntz 1994, Oglesby et al. 1989, Rad 1980, Sanders et al. 1989). Sanders et al. (1989) report efficiency losses of up to 65% due to congested workspace and up to 58% due to restricted access. Howell et al. (1993) suggest elimination of sharing of resources, such as work areas, as a first step for performance improvement at construction sites.

The application of lean thinking to construction requires that this type of unnecessary productivity losses be eliminated or reduced. The main reason for high productivity losses due to time-space conflicts is the reactive approach of current industry practice to space management at construction sites. Currently, managing space is mainly left to superintendents and field engineers during construction. However, major decisions, such as construction methods and activity sequencing, which determine the space demand at construction sites are being made during planning.

Ideally, work space requirements of activities should be represented and decisions about what to do in time-space conflict situations should be incorporated in the detailed planning process. However, planning tools and techniques used in current practice do not explicitly model time-space relationships between activities. Critical Path Method (CPM) schedules show the logical dependencies between activities. However, they do not model the time-space relationships that exist between activities.

Realizing this deficiency of CPM and the need for proactive space management, many researchers have focused on developing methodologies to improve space management at construction sites. We have grouped related research studies into four categories: (1) Modeling of construction activities flowing through a work area as a queuing theory application, also known as vertical production method and line of balancing method (Birell 1981, Howell et al. 1993, O'Brien 1975, Stradal and Cacha 1982), (2) Modeling of construction site layout planning as a configuration task problem (Alshawi 1997, Eastman 1975, Levitt et al. 1989, Tommelein and Zouein 1993), (3) Modeling of material transportation as a path planning application (Latombe 1988, Morad et al. 1992, Zhu and Latombe 1989), and (4) Modeling of space allocation as a resource allocation problem leading to the development of space scheduling methodologies (Riley 1994, Thabet and Beliveau 1994, Thabet and Beliveau 1997, Tommelein et al. 1992, Zouein and Tommelein 1993). A detailed discussion about these four approaches for improving space management at construction sites is provided in Akinci and Fischer (1998).

All of these four approaches to space management stated above are generative approaches, i.e., they generate a site layout, a schedule or a material path that minimizes spatial interferences between activities. Our research incorporates an analysis approach for space management. It analyzes a given plan with respect to time-space conflicts and incorporates the impacts of time-space conflicts on activity performances and on a given schedule as a whole. One of the major reasons for choosing an analysis approach is that a complete generative approach requires incorporation of many different strategies and trade-offs within space management that are not fully understood in current practice and research. Furthermore, optimizing a plan with respect to one requirement such as space allocation (as done in space scheduling) can result in a plan that does not satisfy other constraints such as overall project duration and cost. With an analysis approach, construction managers can quickly assess the impacts of time-space conflicts that might exist in their schedules.

We build on the previous research studies done in construction space management area to formalize and automate time-space conflict analysis of a given schedule. We particularly use the previous research studies in identifying and representing work space requirements of construction activities. Besides representing activity work space requirements, we are also defining taxonomy of time-space conflicts and how interfering activities react in particular types of time-space conflicts. We are using this taxonomy in formalizing and automating time-space conflict analysis prior to construction.

The study presented here is part of this overall effort to formalize and automate time-space conflict analysis of a given schedule. In this paper, we highlight the challenges involved in incorporating activity work space requirements in construction planning using a sample case. We focus our discussion on an initial framework that we have developed for time-space conflict analysis. This initial framework can be used to determine the type of a time-space conflict and its schedule impacts. We demonstrate the use of the framework by applying it to a time-space conflict incidence that occurred in the sample case. We conclude by stating how the framework described in this paper fits in our overall research effort of automation of time-space conflict analysis. We also highlight our future research directions.

CASE OVERVIEW

The sample case described here aggregates some of the time-space conflicts occurred during the construction of the Haas School of Business in Berkeley, USA, and the Cinar Sitesi housing project in Ankara, Turkey. This sample case is created to describe the challenges involved in time-space conflict analysis and to demonstrate our research approach in addressing those challenges efficiently and effectively.

The sample case consists of four activities: installation of windows, installation of c-channel, installation of roof, and installation of concrete pavement. It focuses on the execution of these four activities on Side A of the building. Figure 1 depicts the case environment, the initial three-week look-ahead schedule developed prior to construction (Figure 1a.), and the realized schedule encompassing the effects of time-space conflicts between activities (Figure 1b). The differences between the initial and realized schedule are significant. Time-space conflicts result in a 27% increase in the total duration. Moreover, the workflow is changed with the addition of new space-based predecessor-successor relationships (shown as dark arrows in Figure 1b). If construction managers could identify time-space conflicts prior to execution of a schedule and incorporate the impacts of these time-space conflicts into their schedules, they could increase the reliability of their schedules, eliminate non-value adding activities due to time-space conflicts, and make decisions proactively to improve space management at their sites.

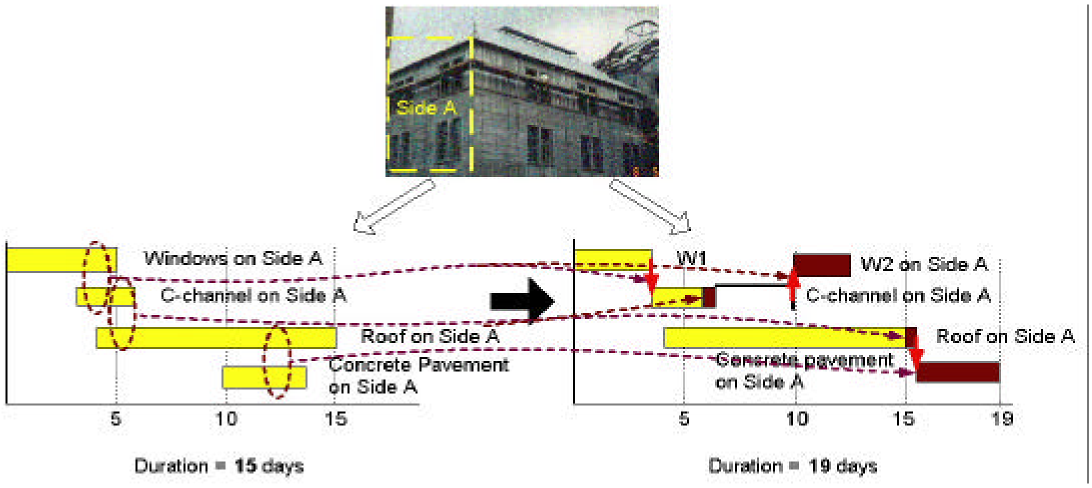
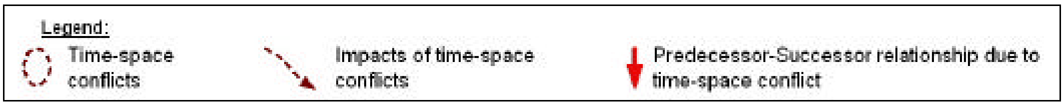


Figure 1a. The Initial Schedule **Figure 1b**. The Realized Schedule

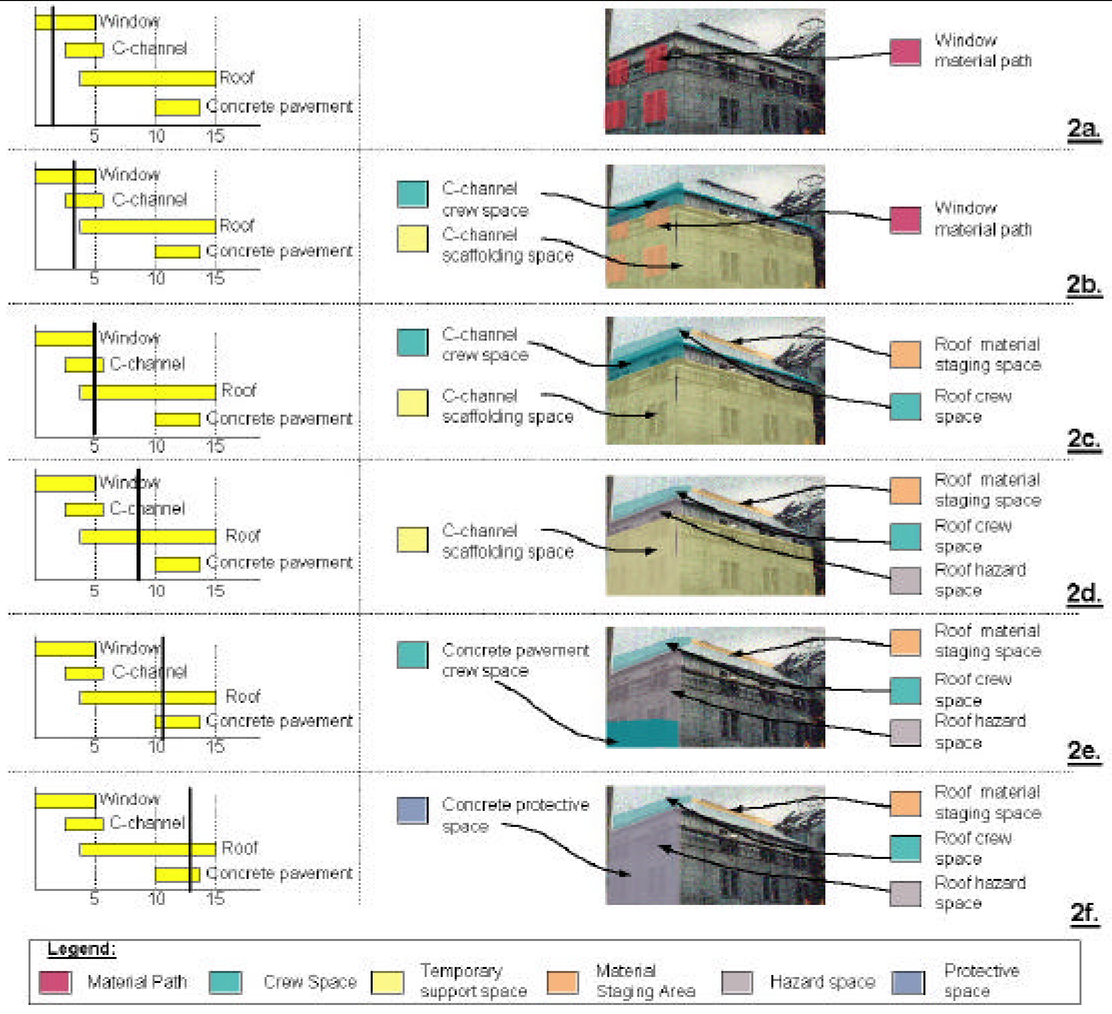


The sample case focuses on the execution of four activities on side A of the building. An initial three-week look-ahead schedule with a target duration of 15 days has been developed prior to construction. Due to the time-space conflicts between window and c-channel installation, c-channel and roof installation, and roof and concrete pavement installation, the initial schedule cannot be executed as is:

- The time-space conflict between the installation of the windows and the c-channel has caused interruption in the installation of windows. As a result, the installation of windows has to be completed after the c-channel is installed and the scaffolding is removed.
- The time-space conflict between the c-channel and the roof installation has increased the duration of both activities as a result of productivity loss due to congestion.
- The time-space conflict between the roof and concrete pavement installation has postponed the start of concrete pavement work until after the installation of the roof for safety reasons.

Figure 1: Overview of the sample case

The first step for incorporating activity space requirements in process design is to represent activity space requirements over time. Riley (1994) has identified twelve unique types of spaces required by activities: work elements, layout area, unloading area, material path, personnel path, storage area, staging area, prefabrication area, work area, tool and equipment area, debris path, protected area, and hazard area. The combination of space types that an activity requires depends mostly on the construction method that will be used. The four activities in the sample case utilize six different types of work spaces, as shown in the legend of Figure 2. Figure 2 shows these work space requirements and demonstrates how the space demand at a construction site changes over time. In some cases, activity space requirements vary over the duration of an activity. For example, the installation of concrete pavement in front of the building requires a crew space during the pouring of concrete (Figure 2e) and a protective space during the curing process (Figure 2f). In some other cases, a particular space is occupied even after the activity is completed in that specific area. For example, the scaffolding space required for c-channel installation at side A will occupy the same space until the c-channel components at all sides of the building are installed (Figure 2e). These two examples demonstrate that activity space requirements should be represented not only in all three dimensions but also across time.



This figure illustrates the evolution of space usage across time. Each space type, such as material path, crew space and hazard space, is represented with a different color as shown in the legend of the figure.

Figure 2: Space requirements of the activities in the sample case

Through representation of activity space requirements, construction managers can identify time-space conflicts and spatial interferences between activities. Figure 3 shows the spatial interferences and time-space conflicts existing in the sample case, the problems created by time-space conflicts, and the behaviors of interfering activities. Within the context of this research, we define spatial interference as the physical conflict of an activity's space requirement with another activity's space requirement or work-in-place. Not every spatial interference incidence creates a problematic situation at a construction site. For example, the spatial interference between the roof installation hazard space and the scaffolding used for installation of the c-channel (Figure 3d) does not hinder either of the activities. It even leads to an advantageous situation since the scaffolding limits the hazard space created by the roofing work. Time-space conflicts are special cases of spatial interferences that create problematic situations at construction sites, and they impact the performances of interfering activities. Figure 3 exemplifies productivity, constructibility, safety, and damage problems created by time-space conflicts in the sample case. In incorporating activity space requirements in a process design, construction managers need to understand the characteristics of spaces in relation to one another so that they can differentiate between a spatial interference that has no impact and a time-space conflict, and between different types of time-space conflicts.

The type of problem created by a time-space conflict affects how the interfering activities react to that specific conflict situation. Figure 3 states the behaviors of interfering activities in the sample case. Depending on how interfering activities behave, time-space conflict situations have different impacts on a given schedule (Figure 4). To prioritize the space allocation at a construction site, it is important to predict how interfering activities behave in specific time-space conflict situations and assess the schedule impacts of these behaviors.

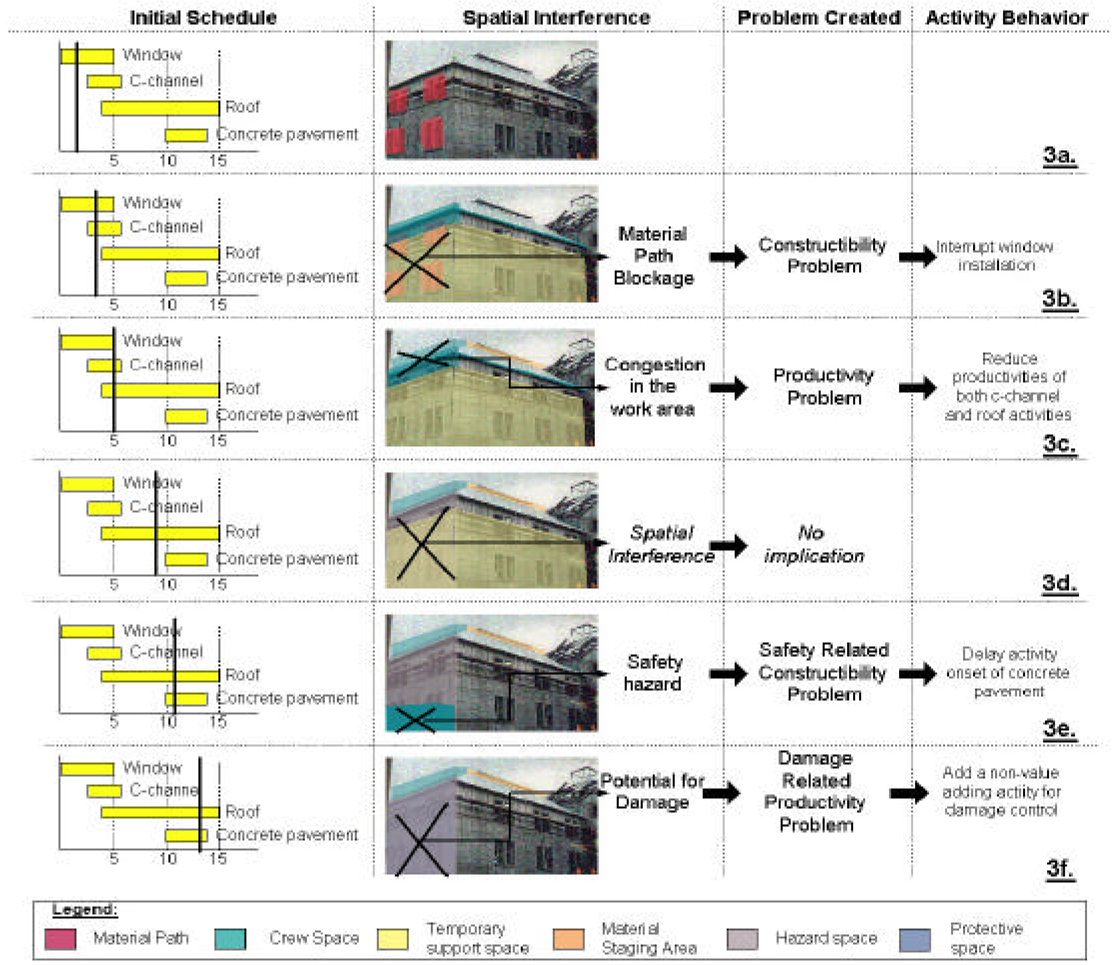
In some cases, a time-space conflict during an earlier phase of a project has ripple effects on succeeding activities. For example, during the c-channel activity the productivity loss due to congestion further delays installation of windows (shown as the black arrow in Figure 4b). At the end of these ripple effects, the schedule realized can be completely different from the one planned. Therefore, construction managers should not only consider the impacts of time-space conflicts on interfering activities, but also propagate the effects of those specific impacts throughout a given schedule. An overall assessment of schedule impacts of time-space conflicts will give construction managers the quantitative feedback to evaluate different options for construction process design and space management.

The next section summarizes the major challenges involved in time-space conflict analysis of a given schedule by reflecting on the case discussion presented in this section.

SUMMARY OF CHALLENGES IN TIME-SPACE CONFLICT ANALYSIS OF A GIVEN SCHEDULE

The major challenges involved in incorporating work space requirements in a construction process design are:

1. **Representation of activity space requirements.** Riley (1994) has identified twelve unique types of spaces required by activities: work elements, layout area, unloading area, material path, personnel path, storage area, staging area, prefabrication area, work area, tool and equipment area, debris path, protected area and hazard area. The combination of space types that an activity requires mostly depends on the construction method that will be used. Some of these work spaces are required around the component being installed, e.g., crew space, and some of them are required at fixed locations at a construction site, e.g., storage area. Activity work space requirements also vary within time. For example, during the concrete pavement installation a crew space is required at the beginning of the concrete pouring (Figure 2e) and a protective space is required during the curing process (Figure 2f). It is a challenging task to manually represent the locations and quantities of different activity space requirements over time. To address this challenge, we are working on automating the generation of work space requirements from 4D production models. 4D production models are integrated



Each spatial interference incidence is explained below:

Figure 3b shows that the scaffolding used for c-channel installation blocks the material path for window installation. This time-space conflict situation is labeled as material path blockage. It results in a constructibility problem since both of the activities cannot be performed at the same time with the current construction methods. As a result, the window installation is interrupted until the c-channel is installed and the scaffolding is removed.

Figure 3c shows that the crew space required for c-channel installation conflicts with the crew space required for roof installation. This time-space conflict situation translates into a congested work area, lowering the productivity rates of both activities.

Figure 3d shows that the scaffolding space required by the c-channel installation interferes with the hazard space required by the roof installation. This is just a spatial interference and does not create problem at the construction site.

Figure 3e shows that the hazard space created by tiles falling off the roof interferes with the crew space required by the concrete pavement installation. This safety hazard situation translates into a constructibility problem, resulting in a delay to the start of the concrete pavement installation.

Figure 3f shows that the hazard space created during the roof installation interferes with the protective space required during the curing of the concrete pavement. This time-space conflict creates a potentially damaging situation for the concrete pavement. As a result, additional non-value adding activities might be required for rework on the damaged areas on the concrete pavement.

Figure 3: Spatial interferences and time-space conflicts existing between activities, problems created by the time-space conflict situations, and behaviors of interfering activities in the sample case

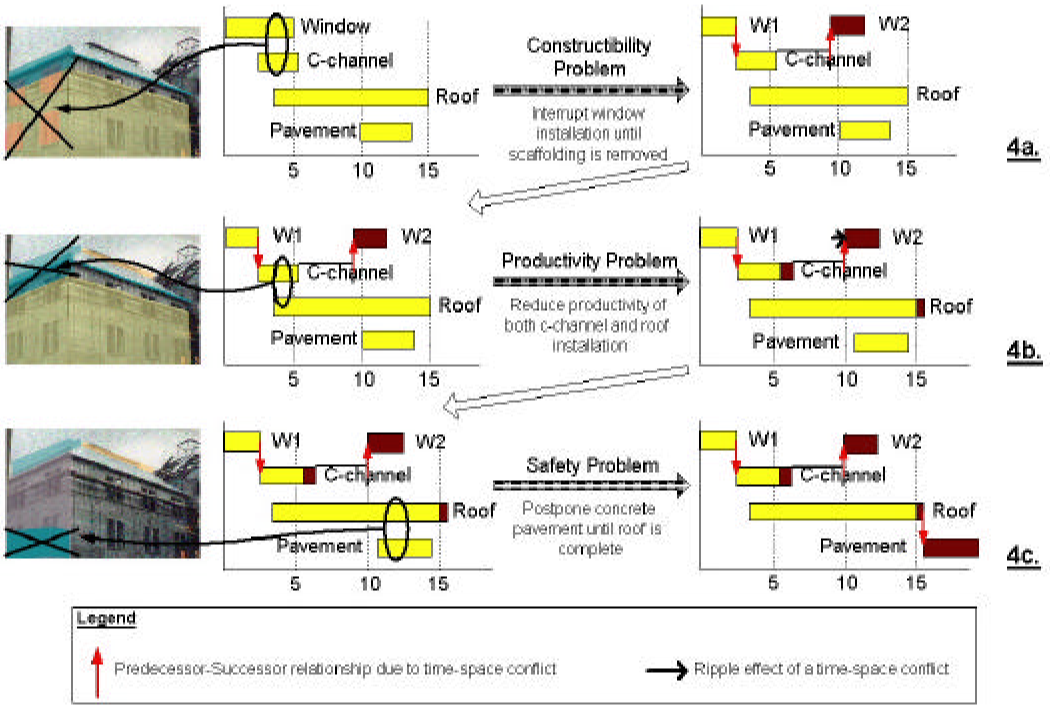


Figure 4a shows that the time-space conflict occurring between the window and c-channel installation has divided the window operation into two sub-activities: (1) installation of windows at the first two floors of side A, denoted as W1, and (2) installation of the windows at the 3rd and 4th floors of the building on side A, denoted as W2. Due to this time-space conflict, the W2 activity has to be postponed until the scaffolding is removed. Since scaffolding is going to be in place until c-channel components are installed on all sides of the building, W2 is further delayed until the last c-channel activity is completed, leading to a space-based predecessor-successor relationship between the last c-channel installation activity and W2 installation.

Figure 4b shows that the time-space conflict between the c-channel and the roof installation has resulted in an increase in the duration of both activities. The increase in the duration of the c-channel further postpones the start date of the installation of W2, due to the space-based successor relationship between the c-channel and W2.

Figure 4c shows that the time-space conflict between the roof and concrete pavement installation has resulted in the creation of a space-based predecessor-successor relationship between the two activities.

Figure 4: Schedule impacts of time-space conflicts in the sample case

product and process models with explicit construction method knowledge. We are currently working on representing activity work space requirements as resources in the construction method knowledge of 4D production models.

2. **Recognizing time-space conflict situations.** Spatial conflicts between activities create different types of problems at construction sites. Sometimes spatial interferences do not cause any problems. For example, the spatial interference between the hazard space created by the roof tiles falling off the roof and the scaffolding used for installation of c-channel in another zone (Figure 3d) does not create problem. Time-space conflicts, on the other hand, can cause constructibility

(Figure 3b), productivity (Figure 3c), safety (Figure 3e) and damage (Figure 3f) problems at construction sites. It is important to categorize time-space conflicts depending on the types of problems that they create at construction sites to predict their temporal implications and to decide on the remedies that should be incorporated. Currently, there is no formalized way of predicting the type of problem that a time-space conflict creates on construction sites. To address this challenge, we are developing a taxonomy of time-space conflicts and identifying factors that determine the type of problem that a time-space conflict creates at a construction site.

3. **Predicting the temporal implications of time-space conflict situations.** Activities react differently depending on the time-space conflict situation. These behaviors include reduction in productivity (Figure 4b), delay of activity start (Figure 4c) and addition of non-value adding activities. It is important to predict how activities will react in time-space conflict situations to capture the schedule impacts of those reactions. Consequently, by assessing the schedule impacts of time-space conflicts, construction managers can prioritize space allocation, minimize waste of time and non-value adding activities, and take proactive remedies to manage time-space conflicts. Currently, there is no formalized way of predicting the behaviors of interfering activities in certain time-space conflict situations. To address this challenge, we are identifying factors, which are inherent in certain time-space conflicts and which derive the different behaviors of interfering activities.

We have developed an initial time-space conflict analysis framework incorporating factors that determine the type of a time-space conflict, behaviors of interfering activities, and schedule impacts of those behaviors. The next section describes our initial time-space conflict analysis framework.

TIME-SPACE CONFLICT ANALYSIS FRAMEWORK

Within the context of this research, we define a framework as a knowledge map of time-space conflict analysis. Knowledge maps are special types of relevance (influence) diagrams that do not include uncertainties (Howard 1988). The framework we have developed presents the interaction between different factors that determine the schedule impacts of time-space conflicts. This framework can be used to formally assess schedule impacts of time-space conflicts. We are also using this framework to automate time-space conflict analysis of a given 4D production model.

We have started developing a framework for time-space conflict analysis through four industry case studies and our observations at construction sites. This framework has not been fully verified. It is one of our research tasks to verify this framework with concurrent and prospective case studies, and interviews with experienced construction managers.

Figure 5 shows the initial framework for time-space conflict analysis. Boxes represent the factors that determine the schedule impact of a time-space conflict. Arrows denote the relationships between different factors. An arrow entering into a box means that the factor at the other end of the arrow determines the value of the factor in that box.

The framework (Figure 5) consists of three distinct sections as denoted by boxes with shadows: (1) determination of time-space conflict type, (2) determination of behaviors of interfering activities, and (3) determination of schedule impacts of a time-space conflict. These three sections represent the three main consecutive steps of time-space conflict analysis. The following subsections describe the factors in each of the three sections of the framework:

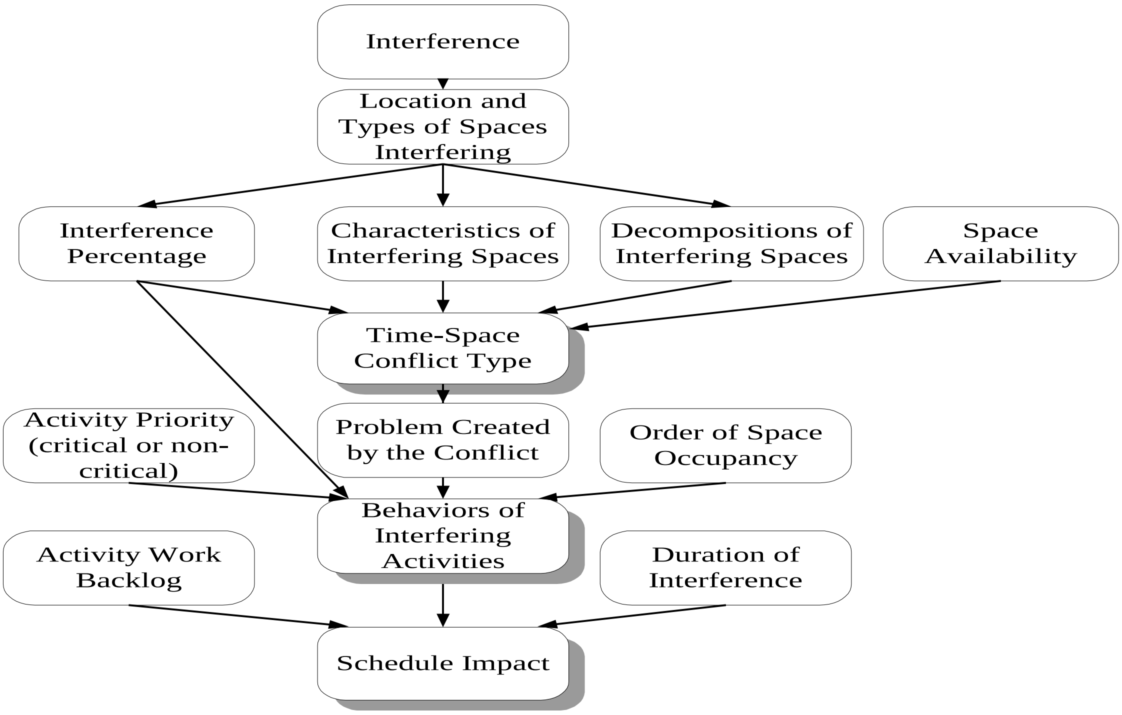


Figure 5: Initial time-space conflict analysis framework

1. Determination of Time-Space Conflict Type

Once a spatial interference is detected, there are two major factors that determine the type of a time-space conflict: (1) the location of interference, and (2) the types of interfering spaces, such as equipment space, crew space, material path space, etc. The types of spaces refer to Riley's (1994) categorization of activity space requirements. Table 1 provides examples of types of interfering spaces and the resulting time-space conflicts.

Table 1: Examples of how types of interfering spaces determine time-space conflict

Type of Interfering Space #1	Type of Interfering Space #2	Time-Space Conflict
Material Path Space e.g., Material path for installation of windows	Immobile temporary support space e.g., Scaffolding used for installation of c-channel	Access Blockage (Figure 3b)
Crew space e.g., Crew space of installation of c-channel	Crew space e.g., Crew space of installation of roof	Congestion (Figure 3c)
Hazard space e.g., Hazard space created during installation of roof	Crew space e.g., Crew space of installation of pavement	Safety (Figure 3e)
Hazard space e.g., Hazard space created during installation of roof	Protective space e.g., Protective space required during the curing of pavement	Damage (Figure 3f)

From the types of interfering spaces and the location of interference, we have derived three more specific factors that determine the type of a time-space conflict: (a) *interference percentage*, (b) *characteristics of interfering spaces*, and (c) *decompositions of interfering spaces*. In addition to these three factors, another factor, *space availability*, also influences the time-space conflict type.

1.a. Interference Percentage

We have defined the interference percentage as the percent of the quantity of space that is interfering relative to the total space required by an activity. Hence, it is calculated as:

*Interference Percentage = (Quantity of interfering space/ Quantity of required space) * 100*

The interference percentage will be different for each interfering activity, because of different quantities of required spaces.

The interference percentage implies the significance of a time-space conflict to an interfering activity. For example, a higher interference percentage means that most of the space requirement of an activity is conflicting with the space requirement of another activity. In higher percentage cases, a time-space conflict can lead to a constructibility problem. Conversely, an activity with lower interference percentage might not encounter any problem.

1.b. Characteristics of Interfering Spaces

The characteristics of interfering spaces can be determined when the types of interfering spaces are identified. A characteristic of a space that is relevant for time-space conflict analysis purposes is its mobility. The mobility of interfering spaces impact the type of problem that a time-space conflict creates at construction sites. For example, in the sample case, the time-space conflict between the material path used for window installation and the scaffolding used for c-channel installation results in a constructibility problem (Figure 3b) leading to a discontinuity in installation of windows. Now, let's say that, instead of scaffolding, which is an immobile resource, a mobile lifting mechanism such as a scissors lift is used. In that case, the constructibility problem between window and c-channel installation would have been eliminated since mobile equipment can be moved to provide the required access for transportation of windows.
We are currently in the process of identifying additional characteristics of spaces that are relevant for time-space conflict analysis purposes.

1.c. Decomposition of Interfering Spaces

The decomposition of interfering spaces and the location of interference with respect to this decomposition also affect the resulting time-space conflict situation. For example, an equipment space is composed of a physical space, a safety space, and a maneuvering space. A spatial conflict located within the physical space or safety space of equipment will lead to a constructibility problem. Conversely, a time-space conflict in the maneuvering space will lead to a productivity problem. Currently, we are identifying the decomposition of different activity space types that differentiate between time-space conflict types.

1.d. Space Availability

Space availability asks the question of whether the interfering space of an activity can be assigned to another location. When there is an alternative space available, which can be used for the same purpose, a time-space conflict situation can be eliminated and there will be no implications to a given schedule. For example, when a material path of an activity interferes with another space, an alternative path might be used to transport the materials. Hence, it is important to search for alternative spaces before assessing the temporal impacts of time-space conflicts.

2. Determination of Behaviors of Interfering Activities

Here, we are using the term, behaviors of interfering activities, to refer to how activities react in a time-space conflict situation. Hence, the behaviors of activities include reduction in productivity, addition of non-value adding activities, interruption in the work flow, and delay of activity start. We have identified four factors that determine the behaviors of interfering activities: (a) *time-space conflict type*, (b) *interference percentage*, (c) *activity priority*, and (d) *order of space occupancy*.

2.a. Time-Space Conflict Type

The type of a time-space conflict is the main factor determining behaviors of interfering activities. Table 2 shows examples of time-space conflicts, the corresponding problems and activity behaviors.

Table 2: Examples of time-space conflicts and corresponding behaviors of interfering activities

Examples of Time-Space Conflicts	Corresponding Problem	Corresponding activity behavior
Access blockage (Figure 3b)	Constructibility	Access blockage can lead to a constructibility problem when there is no other access route available. In that case, the interfering activities cannot be performed at the same place at the same time. The selection of which activity to execute first depends on other factors.
Congestion (Figure 3c)	Productivity	Productivity loss of interfering activities.
Safety hazard (Figure 3e)	Constructibility	The interfering activities cannot be performed at the same place at the same time. The selection of which activity to execute first depends on other factors.
Damage (Figure 3f)	Productivity	Addition of a non-value adding activity for damage control.

2.b. Interference Percentage

Interference percentage is applicable to time-space conflicts resulting in productivity problems, e.g., congestion. In those cases, the amount of reduction in productivity is a function of the interference percentage. Higher interference percentage translates into greater reduction in productivity. Conversely, lower interference percentage translates into less reduction in productivity.

2.c. Activity Priority

Activity priority factor is designated to determine the activity that will take precedence in time-space conflicts resulting in constructibility problems. For example, an activity that is on the critical path might have precedence over a non-critical activity.

2.d. Order of Space Occupancy

Order of space occupancy is another criterion that helps in determining which activity should take precedence in time-space conflicts resulting in constructibility problems. Crews often race to occupy a space first so that they can continue with their work without disruption. The succeeding crews that need to use the same space generally need to work around them. Hence, at construction sites, a first-in-first-out (FIFO) approach mostly governs space management. The order of space occupancy factor is designated to capture the FIFO approach at construction sites. However, other factors, such as activity priority, are often more dominant than the order of space occupancy factor in determining the behaviors of interfering activities. For example, a higher priority activity can take precedence over a lower priority activity no matter what the order of space occupancy is. Hence, the order of space occupancy factor is applicable to situations where both of the interfering activities have equal priority.

3. Determination of Schedule Impacts

We have identified three factors that determine the schedule impacts of a time-space conflict: (a) *behaviors of interfering activities*, (b) *activity work backlog*, and (c) *duration of interference*.

3.a. Behaviors of Interfering Activities

Behaviors of interfering activities determine the schedule impacts of a given conflict situation. Table 3 provides examples of how behaviors of interfering activities impact a given schedule.

3.b. Activity Work Backlog

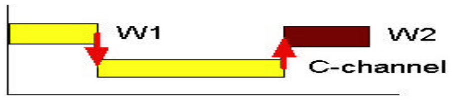
Activity work backlog is the amount of work available for a certain activity at a given time. Activity work backlog is relevant to time-space conflicts resulting in constructibility problems, where one of the interfering activities has to stop working in a particular zone. If that specific activity has a work backlog in another zone of the project, it might perform that work. As a result, the plan of execution for that activity changes, and there is not necessarily an impact on the overall duration of the project. In cases where an activity has no backlog, a delay on the start of an activity due to time-space conflicts leading to constructibility problems can affect the overall project duration.

3.c. Duration of Interference

Duration of interference defines how long the predicted activity behavior is going to occur. For example, if there is congestion only during the first two days of an activity then the loss of productivity due to congestion will be applicable only on those two days.

This section has described the factors determining the schedule impacts of time-space conflicts between activities and presented these factors within a time-space conflict analysis framework. The next section illustrates how this framework can be used to predict the schedule impacts of time-space conflicts using a time-space conflict incidence occurred in the sample case.

Table 3: Examples of how different behaviors of activities impact a given schedule

Behaviors of Interfering Activities	Resulting Schedule Impact
Interruption of the execution of an activity due to a constructibility problem E.g., interruption in the installation of windows due to conflict with the c-channel installation (Figure 4a)	Separation of activity into two activities and addition of a space-related predecessor-successor relationship between the first portion of the interrupted activity, the interfering activity, and the last portion of the interrupted activity. 
Reduction in productivity due to congestion E.g., productivity loss of c-channel and roofing activities due to congestion. (Figure 4b)	Increase in duration of the interfering activities 
Delay of activity start due to a constructibility problem E.g., delay of installation of pavement due to conflict with the roof installation (Figure 4c)	Addition of a space-related predecessor-successor relationship between interfering activities 

EXAMPLE APPLICATION OF INITIAL TIME-SPACE CONFLICT ANALYSIS FRAMEWORK

We have chosen to use the spatial conflict between the scaffolding used for c-channel installation and the material path required by the window installation (Figure 3b) as an example to demonstrate the application of the initial time-space conflict analysis framework described in the previous section. Figure 6 shows the values of the factors in the time-space conflict analysis framework for the c-channel and window installation activities.

Step 1: Determination of time-space conflict type

50% of the scaffolding space blocks 100% of the material path space. Since scaffolding is an immobile resource and the conflict is at the physical space of both of scaffolding and material path, and there is no alternative way to transport windows or to install the c-channel, the resulting time-space conflict is called access blockage.

Step 2: Determination of behaviors of interfering activities

Access blockages create constructibility problems at construction sites. The constructibility problem implies that both of the interfering activities cannot be performed concurrently as planned in the initial schedule. The selection of the activity that will be executed first depends on the activity priority and the order of space occupancy. Since the c-channel installation is on the critical path, it has a higher priority than the window installation. Consequently, the c-channel installation is executed and the window installation has to be interrupted until the c-channel work is finished, even though installation of windows occupied the space first.

Step 3: Assessment of the schedule impact

Since the installation of windows has no work backlog, there will be no window installation during the duration of this time-space conflict. The duration of interference, in this case, is equal to the whole duration the scaffolding is in place, which is greater than the duration of the c-channel installation in that particular zone, since scaffolding will be dismantled after c-channel components at all sides of the building. Since all of the c-channel components are scheduled to be installed in 10 days, the duration of interference for this time-space conflict is 10 days.

The schedule impacts of the time-space conflict between window and c-channel installation are: (1) division of installation of window activity into two sub-activities, and (2) insertion of new space-based predecessor-successor relationships between the first window installation sub-activity and the first c-channel installation activity, and between the last c-channel activity and the second window installation sub-activity.

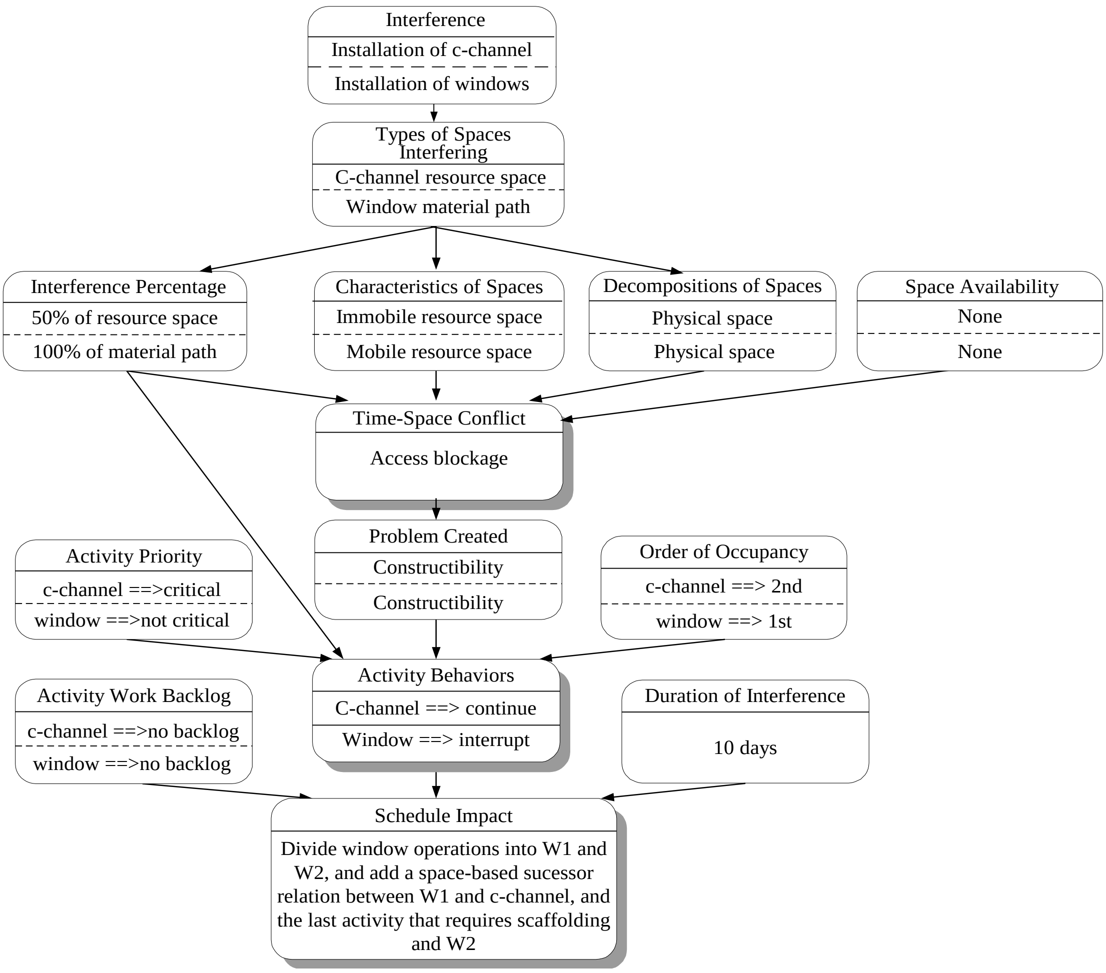


Figure 6: Application of the initial time-space conflict analysis framework for conflict between c-channel and window installation in the sample case

CONCLUSION

Construction managers can manage time-space conflicts proactively through identifying and formally analyzing time-space conflicts, and assessing their schedule impacts prior to construction. The challenges involved in proactive time-space conflict management are representation of activity work space requirements in all four dimensions (3D + time), recognition of time-space conflicts and prediction of behaviors of interfering activities in particular time-space conflicts. In this paper, we have described a formal way to predict the behaviors of interfering activities and schedule impacts of those behaviors given a spatial conflict. This formal way is just one part of formalization and automation of time-space conflict analysis prior to construction. By implementing the presented framework, we are automating the determination of schedule impacts of time-space conflicts. In addition, we are also working on automating the generation of work space requirements and detection of spatial conflicts using 4D production models. Our future research directions include verification of the initial time-space conflict analysis framework described in this paper by applying it to additional cases and development of an automated time-space conflict analysis prototype system. By having an automated system, construction managers can quickly realize the impacts of time-space conflicts and proactively manage the time-space conflict situations before they occur at construction sites. Consequently, they will increase the reliability of their schedules, eliminate non-value adding activities due to time-space conflicts, and increase safety and productivity at construction sites.

REFERENCES

Ahuja, H. N. and Nandakumar, V. (1984). "Enhancing Reliability of Project Duration Forecasts." *American Assoc. of Cost Engineers Transactions*, E6.1-E.6.12.

Akinci, B. and Fischer, M. (1998). "Time-Space Conflict Analysis Based on 4D Production Models." To appear in ASCE, *Proc. Computing Congress*.

Alshawi, M. (1997). *SPACE: An Integrated Environment for the Construction Environment*. Time Research Institute, Salford University, Salford.

Birell, G. (1981). "Construction Planning - Beyond the Critical Path." *J. Constr. Division*, Proc. American Society of Civil Engineers, 106(CO3), 389-407.

Eastman, C. (1975). *Spatial Synthesis in Computer-Aided Building Design*. John Wiley and Sons, New York.

Howard, R.A. (1988). "From Influence to Relevance to Knowledge." in R.M. Oliver and J.Q. Smith (eds.) *Influence Diagrams and Belief Nets and Decision Analysis*. John Wiley and Sons, Chichester, West Sussex, England.

Howell, G., Laufer, A. and Ballard, G. (1993). "Interaction Between Subcycles: One Key to Improved Methods." ASCE, *J. Constr. Engrg. and Mgmt*., 119 (4) 714-728.

Kuntz, K. (1994). "A Construction Crew Evaluation Model." *Technical Report # 33*, Computer Integrated Construction Research Program, Department of Architectural Engineering, the Pennsylvania State University, University Park.

Latombe, J.-C. (1988). "Global Path Planning Approaches for Material Movements in a Worksite." *Technical Report # 3*, Center for Integrated Facility Engineering, Stanford University, CA.

Levitt, R., Tommelein, I., Hayes-Roth, B. and Confrey, T. (1989). "SightPlan: A Blackboard Expert System for Constraint Based Spatial Reasoning about

Construction Site Layout." *Technical Report # 20*, Center for Integrated Facility Engineering, Stanford.

Morad, A., Cleveland, A., Beliveau, Y., Francisco, V. and Dixit, S. (1992). "Path-Finder: AI-based Path Planning System." ASCE, *J. Comp. in Civil Engrg*., 6 (2) 114-128.

O'Brien, J.J. (1975). "VPM Scheduling for High-Rise Buildings." ASCE, *Journal of the Construction Division*, 101 (CO4) 895-905.

Oglesby, C.H., Parker, H.W. and Howell, G.A. (1989). *Productivity Improvement in Construction*, Mc Graw-Hill Inc., New York, N.Y.

Rad, P. (1980). "Analysis of Working Space Congestion from Scheduling Data." *American Association of Cost Engineers Transactions*, F4.1-F4.5.

Riley, D. (1994). *Modeling the Space Behavior of Construction Activities*. Ph.D. Dissertation, Department of Architectural Engineering, Pennsylvania State University, University Park.

Sanders, S.R., Thomas, H.R. and Smith, G.R. (1989). "An Analysis of Factors Affecting Labor Productivity in Masonry Construction." *PTI # 9003*, Pennsylvania State University, University Park, PA.

Stradal, O. and Cacha, J. (1982). "Time Space Scheduling Method." ASCE, *Journal of the Construction Division*, 108 (CO3) 445-457.

Thabet, W. and Beliveau, Y. (1994). "Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings." ASCE, *Journal of Construction Engineering and Management*, 120 (1) 96-116.

Thabet, W. and Beliveau, Y. (1997). "SCaRC: Space-Constrained Resource Constrained Scheduling System." ASCE, *J. Computing in Civil Engineering*, 11 (1) 48-59.

Tommelein, I.D., Castillo, J. and Zouein, P.P. (1992). "Space-Time Characterization for Resource Management on Construction Sites." ASCE, *Proc. 8th Conf. on Computing in Civil Engineering*, 623-630.

Tommelein, I.D. and Zouein, P.P. (1993). "Interactive Dynamic Layout Planning." ASCE, *J. of Construction Engineering and Management*, 119 (2) 266-287.

Zhu, D. and Latombe, J.-C. (1989). "New Heuristic Algorithms for Efficient Hierarchical Path Planning." *Technical Report # 18*, Center for Integrated Facility Engineering, Stanford University, CA.

Zouein, P.P. and Tommelein, I.D. (1993). "Space Schedule Construction." ASCE, *Proc. 5th Intl. Conf. on Computing in Civil Engrg.*, New York, 1770-1777.