PRODUCTIVITY AND COST ANALYSIS BASED ON A 4D MODEL

Burcu Akinci[1], Sheryl Staub[2], Martin Fischer[3]

Abstract

Four-dimensional (4D) CAD models are being used more and more frequently to visualize the transformation of space over time. To date, these models are mostly purely visual models. Any evaluation of a 4D model, e.g., whether it presents a workable construction sequence, is left to the viewer. The evolution of 4D CAD demonstrates the ability to provide a tighter link between visualization and analysis tools. In this paper, we discuss how an intelligent 4D model helps identify time-space conflicts between concurrent activities and provide assistance in calculating more realistic cost estimates. The 4D system (4D Work Planner) presented here is based on symbolic and graphic product and process models, and provides both the visual and analytical feedback necessary to reengineer construction sequences.

Introduction

A major task for construction planners is to determine the sequence for how construction activities are to proceed so that resources are allocated appropriately and limited site space is used effectively. The main objectives are to provide a workable schedule that coordinates the workflow through the project efficiently, and to develop a cost estimate that incorporates the activity interdependencies represented in the schedule. In a workable schedule, time-space relationships that exist between activities are considered to minimize the interferences in a given work area and to enhance the productivity of crews. Similarly, a cost estimate based on a workable schedule would reflect the reduction in productivity when there is a work area interference between activities.

Current project management practice uses CPM (Critical Path Method) schedules to represent the completion of a facility over time. CPM schedules show the dependencies between activities, but they do not model the time-space relationships that exist between activities. For example, CPM schedules do not explicitly show whether workers working on concurrent activities have to share a common workspace and might therefore interfere with each other, reducing each other's productivity. Cost estimates today are based on unit cost or productivity rate data, and do not reflect the impact of time-space conflicts on productivity. Time-space conflicts between concurrent activities not only reduce productivity rates, but can also prevent the execution of one or more affected activities. As a result, if time-space conflicts between activities are not identified during planning, project managers can face constructability and productivity issues when implementing CPM schedules, and face cost overruns at the end of a project due to unrealistic cost estimates.

During the construction of the Haas School of Business at the University of California at Berkeley, a $34 million project under tight schedule constraints, the development of a workable schedule was an issue. The Administration Wing was demanding

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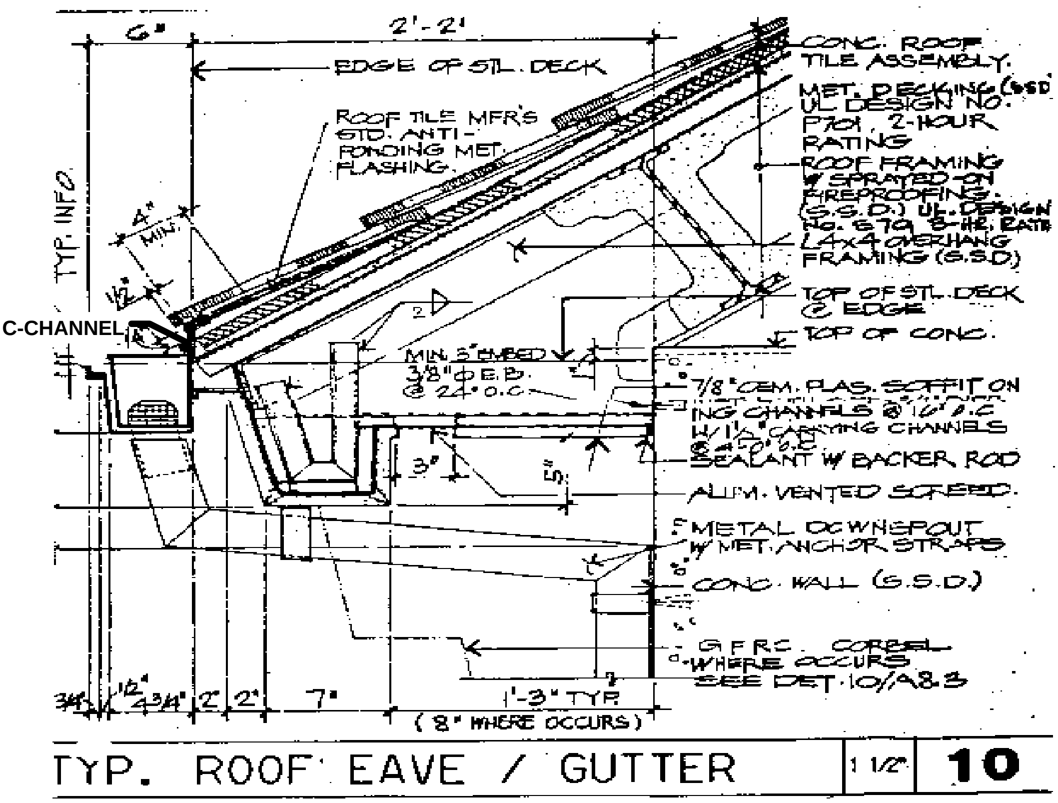
[1] Graduate Research Asst., Dept. of Civil Eng., Stanford University, Stanford, CA 94305-4020, USA.
[2] Graduate Research Asst., Dept. of Civil Eng., Stanford University, Stanford, CA 94305-4020, USA.
[3] Assistant Professor, Dept. of Civil Eng., Stanford University, Stanford, CA 94305-4020, USA.

increased attention, requiring early turnover and having very little float to accommodate delays. Completion of the roof was the top priority, as installation of the mechanical equipment depended on the building being watertight. The initial schedule was as follows: window installation, followed by roof installation. The original roof design included a one-piece c-channel; a critical item for the roof subcontractor to reach maximum productivity (Figure 1).

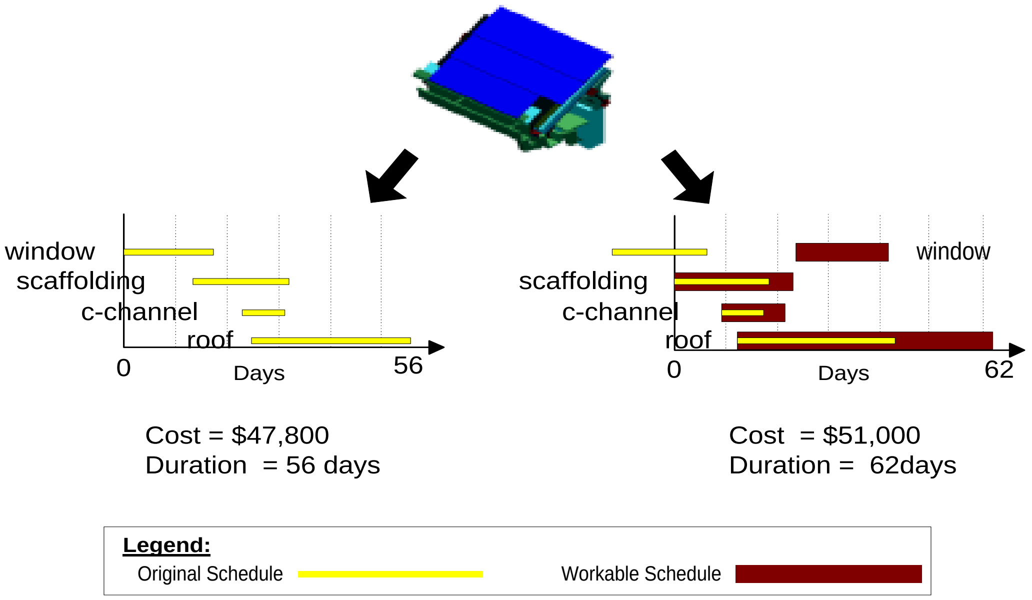
Figure 1: The Original 2-D Design Drawing of the Haas School of Business at University of California at Berkeley



Unfortunately, the original schedule did not include an activity to install the c-channel. As a result, the schedule had to be modified to incorporate the c-channel and the scaffolding required for its installation. After evaluating various schedule alternatives, the general contractor proposed the schedule shown in Figure 2a and the corresponding cost by using base productivity rates. However, he did not realize the two time-space conflicts present in this schedule (Figure 3):

1. Window and scaffold: Installing the c-channel prior to the roof prevents the installation of the windows, as the scaffolding for the c-channel (labeled as C in Figure 3) now blocks the window access (labeled as D in Figure 3).
2. C-channel and roof: Work area for the installation of the c-channel (labeled as B in Figure 3) interferes with placement and installation of roof materials (labeled as A in Figure 3) at the same approximate locations. This would result in a lower productivity in roof and c-channel installation activities.

Figure 2: Original Schedule versus Workable Schedule

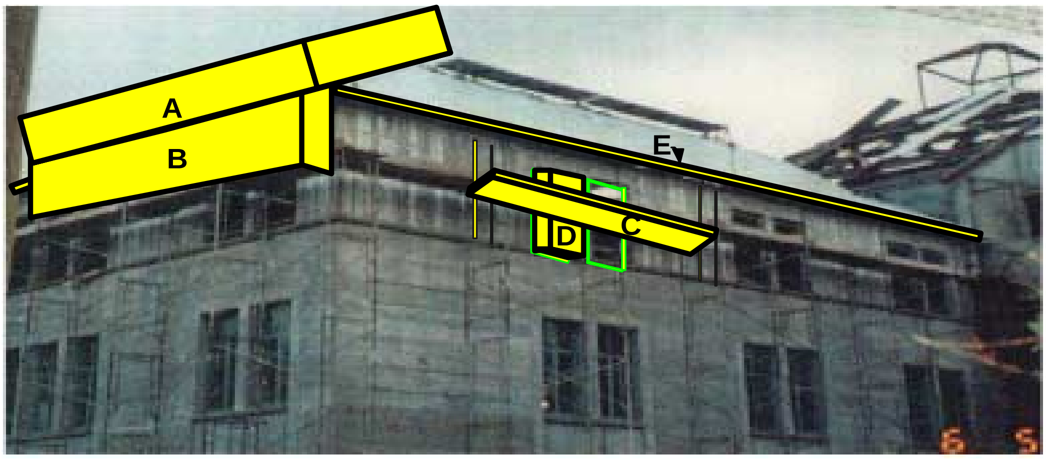


Cost = $47,800
Duration = 56 days

Cost = $51,000
Duration = 62days

Figure 2a: Original Schedule **Figure 2b: Workable Schedule**

Figure 3: Work Space Requirements and Interference



Legend:

A	Work Space Requirement for Roof System Installation
B	Work Space Requirement for C-channel installation
C	Scaffolding
D	Work Space Requirement for Window Installation
E	C-Channel

These time-space conflicts, if identified in a timely fashion, could lead to the development of a workable schedule given in Figure 2b where window installation is delayed to allow a timely completion of the c-channel and roof work. Note the cost and duration differences between the two schedules. The cost based on the workable schedule is 10% higher due to the decreased productivity caused by the time-space conflict between the c-channel and roof. Hence, the original schedule results in durations and costs that are too optimistic, as it did not consider time-space interferences.

This case illustrates that even though the time-space relationships between activities are important, today's stand-alone scheduling tools based on CPM do not model these relationships. CPM schedules model the temporal dependencies between activities explicitly. However, interferences that might occur between activities due to the sharing of a common workspace are not represented and cannot be detected. Similarly, current cost estimates are based on a typical productivity rate of performing an activity, and they often fail to consider the productivity impacts of possible time-space conflicts between activities.

To identify the time-space conflicts between activities, we need both spatial, temporal, and logic information about an activity. The spatial information includes the location of an activity and the space it occupies, the temporal information includes activity start time, activity finish time, activity duration, and the logic information includes the preceding and succeeding activities. A 4D model integrates 3D CAD components with schedule activities of a facility. In the next section, we will provide some background on 4D modeling and describe how an intelligent 4D model would help in identifying the time-space conflicts. In the following section, we will describe the system architecture of the 4D WorkPlanner.

4D Modeling

4D Simulation combines 3D CAD models with CPM schedules. Earlier research (Collier and Fischer 1996) demonstrates the use of 4D CAD as a visualization tool. Visual 4D CAD provides timed construction animation sequences to facilitate communication between client and other project team members. However, a visual 4D CAD model does not contain semantic knowledge about the 3D graphical elements and the schedule.

McKinney et al. (1996) create a 4D model by representing the 3D model and the schedule information both graphically and symbolically, in product and process models respectively. Their Collaborative 4D CAD prototype links a 3D graphical model in AutoCAD to a symbolic model in Design ++. With the Collaborative 4D CAD tool, the process of building a 4D model from a 3D model produces both a traditional CPM schedule as well as a 4D CAD simulation. In the process of building a 4D model, the user links symbolic models of physical components and schedule activities. The resulting symbolic 4D model then supports interactive and dynamic changes of the 3D model or the schedule. Furthermore, the symbolic or intelligent 4D CAD model forms a basis for analysis, since the system captures knowledge about building components and schedule activities.

Building on this system, our research on 4D WorkPlanner uses 4D CAD not only as a visual tool but also an analysis tool. 4D WorkPlanner analyzes a given schedule and 3D model of a facility by identifying the time-space conflicts between activities and considering the cost and duration impacts of these conflicts. Specifically, we have expanded the capabilities of existing 4D tools by:

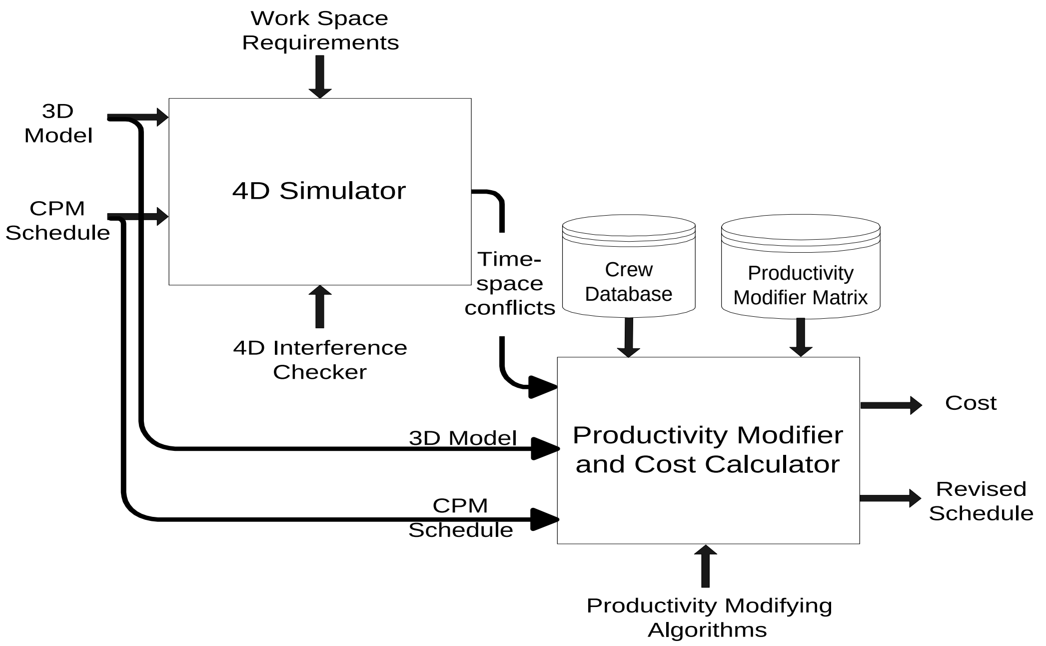
1. Graphically and symbolically representing workspace requirements to support the user in identifying time-space conflicts for each activity.
2. Developing algorithms that consider time-space impacts in adjusting productivity rates and durations and calculating activity costs.

The next section will describe the overall system architecture of the 4D WorkPlanner with examples from the Haas case introduced above.

Overall System Architecture

The 4D Work Planner system consists of two distinct parts: (1) 4D Simulator and (2) Productivity Modifier and Cost Calculator (Figure 4). The 3D model and the initial schedule of a project are linked in the 4D Simulator. Using this project-specific information together with workspace requirements of each activity and 4D interference-checking algorithms, the 4D Simulator identifies the time-space conflicts of activities that might exist in a particular schedule. It provides feedback to the user by highlighting the conflict areas shown in Figure 3, while simulating the construction of the 3D model over time. Once the simulation is complete, the system provides the option to either change the schedule or use the current schedule and modify the productivity rates of the conflicting activities. When the user chooses to modify the productivity rates, the Productivity Analyzer and Cost Calculator makes cost calculations and schedule adjustments by utilizing the crew database, productivity modifier matrix and productivity modifying algorithms. The following two subsections explain the 4D Simulator and the Productivity Modifier and the Cost Calculator.

Figure 4: 4D Work Planner



4D Simulator

Coordination of resources and available workspace is a major task for schedulers. It requires that the schedule be represented with sufficient detail to enable an engineer to recognize and minimize spatial conflict to maximize productivity. Schedule activities are typically broken down by zones or work areas, and 4D models graphically display the building components, but neither represents the workspace needs of each crew to install a component. For example, in the case presented previously, to achieve maximum productivity, the roof tile installation may require a prismatic space encompassing one-half the width of the roof, and measuring seven feet perpendicular from the roof component (Figure 3). Representing the spatial requirement for each activity facilitates the early detection of time-space conflicts.

Creation of a 4D CAD simulation is currently implemented with Jacobus Technology's PlantSpace Object Engine (Jacobus 1997). Given the 4D model of a facility, the 4D Simulator represents and visualizes user-defined workspace requirements of activities and detects time-space conflicts using 4D interference-checking algorithms. The next section describes how the workspace requirements are represented, and the following section explains the 4D interference-checking algorithms.

Representation of workspace

Representation of workspace of activities is a complex issue because of the different types of workspaces required by activities. Thabet and Beliveau (1994) quantify the workspace demand for an activity by evaluating the total space demand of all resources necessary to perform the activity. Space demand for any resource is composed of the actual physical space the resource occupies in the work area enclosure, and the space adjacent to the physical space of the body of the resource, which is considered as a safety zone for the movement of the resource. According to the spatial needs over time, Thabet and Beliveau divide the activities into three classes: (1) Class A activities, which use the total available space of the work area in the floor, (2) Class B activities, which accumulate their space demand mainly from the requirement of their manpower and equipment for workspace, and (3) Class C activities, which convert a large material storage space prior to the progress of work into work in place as work progresses. In the 4D Simulator prototype, we have modeled Class B activities since the relevant activities for the Haas case, installation of windows, c-channel and roof tiles, are of Class B. Hence, the system represents the space needs of resources which consists of the actual space needed by components and the surrounding workspace. It considers these needs as constant throughout the activity.

Tommelein and Zouein (1993) and Riley (1994) also represent the workspace requirements of activities in their systems. Workspaces are represented on the 2D plan view. We have added the third dimension (the z-axis) to these representations.

4D Interference Detection

Minimizing time-space conflicts that arise throughout the construction process has been the focus of other researchers. The MovePlan system developed by Tommelein and Zouein (1993) links the spatial needs of resources with the construction schedule.

It generates site layouts that minimize spatial conflicts caused by temporary facilities over the duration of a project. Riley (1994) models the space behavior of activities and provides a space planning model that helps a construction planner to design a productive work environment that minimizes workspace congestion and interference. The space model describes the type of construction spaces needed for construction processes, the space occupied by completed work units and the typical patterns in which these spaces exist and move over time. Shown as 2D views, the outputs of Riley's model are a work sequence, a layout sequence and a construction schedule.

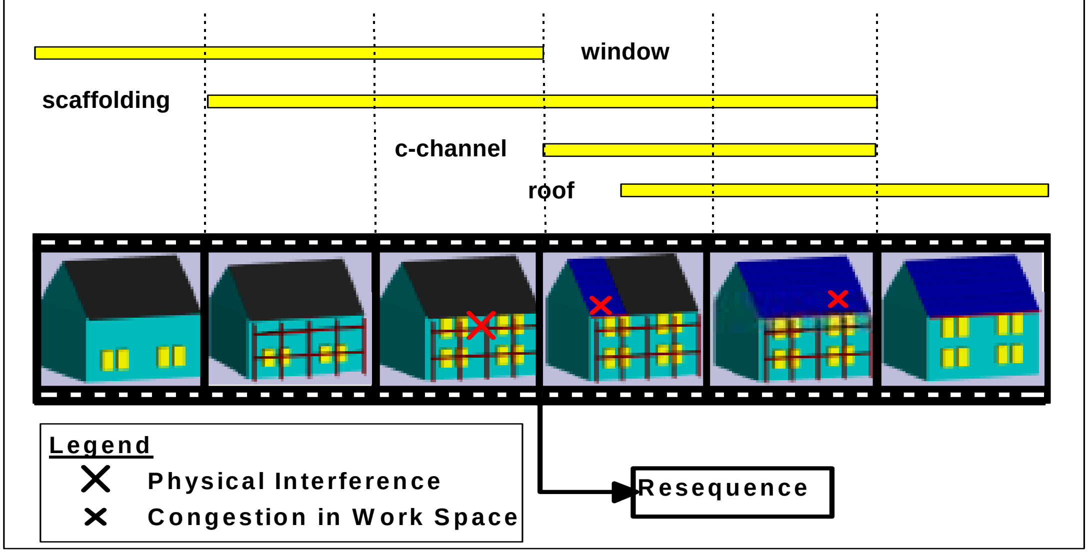
The two systems developed by Tommelein and Zouein (1993) and Riley (1994) are planning tools that focus on minimizing spatial conflicts that might occur on the plan-view. In contrast, 4D WorkPlanner is an analysis tool that represents workspace requirements of activities graphically and symbolically in three-dimensions and evaluates a user-developed schedule with respect to time-space conflicts and their impacts on productivity.

There are commercially available tools, such as Dynamo (http://mars.tecnomatix.com/), that perform both static (3D) and dynamic (4D) interference checking. For example, Dynamo highlights physical space conflicts that might occur between a component and a sub-assembly during the installation of a component. However, we are also interested in detecting interferences of workspaces - not just the physical component(s) - required by each activity. Therefore, we have developed 4D interference-checking algorithms that search for component and workspace interferences for partially or fully concurrent activities.

An important aspect of interference detection is the distinction between the interferences that prevent the execution of one or several activities and interferences that reduce the productivity when performing an activity. This distinction helps identify activities that have to be resequenced to allow construction and activities that should be resequenced to maximize productivity. For the initial schedule of the Haas case (Figure 5), the system has identified two interferences. There is a physical interference between the installation of the windows and the installation of the c-channel which requires the scaffolding. There is also a congestion in the work place during the installation of the c-channel and the roof tiles. Since there is a physical interference in the given 4D model, the system prompts the user to resequence the schedule.

In summary, the 4D Simulator graphically highlights time-space conflicts between concurrent activities. The user can then resequence the activities or modify the productivity rates and the activity durations. In the latter case, the Productivity Modifier and Cost Calculator part of the system proposes modifications of the productivity rates and calculates the cost of the facility based on the workable schedule.

Figure 5: Simulation based on Original Schedule



Productivity Modifier and Cost Calculator

Various factors affect the productivity of performing an activity, such as planning, coordination, and workspace distribution (Oglesby et. al. 1989, Kuntz 1994). Many researchers have focused on productivity improvement issues in construction (Sanvido 1984, Oglesby et. al. 1989, Kuntz 1994). Thabet and Beliveau (1994) discuss the decrease in productivity rates that often occurs when activities are scheduled concurrently and work spaces overlap. In determining productivity rates, cost estimators often rely on cost data of a similar project recorded in a company's historical database and on their own experience. Although they know that factors like the sequence of activities and workspace allocation affect productivity, they often cannot consider their impact in detail since no commercially available scheduling and estimating tool helps estimate the cost impact of time-space conflicts.

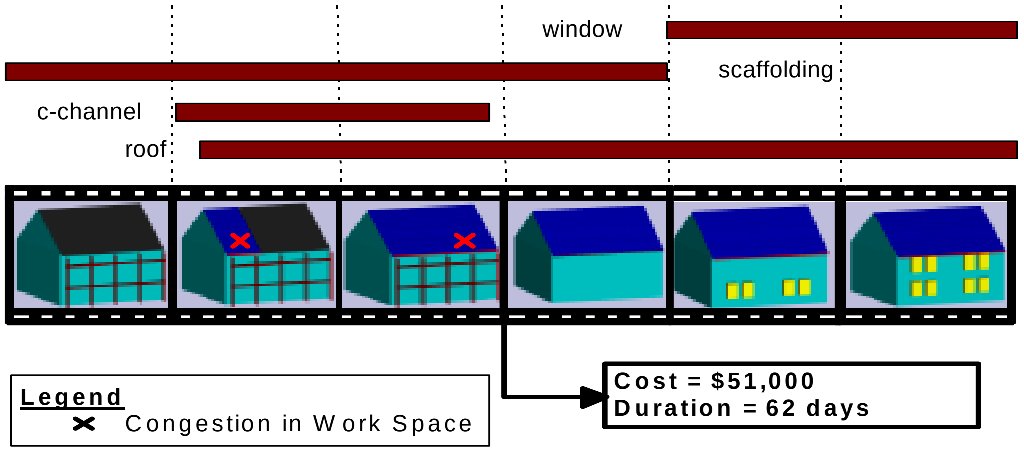
In practice, two approaches are used for cost estimating: (1) unit cost and (2) production rate. In unit-cost-based cost estimating, unit costs from a company's historical database or from published databases are used to determine the cost of an item. In production-rate-based cost analysis, the duration of an activity is determined by considering the productivity rate of its crew. This duration is then multiplied by the hourly crew cost to calculate the cost of an activity. These approaches do not explicitly account for the effects of time-space relationships between activities. Therefore, we have complemented these approaches with algorithms that account for the productivity impact of workspace congestion.

Realizing the significance of time-space relationships between activities, we have developed algorithms that consider the productivity impact of time-space conflict of activities to modify the base productivity rate. These algorithms consider the fraction of an activity's duration and space use that is in conflict with another activity. For example, in the Haas case described above, the c-channel encroaches marginally on the roof workspace, but the roof work encroaches significantly on the c-channel (Figure 3). Furthermore, there is time-space conflict during the entire c-channel activity, however, once the c-channel is complete, there is no more interference problem for the installation of the remaining roof tiles. The Productivity Modifier Matrix stores how much each activity will be affected from various fractions of time-space conflicts. The Productivity Modifier Matrix also incorporates how sensitive an activity is to time-space conflict. This information allows the 4D Work Planner prototype to propose adjusted productivity rates based on time-space conflicts present in a particular 4D model.

The Productivity Modifier and Cost Calculator utilizes time, space and crew information to generate cost estimates that incorporate time-space conflicts. The crew information comes from a crew database consisting of base productivity rates, daily crew costs, overtime crew costs and the crew type. The final output is a revised schedule that incorporates modified durations of activities resulting from decreased productivity when there is time-space conflict, and a cost estimate for each activity reflecting the reduced productivity rates due to time-space conflicts.

For the Haas case, after the 4D simulation of the original schedule, the user is prompted to resequence the construction process, since there is a physical interference between the installation of the windows and the c-channel requiring a scaffold (Figure 5). Once, the user resequences and resubmits the new schedule, the 4D Simulator generates another 4D simulation and identifies the time-space conflicts that might occur in the revised schedule (Figure 6 shows the results of the second simulation run for the Haas case). The system has identified a congestion in the workspace during the installation of the c-channel and the roof tiles. The user now submits the schedule for productivity and cost analysis. Accordingly, the Productivity Modifier and Cost Calculator proposes modified productivity rates for the c-channel and roof tile installation, and shows the resulting cost and duration.

Figure 6: **Second-Run Simulation of the Haas case**
Resultant Cost & Schedule



Conclusion

Identification of time-space conflicts during the construction planning stage is essential for the development of workable and cost-effective schedules and accurate cost estimates. By reasoning about the construction schedule and the design of a facility, the 4D Work Planner is able to identify time-space conflicts between activities. It provides graphical feedback by highlighting time-space conflicts while simulating the construction process. It distinguishes between the conflicts that prevent the execution of certain activities and conflicts that reduce crew productivity. Hence, users will know whether the schedule they developed is likely to be workable. Workable schedules can further be evaluated quantitatively through cost estimates incorporating the productivity impacts of time-space conflicts. As a result, the 4D Work Planner provides graphic and quantitative feedback about a given 3D model and schedule, helping users to develop workable schedules and accurate cost estimates.

We plan to generalize the 4D WorkPlanner to incorporate components other than c-channel, windows, and the roof tiles. We will formalize the 3D workspace requirements of activities. This formalization will be used to model workspaces and to support 4D interference detection for a given 4D model.

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