CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Feasibility Study of 4D CAD in Commercial Construction

By

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SUMMARY
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1. Abstract:

The primary objective of this thesis is to determine the benefits and limitations of 4D CAD by conducting a feasibility study of the project planning tool. 4D CAD links three dimensional graphic images to the fourth dimension of time (*3D CAD + time*). The resulting *4D simulation* or *4D model*, visually demonstrates building components being built according to the sequence of the original building construction. As 4D models communicate the schedule as objects within the graphical model, the temporal and physical aspects of the project are inextricably linked. This increases the possibility of detecting unanticipated problems beforehand by viewing the 4D model. The 4D model also allows multiple project participants to communicate and interact through a single medium while developing the 4D model, and can be used to conduct additional planning related analyses.

These benefits are demonstrated in a case study implemented by adapting 4D CAD for a commercial construction project. A 4D model is developed for an office building by linking 3D CAD components to an as-planned CPM schedule using commercially available 4D tools. By documenting the procedural difficulties involved in generating and analyzing the 4D model, the shortcomings of current 4D models and 4D tools are also established.

Future improvements of current 4D models and 4D tools include expedition of the development process, manipulation of the 4D model, and the enhancement of its functional features to detect problems and convey the information to users. Current research which have addressed these issues are introduced and additional solutions based on the experience gained from the case study are also suggested.

2. Subject:

- What is the report about in laymen's terms? 4D CAD is a planning tool that users can use as an alternative to conventional CPM networks or bar chart schedules. We compare the two mediums and document the advantage, limitations and required future improvements of 4D CAD.

• What are the key ideas or concepts investigated? Development and analysis of 4D CAD and its usefulness and shortcomings as a scheduling tool

• What is the essential message? Although 4D CAD conveys more planning information to users, there are still major improvements that need to be made to current 4D models and 4D tools.

3. Objectives/Benefits:

• Why did CIFE fund this research? To document the procedural difficulties involved in generating a 4D model, to determine the benefits 4D CAD has over traditional scheduling tools, to disclose on-going research being conducted as CIFE, and to promote and suggest new issues of development.

• What benefits does the research have to CIFE members? The report shows the effort and time required to generate the 4D model and also what kinds of planning information the 4D model can and cannot convey to its users.

• What is the motivation for pursuing the research? To accelerate the acceptance of 4D CAD in the AEC industry, by enhancing its benefits and minimizing its limitations.

• What did the research attempt to prove/disprove or explore? We explore the use of 4D CAD and prove its usefulness as a project planning tool.

4. Methodology:

• How was the research conducted? Four MS students at the CEM program generated a 4D model by using as-planned CPM schedules provided by the project managers of the McWhinney project and generating 3D CAD models from original 2D drawings of the building.

• Did the investigation involve case studies, computer models, or some other method? The investigation involved the generation of a 4D model to detect problems previously overlooked in the original CPM schedule.

5. Results:

• What are the major findings of the investigation?

4D model development stage: It is crucial to have a complete schedule and to establish the level of detail to be used prior to 3D CAD model development for the 4D model to be used according to its original purpose.

Current limitations of 4D CAD: Current 4D models and 4D tools are not flexible and their applicability limited.

Future required improvements: Future improvements include facilitating 4D model generation, its manipulation and relaying detected problems to users through knowledge based systems.

• What outputs were generated (software, other reports, video, other)?

4D model of FDC office building, this report.

6. **Research Status:**

- What is the status of the research? Completed.
- What is the logical next step? Conduct further research pertaining to the limitations described in the report.
- Are the results ready to be applied or do they need further development? Both.
- What additional efforts are required before this research could be applied? A more detailed 4D model, improvements of current 4D tools.

Abstract

The Architecture, Engineering and Construction industry is under constant pressure to increase the quality and speed of its production delivery processes. This is due to the mutual competition amongst the industry's constituents and the growing demands of clients who expect faster delivery and higher quality. This has encouraged the AEC community to explore alternative ways in conducting project execution, which can provide a competitive edge over their contemporaries and satisfy the requirements of their customers.

Research members at the Center for Integrated Facility Engineering (CIFE) at Stanford University have responded to these challenges by investigating ways of using Information Technology (IT) innovations that can improve and automate production processes. One such development is 4D CAD, which can be used as an alternative to CPM networks or bar chart schedules for project planning and control.

The primary objective of this thesis is to determine the benefits and limitations of 4D CAD by conducting a feasibility study of the project planning tool. 4D CAD links three dimensional graphic images to the fourth dimension of time (*3D CAD + time*). The resulting *4D simulation* or *4D model*, visually demonstrates building components being built according to the sequence of the original building construction. As 4D models communicate the schedule as objects within the graphical model, the temporal and physical aspects of the project are inextricably linked. This increases the possibility of detecting unanticipated problems beforehand by viewing the 4D model. The 4D model also allows multiple project participants to communicate and interact through a single medium while developing the 4D model, and can be used to conduct additional planning related analyses.

These benefits are demonstrated in a case study implemented by adapting 4D CAD for a commercial construction project. A 4D model is developed for an office building by linking 3D CAD components to an as-planned CPM schedule using commercially available 4D tools. By documenting the procedural difficulties involved in generating and analyzing the 4D model, the shortcomings of current 4D models and 4D tools are also established.

Future improvements of current 4D models and 4D tools include expedition of the development process, manipulation of the 4D model, and the enhancement of its functional features to detect problems and convey the information to users. Current research which have addressed these issues are introduced and additional solutions based on the experience gained from the case study are also suggested.

To proliferate the use of 4D CAD as a project planning tool, both the research and business sector of the AEC community industry must make a concerted effort. Advocates of the 4D CAD model must inform the industry of the benefits that can be gained from its usage as a project planning tool. The AEC industry, in turn, must be willing to explore this new technology and encourage its constituents in using it.

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Chapter 1. About this Thesis

This thesis investigates the usefulness of 4D CAD as an alternative project planning tool to traditional scheduling tools. The thesis reports on the advantages 4D models have over traditional CPM/bar chart schedules, and discusses the limitations of current 4D models and the commercially available 4D tools used in generating the 4D model. I also provide and overview of current research related to this new technology and suggest future research required to overcome current limitations of 4D models.

1.1 Introduction

Commercially available project management software used in designing and planning the construction sequence can only partially convey the conceptual planning of the modern construction manager. Although the sequences of the activities can be represented logically by CPM networks and bar charts, the absence of visualization makes collaborative communication amongst the designers involved difficult. Most construction managers, through years of experience in the field, can visualize the process in their heads. Hence extensive experience and repetition in the field becomes an integral part of a construction manager's career. However, conveying the experience and conceptualization of such information to a less experienced counterpart or discussing the design amongst several planners is difficult and mistake prone. It is also arduous to relate the information through these conventional applications and form a consensus amongst the designers as to the optimum method of construction.

As a result, potential problems pertaining to a project are not easily discovered in the planning stages and therefore changes in the schedule during construction are commonplace in the field. Problems that cannot be discovered through the use of conventional project management software are left unresolved to be determined only by the experience of the construction manager.

Recent advances in the integration of commercial software have made it possible to associate schedules with visual representations of the constructed components. The Architecture, Engineering and Construction (AEC) community have recognized the importance of such possibilities and have committed their efforts in enabling schedules to be visualized through the desktop environment. One such research is the design of a 4D CAD Model initiated at the Center for Integrated Facility Engineering (CIFE) laboratory at Stanford University.

A 4D CAD model results from the linking of 3D graphic images to the fourth dimension of time. This linking process yields a 4D model, which represents the product model and graphically incorporates the information traditionally represented in the construction schedule. By communicating the schedule as objects within the graphical model, the temporal and physical aspects of the project are inextricably linked, as they are during the actual construction process (Fischer, 1995). Such a model allows the engineers involved in the planning of the construction process (i.e., *process designers*) to visualize the construction sequence as it would actually be built. It also creates a single medium for integration - all of the parties involved can now collaborate in the design using the same 3D model without misinterpretation or repetitive conceptualization. The 4D model provides an environment for easier interaction and communication amongst the process designers and therefore is conducive to the detection of potential problems that may otherwise be overlooked when using traditional planning software.

1.2 Research Objectives and Analysis Approach

The principal objective of this paper is to determine how the 4D model can aid the process designer in planning the project sequence and therefore legitimize its usefulness as a project planning tool. To do so, I need to establish the advantages 4D models and 4D tools have over conventional CPM schedules and traditional scheduling tools. On the other hand, I also need to verify the limitations of current 4D models and 4D tools, which can provide insight to aspects of the 4D model that require future improvement, and therefore stimulate future research into the identified areas. Three steps are conducted to achieve this analysis.

First, schedules generated from project management software widely used by the AEC industry is compared to the 4D model. The comparison is conducted with respect to each planning tools' ability to visually convey planning information (*visualization tool*), their respective ability to enhance collaboration amongst project participants (*integration tool*) and the ability to support users in conducting additional analyses (*analysis tool*). Through comparative analysis in regard to these perspectives, the advantages the 4D model possesses over conventional CPM networks and bar chart schedules are established.

Second, a case study is conducted in an attempt to reinforce the advantages previously established and to discover limitations of current 4D models and 4D tools. McWhinney Enterprises Inc., contracted with the Neenan construction company to build three two-story office buildings in Loveland, Colorado. Using commercially available 4D tools, a team of graduate students at the Construction Engineering and Management (CEM) Program at Stanford University built a 4D model to simulate the construction of the first of three identical buildings. In the thesis, I describe in detail the procedures involved in building the 4D model (*development of the 4D model*), summarize the problems that were detected from 4D model analysis (*analysis of the 4D model*), and categorize the benefits and limitations of the 4D model (*limitations of current 4D models and 4D tools*). Based on the documented limitations of current 4D models and 4D tools, I suggest future developments that need to be made to facilitate the generation of the 4D model and functional improvements of 4D tools required in conducting 4D model analysis.

Third, current research topics being conducted by the CIFE community are introduced to inform readers of the proposed solutions to some of the limitations previously discovered in the case study. I also suggest future research objectives based on the experiences gained from developing and analyzing the 4D model.

1.3 Comparison of CPM/bar chart schedules to 4D CAD

CPM networks and bar chart schedules generated from project management software are a graphic and abstract representation of the construction sequence. In contrast to the multiple factors construction planners must consider to generate a CPM schedule, the original assumptions behind the shared data cannot be communicated through these schedules. Therefore, viewers of CPM schedules need to conceptualize the construction sequence in their minds by associating the components in the 2D drawings together with the activities in the schedule. 4D models integrate the logical, temporal and spatial aspects of construction planning information (*Fig 1.1*), thereby reducing the need for individual conceptualizations of the construction schedule. With the 4D model, users can detect potential problems, such as contradictions in the logic of the schedule or constructibility issues. 4D models can also help in detecting the affected activities of a schedule due to a change in the schedule sequence and also facilitate the communication of such changes to project participants.

Traditional scheduling tools are predominantly used by construction planners or contractors as a managerial tool. However, the 4D model's applicability can be extended to an integration tool and also an analysis tool. Designers and builders can use the 4D model to formalize the design and construction information, which can improve communication and collaboration between the two entities. Using 4D models, users can also conduct further analyses concerning cost, productivity and safety issues, or allocation of resources at the jobsite.

Both the CPM schedule and the 4D model reflect the conceptual planning information sequenced in the minds of process designers. However, the 4D model allows further evaluation and analysis of this sequence through the integration of the temporal and spatial aspects of planning information, which allows users to develop a more realistic and feasible construction schedule.

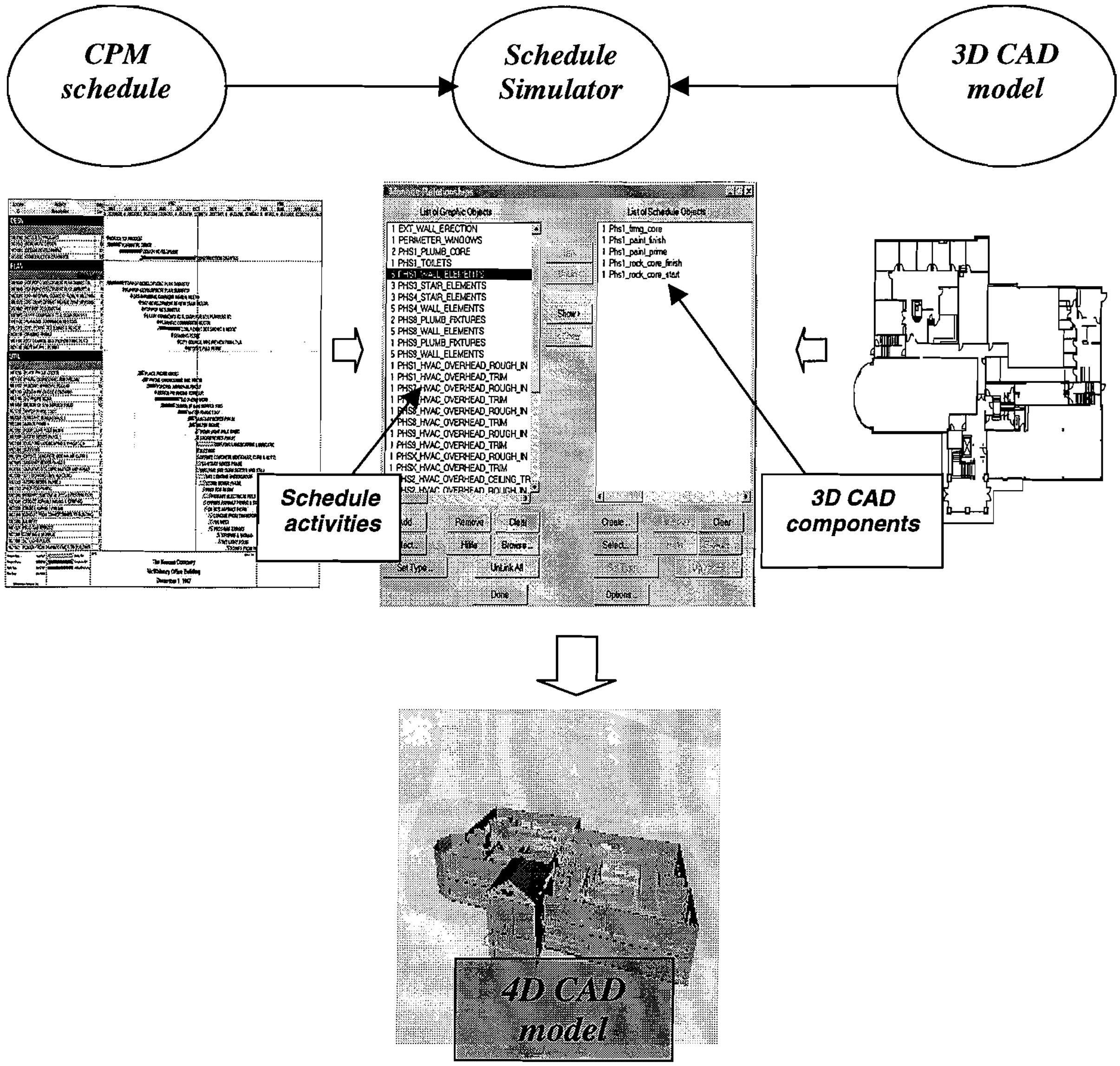

Fig 1.1 Overall system architecture of 4D CAD model development

1.4 Case Study

By developing the 4D model for the McWhinney project, our project team was able to detect problems in the sequence of the schedule that were not anticipated by the project managers, and also identify limitations of current 4D models and the 4D tools used to generate them.

During the initial evaluation of the original CPM schedule, we discovered that individual members of our project team had different interpretations of the schedule sequence. This made it difficult to detect any potential problems by viewing the CPM schedule. When we viewed the 4D model, we were able to better comprehend the schedule sequence which allowed us to detect previously unforeseen problems. Our team identified problems such as the inconsistency in the level of detail amongst schedule activities, omission of certain activities to represent components of the building, and contradictions in the logic of the schedule. We also detected potential problems due to time-space conflicts and accessibility issues that were not considered while developing the original schedule. Some of these problems had actually taken place and had delayed the project schedule when constructing the building. This confirmed our initial assumption that the 4D model allows the detection of potential conflicts that otherwise might be overlooked when using conventional scheduling tools and CPM schedules.

However, we also discovered present limitations in the development and analysis stages of the 4D model. Developing the 4D model involved categorizing the activities of the original schedule, creating 3D CAD models from 2D drawings, and creating relationships between the schedule activities with the 3D CAD model components in a 4D-simulation application. Such a process demanded a lot of labor-intensive work hours amongst our team members.

Although the 4D model conveyed several problems in the original schedule, it was difficult to detect time-space conflicts or other constructibility issues by viewing the 4D model alone. Such problems required the manifestation of additional construction information which current 4D models did not convey. Another problem was that current 4D models only conveyed one perspective of the project and could only be viewed at a single level of detail. This made it difficult for multiple participants of a project to use the model for individual purposes and also augmented the ramifications initial decisions have on the flexibility of the final 4D model. Current 4D tools do not support the rapid generation of alternative scenarios. Such limitations restricted our ability to view and investigate multiple options to resolve the detected problems.

Functional improvements are needed to convey more detailed construction information and allow rapid generation of alternative scenarios, and methods to create multi-leveled 4D models are required.

1.5 Current and Future Research

However valuable the information may be, 4D models cannot be used widely in real construction projects if they are not economically feasible. The 4D model's purpose is the same as for any other Information Technology (IT) innovations being explored and implemented in the AEC industry. By automating and improving planning processes and eliminating human errors or misinterpretations, it must be able to save time, resources and ultimately the cost of the entire project.

Developing the 4D model requires users to invest significant time and effort, which means that additional up-front costs will be incurred. For the 4D model to be used as a planning tool that is economically viable for construction projects, improvements to the 4D model and current 4D tools must be made to accelerate the development process and enhance their ability in detecting and conveying potential problems.

Efficient schedule data preparation and acceleration of 3D CAD model generation are the two major aspects that require the most improvement to expedite the development of the 4D model. Initial decisions concerning the purpose of the 4D model determines the level of detail of the 4D model. Therefore, methods must be developed to assist users in making the appropriate decisions and automating schedule data preparation. To expedite 3D CAD model generation, better CAD tools need to be developed which can automate the repetitive steps involved in creating 3D CAD models.

During 4D model analysis, users must be able to create and view alternative scenarios of the construction sequence, and also allow individual participants of the project to view 4D models at multiple levels of detail.

To allow easier and faster generation of alternative scenarios, a research prototype CIFE 4D CAD (McKinney et al., 1996) has been developed by the CIFE community which allows the schedule and CAD data to be manipulated in a single environment. The

Construction Method Modeler (Fischer et al., 1996), can generate schedules at different levels of detail and subsequently generate multi-leveled 4D production models.

To promote additional analyses using 4D models, a knowledge-based system using semantic 4D models must be developed to infer potential problems and relay the information to users. The 4D Work Planner (Akinci et al., 1997) is one example of applications developed by the CIFE community to apply the 4D model for additional construction analyses. The application quantifies impact of time-space conflicts and reflects information in the original schedule and cost estimate.

Also new interfaces such as the *Responsive Workbench* (Krueger, 1993) and *Information Mural* (Winograd and Hanrahan, 1997) can provide multiple participants to concurrently view and manipulate the 4D model.

The realization of these improvements will not only allow users to visualize the construction sequence, but also allow them to create, evaluate, and analyze schedules while considering multiple planning information through a single application.

1.6 Reader's Guide

In the following chapters the issues and solutions described in the preceding sections are further discussed. Chapter 2 introduces the theoretical advantages of 4D models over conventional CPM/ bar chart schedules. Chapter 3 describes the experiences and lessons learned by the research team through building the 4D model for the McWhinney project. Chapter 4 describes the current and future research required to improve the functionality and applicability of current 4D models and 4D tools. Finally, Chapter 5 summarizes the thesis and also discusses changes needed in the AEC industry to expedite the acceptance of the 4D model as a project planning tool.

Chapter 2. Comparing 4D CAD with Traditional Scheduling Tools

2.1 Introduction

This chapter identifies the shortcomings of schedules generated from conventionally used project management software and introduces the 4D model as an alternative method to conveying construction sequence information. A comparative analysis between schedules generated from project management software and the 4D model is conducted with respect to the level of quantitative and qualitative information shown, and to the level of applicability as an integration and analysis tool. The objective is to validate the application of a 4D model as a planning tool in the construction industry as a preferred alternative to schedules generated from currently used project management software.

2.2 Schedules generated from Project Management Software

Construction planners rely on schedules generated from project management software to formalize and organize work activities. Schedules (such as bar charts and CPM networks) generated from commercially available management software are an abstract, graphic representation of the logical sequence of how a building or structure is to be built.

Generating the schedule

Scheduling involves reasoning about a building project that is initially represented only by architectural and engineering drawings. The reasoning process must integrate knowledge and data about construction practice, cost and productivity with the specifics of the design (Cherneff, 1991). When generating a schedule, construction planners must take into consideration an abundant amount of information relevant to the project. In addition to interpreting 2D drawings and specifications, they must also deal with constructibility issues, optimum productivity evaluation, resource and equipment allocation, time-space conflicts at the site, time-cost trade-offs, and many other factors specific to the project. Only after careful consideration to all details can a reliable and efficient schedule be generated. Even then it is difficult to completely detect all the conflicts that remain hidden inside the relatively disconnected plan views, sections and elevations, of the contract and shop drawings.

Interpreting the schedule

In contrast to the extensive amount of information that was input in developing the schedule, the final schedule does not convey the thought processes or logic that went into generating it (i.e., the assumptions behind the schedule sequences are not made explicit). Without prior knowledge and background of the logic in generating the schedule, it is difficult to understand the sequence of the schedule by itself. The lack of information of such schedules poses problems for the participants of the project not involved in the design of the schedule, but who need to interpret and implement the schedule. Subcontractors and vendors rely on the schedule to implement and coordinate their work with other participants of the project. Many find themselves having to relate the schedule activities with the 2D drawings to make any sense of the logic. Incomplete comprehension of the logic of the schedule limits their ability to detect conflicts hidden in the schedule. In consequence, potential problems are only detected during actual construction in the field resulting in costly rework and revisions, which could have been minimized if they had been detected in the earlier planning stages.

2.3 Comparison of 4D CAD to Traditional Project Scheduling Tools

This section addresses the limitations of schedules generated from current project management software and also how the 4D model can help in mitigating those limitations. The analysis is conducted with respect to its applicability and usefulness as a visualization tool, an integration tool and as an analysis tool.

2.3.1 Using the 4D model as a Visualization tool

i) Visualizing and interpreting the construction sequence

Although bar charts and CPM networks are the most prevalent method in conveying sequences of activities in the construction industry, there are several alternative scheduling methods still being used in different sectors of the industry. The variety of scheduling methods seems to indicate that some schedules are better at conveying the sequence than others for particular projects. For example, the Time Space Scheduling Method, or Vertical Production Method (VPM), is often used for scheduling projects which consist of repetitive activities and for scheduling the work in sections (Stradal et al.1982). The reason for the specific use of a scheduling method for certain projects is simple - it conveys the information more clearly for the participants involved (i.e. owner, architect, engineer, general contractor, subcontractors, vendors, etc.) Put in another way, a particular scheduling method makes it relatively easier to "visualize" or "conceptualize" in their minds the sequence of activities.

Regardless of the nature of the project, however, most project management software widely used in the AEC industry (Primavera P3, Microsoft Project, etc.) generate CPM based bar charts which do not support the visualization process. Such schedules force users to visualize and interpret the activity sequence in their minds. Therefore, multiple participants of a project must individually conceptualize the sequence by associating the schedule activities to the components of the 2D drawings. The interpretation of the schedule can vary according to the level of experience, knowledge and individual perspective of the participants. An experienced contractor may interpret the schedule differently compared to the interpretation a counterpart with less experience may make. The problem is compounded by the fact that the schedule does not convey the thought processes that went into developing it. Inconsistency in the interpretation of the schedule has the potential for creating miscommunication amongst the participants.

The 4D model shows 3D CAD models of project components being constructed step by step with the progression of time. As the 4D model visually simulates the actual project being built, there is no need to select a particular scheduling method that will best represent the construction sequence. Nor is there a further need to use the 2D drawings and the schedule to conceptualize the sequence of activities. The 4D model obviates much of this interpretation process and allows users to view the two separate documents through a single medium.

Visualization through the 4D model enables the parties involved to mitigate misinterpretation of the schedule and subsequently minimize miscommunication. As all the participants are now working on and communicating with the same model, the disparity in their experience or knowledge of the project is less relevant, as it is less likely to lead to varying interpretations. By viewing the identical 4D model, they are able to better understand the logic behind the sequences. Obviously, better perception of the schedule can greatly improve in detecting potential problems. The 4D model allows users to detect contradictions in the logic of the original schedule that may otherwise have been previously overlooked.
For example, in Fig 2.1, a schedule for a building shows a portion of the HVAC duct for the second floor to be built *before* both the second floor frame and truss, and the roof of the building (A). This is a mistake in the logic of the schedule as there is no support on which to hang the HVAC ducts and no platform for the HVAC subcontractors to work on. The general contractor or subcontractor reviewing the schedule may not be able to detect this mistake amongst the hundreds of other activities in the master schedule. However, this problem can be easily detected in the 4D model as the HVAC ducts are shown hanging in the air (B). The 4D model allows users to evaluate the schedule by detecting such problems and making improvements as required (C).

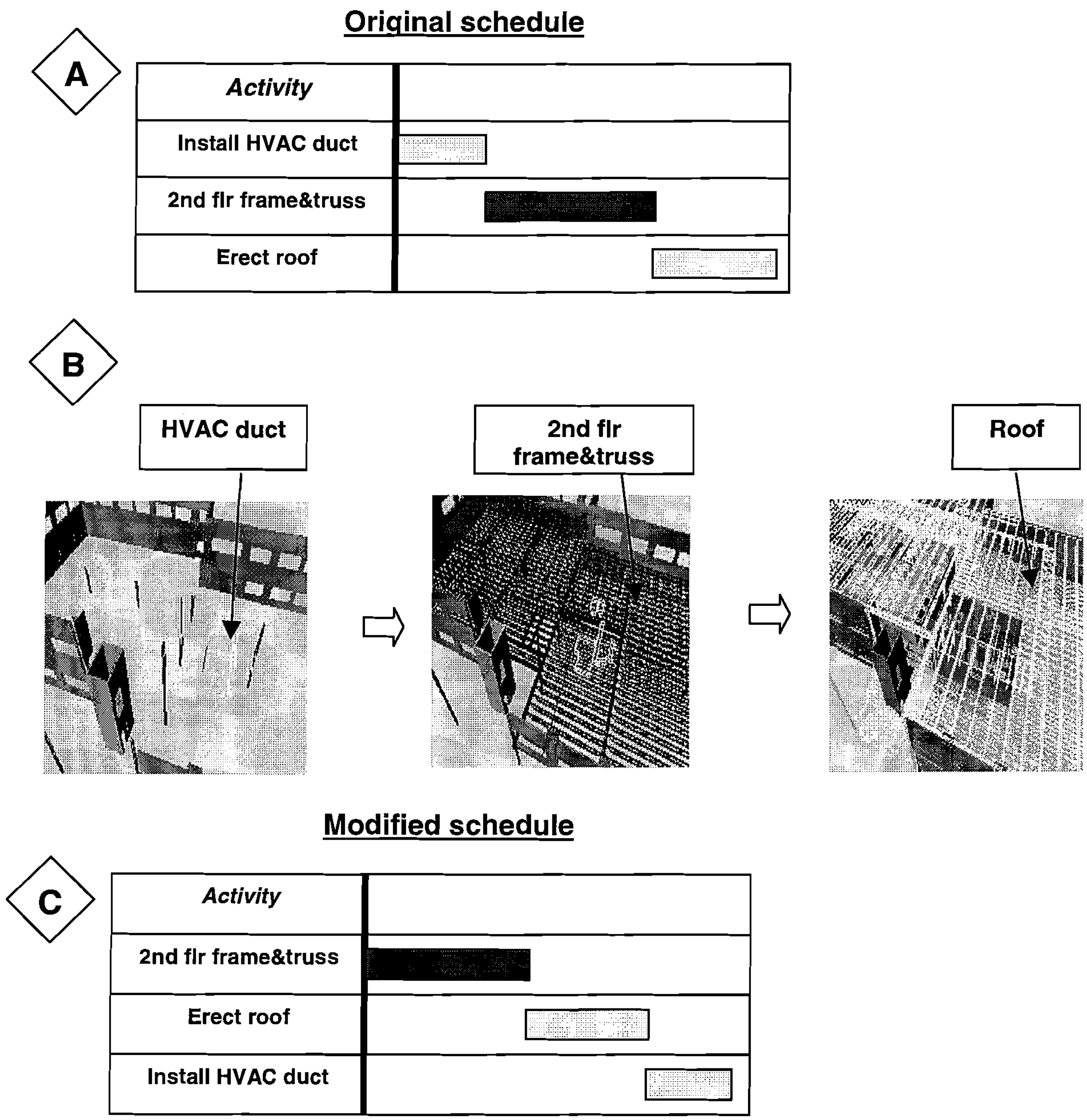

Fig 2.1 4D model showing HVAC ducts being installed prior to 2nd floor frame & truss and roof

Users can also detect such problems while developing the 4D model. When building the 4D model, users must resolve issues not resolved or undetected in the schedule. *If you can't build it in the 4D model, you definitely cannot build it in the field.* The 4D model is the best way of simulating the construction process before actually building the project in the field. The 4D model allows users to walk through the construction process and provides the basis for detecting potential problems previously overlooked in the CPM schedule.

ii) Anticipating time-space conflicts during construction

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. In addition to visually conveying the logic (temporal dependencies) amongst activities of a schedule, the 4D model also shows spatial constraints that exist both on the site and the building. This is an important characteristic of the 4D model because it allows the construction planner to detect time-space conflicts. Time-space conflicts occur when work crews of different specialties working on concurrent activities have to share a common workspace and therefore interfere with each other. This can cause decrease in their productivity as well as preventing the execution of one or more affected activities (Akinci, 1997).

Schedules generated from project management software do not show time-space conflicts between concurrent activities. Although 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 common workspace are not represented and cannot be detected (Akinci, Staub and Fischer, 1997). This is achieved only through the conceptualization of the schedule by construction managers, who rely on their experience to anticipate time-space conflicts and incorporate them into the schedule. Even then, CPM schedules can represent time-space conflicts only as logical relationships, and not communicate the specific nature of, or reason for such relationships to the viewer of the schedule. If time-space conflicts are not identified during planning, often an optimistic schedule will be developed which is not workable in reality. If these conflicts are left to be resolved during the construction stages, the project managers may be faced with time and cost overruns at the end of a project due to unrealistic cost estimates.

For example, in a schedule of a building four activities have been scheduled to be built concurrently in the same location (*Fig 2.2*). The general contractor may see nothing wrong with this sequence, as there is no contradiction in the logic of the schedule. However, the 4D model shows four subcontractors working adjacent to one another in a tight space which can result in decreasing the productivity of the workers. This clearly shows the potential for time-space conflicts and proves that the original schedule can be too optimistic.

Activity	
Wall framing	
Electrical fixtures	
Plumbing fixtures	
HVAC ducts	

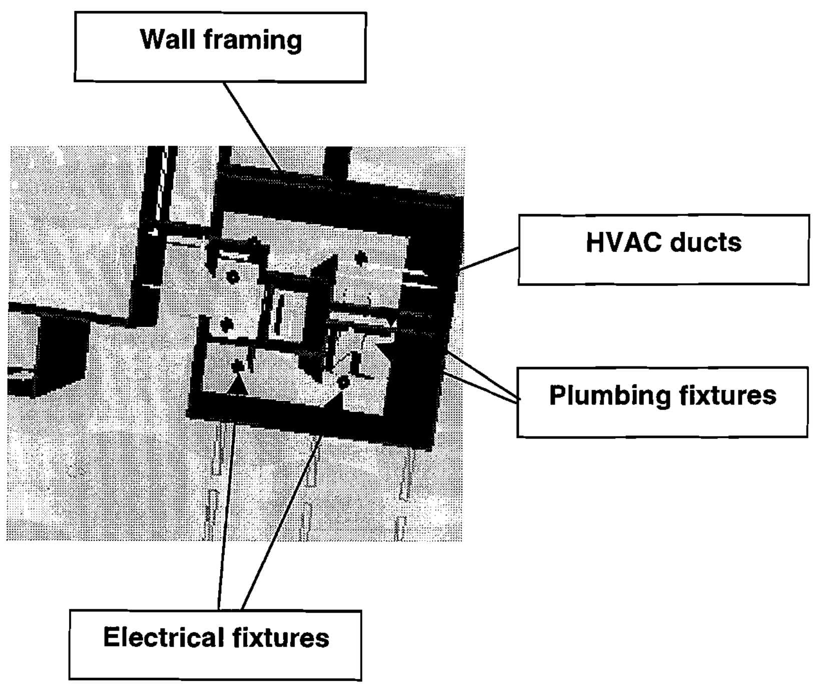

Fig 2.2 4D model showing concurrent activities being installed within a restricted workspace

To identify the time-space conflicts between activities, construction planners need spatial, temporal and logical information about an activity. The spatial information includes the location of an activity and the space it occupies, the temporal information includes activity start and finish time, activity duration, and the logic information includes the preceding and succeeding activities. The construction planner must identify whether concurrent or overlapping activities are being executed in a constrained workspace which can prove to be detrimental to the workers' productivity.

The 4D model allows users to view the temporal, spatial and logical information through a single medium on the screen. While in the CPM schedule, the construction planner can only speculate whether there will be a time-space conflict, the 4D model clearly manifests problems relating to space restrictions.

iii) Conveying the impact of change in the schedule

Changes in the schedule are inevitable in construction. Once a change has been decided, it must be incorporated into the schedule. Schedules are periodically updated to reflect the changes. The operation of current scheduling tools requires complex and time-consuming data entry and the results are frequently not used (Davis, 1974). Furthermore, constant changes in the schedule require continuous updates by management-level personnel whose time is at a premium (Levitt and Kunz, 1986). Because of the sequential nature of construction, a delay due to a change in one activity may cause additional delays to other activities affected as well.

a) Determining which activities are affected by the change

An updated CPM schedule can convey the ripple effect a single activity change has upon other related activities. However, it can be difficult to determine which activities may be affected by the change of a single activity, as these activities can be scattered indiscriminately across the entire schedule. A change in a single activity not only affects the subcontractor responsible for that activity, but also other subcontractors, suppliers and vendors who are dependent on his or her completion. For example, if a partition of a building needs to be relocated, other partitions adjacent to that partition need to be adjusted accordingly (*Fig 2.3*). Apart from the obvious activities that are affected, there may be other activities that cannot be easily assessed when viewing the CPM schedule. For example, the relocation of the partition may also affect the Mechanical, Electrical and Plumbing (MEP) subcontractors installing their equipment adjacent to that partition and subsequently the vendors who are supplying the material to the individual subcontractors (*Fig 2.3*).

To determine all the activities that will be affected through the CPM schedule, the construction planner must refer back to the 2D drawings and the original schedule to conceptualize the change in his/her mind. By viewing the 4D model, the construction planner can immediately determine which activities will be affected by viewing the components that need to be modified. In the 4D model, the relocation of the partition can be shown graphically which will immediately show that other partitions (which are now disjointed from the relocated partition) need to be relocated and also show the impact this change has on the MEP subcontractors and their vendors.

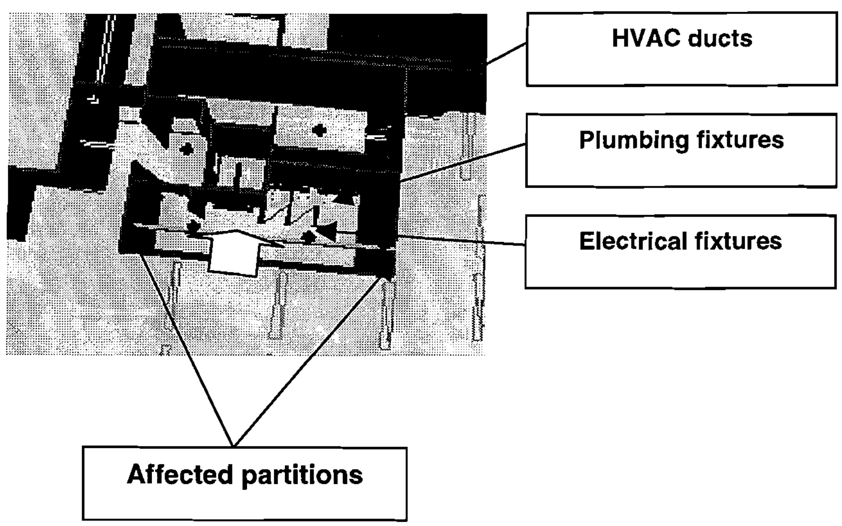

Fig 2.3 4D model conveying the affected components due to relocation of partition

b) Relating the change to project participants

Another problem is relating the changes that have occurred through the modified CPM schedule to a third party. Many clients may not be able to relate all the affected activities by viewing a CPM schedule. They may have difficulty in visualizing the construction sequence and in figuring out why certain activities are affected. Most subcontractors do not work with complete schedules, but partial schedules that only have activities related to the specialty components they need to install. When a change is made, the general contractor may just provide a partial schedule with activities that only concern that subcontractor. This leaves the subcontractor to figure out the reason for the changes by himself without the aid of a complete schedule.

In the CPM schedule, the effect a change has on other activities can only be represented by different durations or different start and finish dates, and hence it is difficult to realize the reasons for the cumulative delays. The 4D model graphically shows which components are affected and allows users to induce and better comprehend the reasons for additional delays to the project. It also allows users to understand the impact of the delay on the final or partial completion of the project. For example, a client unfamiliar with construction might find it difficult to understand why one day of delay might ripple into several days of delay. Animation of the schedule gives the client a better idea of the sequential nature of construction activities. This can make them more aware that postponing the first activity delays the second, and so on.

2.3.2 Using the 4D model as an Integration tool

One of the biggest encumbrances hampering the collaboration amongst the design and construction constituents of the AEC industry is the traditional building process and the medium through which information is exchanged. The building sector of the construction industry relies heavily on subcontracting work to specialty contractors. Therefore clarity in communication amongst the multiple participants involved is critical for the success of the project. In contrast to this proposition, however, the typical facility delivery process is characterized by its sequential processes. Designers produce a design that is input for construction managers, who produce schedules that are then used during construction. Such a process results in a fragmented and linear facility delivery process with minimum feedback amongst the design and construction entities. This is a classic construction problem where early design decisions have a large impact on cost of construction, but these decisions have to be made in a phase in which it is still unknown how and by whom the building will be constructed (Ahuja and Walsh 1983, Ferry and Brandon 1992).

With the objective of saving the total cost of delivering a facility in mind, the project team must focus on the stages of construction in which costs can be most effectively minimized. Costs in the design stage are relatively fixed in comparison to the unpredictable nature of costs incurred during the construction stage. A design which has incorporated constructibility issues in its design decisions can greatly save costs during construction by minimizing changes and rework.

As stated by Howard et. al, the problem of construction scheduling cannot be solved in isolation; rather it is symptomatic of the larger problem of industry fragmentation. Productivity in construction can improve only if communication and coordination within the architecture-engineering-construction (AEC) community improves (Cherneff, 1991).

Recent research has focused on the application of Information Technology (IT) as a way to facilitate the integration process of all parties involved in the planning process. Visualization was recognized as one of the most important tools for achieving this goal (Construct IT, 1997). The demand for better integration of design and construction, also called Design for Construction (DfC), is growing (Luiten and Fischer 1995). Clients demand faster delivery and higher quality and only those who can meet such demands will survive in the highly competitive market. To comply with these demands the existing segregation between design and construction must be decreased.
Integration of design and construction can be achieved by formalizing and standardizing the information, and promoting interaction amongst project participants. The 4D model can be used as an integration tool that can aid in enhancing both of these factors.

i) formalizing design and construction information

There is a lack of standardization and inconsistency in the information used by the designer and the builder. Different professionals interpret 2D-drawings differently and therefore do not necessarily discover inconsistencies. To make matters worse, designers and builders often use different sets of drawings (i.e., design drawings vs. shop drawings). Whereas design drawings are structurally oriented, shop drawings are more planning oriented. Although effective planning of the construction sequence is critical for the project to save costs, designers do not always notice how their design will affect the building sequence. They are also not as familiar with CPM schedules as their construction counterparts and can find it difficult to comprehend the logic of the schedule sequences.

4D models can be used as a tool to escape from the limitations of the 2D drawing and paper document paradigm deeply embedded in the AEC industry, by integrating the design and construction information in a single medium. The designer and builder can and must both work with the same models when viewing the 4D model, which eliminates the use of separate drawings. Because the geometric and planning information is conveyed through a single medium, both entities can benefit from viewing the other's perspective. As 4D models accurately depict the geometric configuration of the building, designers can point out the structurally significant aspects. On the other hand, as 4D models also convey the project sequence, builders can point out how they will be affected by the design. Builders can also convey schedule information without having to rely on CPM schedules, which may require extensive explanations and still not convince the designers.

ii) promoting interaction amongst project participants

Because many issues that are not always addressed during today's planning process must be addressed when building the 4D model, this naturally induces interaction between the designer, planner and builder. The 4D model has been noted as to be especially useful for providing feedback on building design from construction (Luiten and Fischer, 1995). If the 4D model is built in the early planning stages of the project, the construction planner can review alternative scenarios to decide upon the best construction method that is most cost effective and time saving. On the other hand, he can provide feedback to the design by performing feasibility studies and determine which design is most appropriate to the selected construction method. The 4D model can be useful in integrating product and process information and is a stepping stone for concurrent engineering.

By building the 4D model users can evaluate the schedule, but also detect design restrictions that force the schedule to be sequenced in a certain way. Construction planners can alert designers of the problems by showing the 4D model and the problems they will face because of the design. In this respect, the 4D model can definitely be used as a collaboration tool to increase communication between the design and construction entities.

2.3.3 Using the 4D model as an Analysis tool

The ability to evaluate the original schedule holds immense promise for the 4D model. Its applicability is extended from a visual reflection of the schedule to one of an evaluation tool or constructibility critic of the schedule. Because the 4D model integrates the spatial and temporal aspects of construction information, this provides construction planners with the freedom of executing additional analysis without having to mentally associate separate 2D drawings and the schedule.

However, generating the 4D model involves significant work-hours (section 4.1.1) and also creates additional up-front costs to the project. For the 4D model to be a truly useful application, it must be able to convey to the construction planner issues that can save time and ultimately lower the total cost of construction. The 4D model can reduce costs to the project by detecting problems such as time-space conflicts, safety issues, and site workspace restrictions which results in the formulation of more realistic schedules and cost estimates. It also allows the construction planner to decide upon the most appropriate construction method by generating alternative construction scenarios.

i) Supporting Cost and productivity analysis

The detection of potential time-space conflicts in the construction schedule allows the construction planner to develop a realistic schedule. As described in section 2.3.1 and figure 2.2, the 4D model alerts the construction planner to potential time-space conflicts unforeseen in the original schedule. Initially the construction planner had scheduled the activities *wall framing*, *electrical fixtures*, *plumbing fixtures*, and *HVAC ducts* concurrently. However, evaluation of the schedule through the 4D model showed that this would cause congestion in the shared workspace, resulting in lower productivity rates for the work crews. Therefore the activities needed to be rescheduled so that they could be implemented sequentially. The user may first view this as prolonging the project duration. However, working sequentially will enable the individual work crews to work at a higher productivity rate. Also anticipation of such conflicts and prevention in the planning stages will minimize costly changes during actual construction. Changes in the productivity rate and schedule sequence in turn forces the construction planner to reevaluate the initial cost estimates.

ii) Anticipating safety hazard situations

Safety hazards at the construction site can be one of the main causes of unanticipated additional costs. Indeed, the slim profit margins with which contractors often work can quickly diminish with a single accident on site. Many construction companies stress safety to be the prime objective of a project. Safety is an issue where no amount of effort should be spared as it involves the possibility of loss of life, which can't be quantified in terms of cost.

Although many construction companies have safety prevention programs to protect both their workers and their safety records, it can be difficult for project managers to anticipate all the hazard areas existing on the site. This is because all construction projects are unique in nature and accidents occur mainly due to unforeseeable human errors or mishaps.

By viewing the 4D model, project managers can detect areas where accidents may occur and execute prevention measures (such as placing warning signs, restricting access, or providing safety nets, etc.). But more importantly, by viewing the time and location of the workers through the 4D model, project managers can perceive how separate crews may affect one another and therefore inadvertently create hazardous situations.

Once these problems have been manifested, project managers can incorporate these findings into the schedule by re-sequencing concurrent activities into subsequent activities, or adding more activities which represent the installation of safety equipment or prevention measures. These changes in the schedule will subsequently require reevaluation of the initial cost estimate.

iii) Allocating resource and equipment relative to site workspace

One of the restrictions project managers face when allocating resources and equipment is the availability of site workspace. Most site workspaces are occupied by trailers, large equipment, and building materials which can clog up the site and hamper maneuverability of the equipment and their related crews. Therefore using limited workspace economically and effectively can create a significant difference in project time and costs.

Management of site workspace becomes increasingly important when projects are located in urban areas. In some of these projects, project managers can only work on the actual area the building will occupy. In these situations, the project managers need to divide the site into sections so that while constructing the building for one section, other sections can be used for cranes, backfill or material storage.

Project managers must also manage material delivery time. If materials are brought in late, this will affect project schedule by delaying subsequent activities. However, if brought too early, it may cause congestion in the workspace. Therefore, materials must be delivered at the time when it can be immediately installed to minimize delays on other work, and to quickly relinquish the space it occupies.

The 4D model can be used to manage site workspace and schedule material delivery times. Project managers can view when and where workspace will be available or occupied, and appropriate the site area accordingly. In this sense, the 4D model can be used as *a spatial timetable*. Project managers can also use the 4D model to determine the best method of allocating the workspace, by generating alternative scenarios in the 4D model.

iv) Running constructibility reviews

Through visualization of the construction sequence the 4D model allows users to detect problems in the original schedule. It can also provide a basis for analyzing time-space conflicts, safety issues and site workspace management. When conducting constructibility reviews, project managers cannot isolate a specific issue but must consider all of these factors together. Because all of these issues are time-space dependent, they are also all interdependent. For example, a change in the schedule to resolve a time-space conflict may result in reducing the workspace available for other workers or equipment. The true value of the 4D model lies in the ability to consider all of these factors through a single medium. This is possible because the 4D model shows the logical, temporal and spatial information of the construction project.

Users can reinforce their analysis by generating and running multiple scenarios which can be used to determine the best possible approach in alleviating multiple problems. This allows project managers to actually build scenarios and visually examine them, instead of mentally conceptualizing them in their minds and wondering whether they will actually work or not.

2.4 Summary

Table 2.1 summarizes the advantages the 4D model holds over traditional CPM schedules as described in the preceding sections.

		CPM schedules	*4D CAD*
Visualization Tool	➢ *Visualizing and interpreting construction sequence*	• Forces users to visualize in their minds	• Obviates interpretation process
	➢ *Anticipating time-space conflicts*	• Difficult to detect with schedule alone	• Identifies potential conflicts
	➢ *Conveying the impact of changes*	• Difficult to detect with schedule alone	• Clearly shows impact
Integration Tool	➢ *Formalizing design and construction information*	• Based on fragmented, linear facility production process	• Promotes integration • Facilitates information sharing
	➢ *Promoting interaction amongst project participants*	• Does not promote interaction	• Promotes interaction
	▪ *Aiding in design decisions*	• Does not provide support	• Promotes feasible design
	▪ *Providing feedback on design*	• Provides limited feedback	• Encourages feedback
Analysis Tool	➢ *Supporting cost and productivity analysis*	• Does not provide support	• Allows easier to detection
	➢ *Anticipating Safety hazard situations*	• Does not provide support	• Allows easier to detection
	➢ *Allocating resource at site workspace*	• Does not provide support	• Allows easier to allocation
	➢ *Running constructibility reviews*	• Does not provide support	• Allows the generation of alternative scenarios

Table 2.1 Comparison between CPM schedules generated from project management software vs. 4D CAD

The 4D model is a reflection of the construction sequence represented in the original schedule. It allows the participants involved to clarify the logic of the schedule and thereby reach a unanimous consensus in the interpretation. However, whereas the applicability of CPM schedules is limited to that of a managerial tool, the 4D model's usefulness is evident not only as a visualization tool, but also as an analytical tool and an integration medium. It allows construction planners to evaluate the original schedule by detecting potential problems such as time-space conflicts previously undetectable in the CPM schedule. The ability to detect such conflicts allows users to use the 4D model for further analysis pertaining to accessibility, safety issues, site workspace restrictions, and cost and productivity issues. It also allows such factors to be evaluated concurrently through a single application and supports the generation of alternative scenarios to develop the best solution.

It is difficult to perceive all potential conflicts and problems in the planning stages. It is even more difficult to communicate such problems through CPM schedules or cost estimates. However, the use of 4D models allows the user to detect some of the problems and construct a more realistic schedule of the project. In this respect, the fundamental difference between CPM schedules and the 4D model can be surmised as follows. Whereas the former are a graphic and abstract representation of the construction sequence developed in the minds of the construction planners, the latter integrates the logical, temporal and spatial aspects of construction information which allows further evaluation and analysis of the original schedule.

The next chapter introduces a case study I conducted together with 3 other MS students in an attempt to reinforce the arguments made thus far by evaluating a CPM schedule through the 4D model. A two-story office building, which had been built based on a CPM schedule, was rebuilt in the 4D model. The chapter describes the procedural steps and difficulties users face whilst generating the 4D model. I will authenticate the usefulness of the 4D model by comparing the problems encountered during actual construction and the problems that were detected through the 4D model. Also the limitations of the 4D models are introduced to promote future research aimed at enhancing current technology.

Chapter 3. Case Study - The McWhinney Project

In this chapter, I describe the benefits and limitations of the 4D model based on the experience gained from building and analyzing the 4D model built for the McWhinney project, and by comparing the problems detected with the actual problems encountered by the project managers during construction.

3.1 Objective of Case Study

The objective of the case study is to determine whether the application of a 4D model can aid the construction process designer in detecting potential conflicts or problems in a schedule which otherwise could not be found from using traditional project management software.

Although a construction schedule can never be totally foolproof, certain considerations prior to construction can help in minimizing conflicts among subcontractors and reduce inefficiency. Such considerations may include constructibility issues, productivity evaluation, time-space conflicts at the site, time-cost trade-offs, and many other factors specific to the project.

The goal of the research students participating in this endeavor was twofold. By developing a 4D model, we hoped to familiarize ourselves of the processes involved in generating a 4D model. Next, we hoped to corroborate the benefits of a 4D model in helping the process designers to visualize the project sequence and consequently make the comprehension and deployment of such considerations easier in the schedule. In this respect, the 4D model can be most effectively used to evaluate the schedule and ultimately generate a more realistic schedule.

Although the benefit of the final 4D model is relatively apparent, building the 4D model can be a laborious and time-consuming process. Because an initial schedule must be made, it can also be construed as making two schedules for the same project. This provides the argument for experienced process designers to state that the 4D model is redundant work. Therefore we must determine whether the information conveyed from the final 4D model is beneficial enough to outweigh the efforts involved in making the 4D model. In consequence, a detailed description of the processes involved in generating a 4D model is presented here. The limitations and encumbrances faced during the procedure are introduced, accompanied by several methods that were used to resolve them.

Through such description I hope to create future discussions and research aimed at alleviating present limitations and enhancing the advantages the model presents.

3.1.1 Research team

Four MS students in the Construction Engineering & Management (CEM) department at Stanford University (myself, Winnie Hung, Steve Long and Bertrand Wiederhold) participated in generating, analyzing and evaluating the 4D model. All members of the group were new to the 4D model building process with the exception of some of the students who had prior experience in generating 3D CAD models.

Although most of the members had some level of field experience and knowledge of construction planning, none of the members had extensive experience in planning and scheduling a project in its entirety.

The participants were split into two groups to divide up the work involved in generating the 4D model. While the first group focused on breaking up the components in relation to the activities of the schedule, the latter group worked on converting the 2D drawings to 3D CAD models. Constant communication proved to be essential for the 3D CAD model to be built without redundant components or crucial components being left out. All the members participated in familiarizing with the techniques involved in using the 4D-simulation tool, which would link the schedule information to the 3D CAD model. Once the 3D CAD model and schedule was imported into the simulation application to generate the 4D model, all the members participated in evaluating the schedule and focusing on detecting potential problems in the project sequence.

3.2 Analysis Approach

We chose a project that had been constructed using a schedule generated from 2D drawings and traditional project management software as the basis for our analysis. This project was rebuilt into a 4D model by linking the identical schedule used in the actual construction with the 3D CAD model generated from the 2D drawings.

Once the 3D CAD model was completed, Plantspace 4D Visualization Toolkit (Jacobus Technology Inc.), a 4D-simulation application, was used to import the schedule and CAD data and relate the activities with their respective components. The resulting 4D model allowed the user to visualize the construction sequence by viewing consecutive 3D CAD drawings with the progression of time. Running predefined simulation sessions could also play out alternative scenarios.

Whilst reviewing the 4D model, we focused our efforts on detecting possible problems or inefficiencies that may occur during construction due to spatial restraints or other constructibility issues. These problems were compared to the actual problems that were encountered by the project managers during construction but were not anticipated in the planning stages. We deliberately refrained from asking the project managers of the project about the actual problems that they faced. This allowed us to make an objective evaluation of the schedule through the 4D model itself without any preconceived prejudices. The comparison shows the effectiveness of the 4D model in conveying information and validates its usefulness. Finally, we ran alternative scenarios to develop the most appropriate schedule sequence that could minimize the problems previously discovered.

3.3 Background of Project

3.3.1 The McWhinney Project

McWhinney Enterprises contracted with the Neenan Company to build a two-story office building for the Factual Data Corp. (FDC) in Loveland, Colorado. Two identical buildings have been contracted to be built subsequently. At the time of our research, the first of the three buildings was already completed. By analyzing the 4D model of the first building, we would try to detect problems and provide recommendations to improve constructibility for the two remaining buildings.

3.3.2 Building Configuration

The building consists of four office spaces for each floor with a core structure in the center that holds the bathroom and a single elevator shaft. The two-story lobby is situated on the southside providing access to the building via the elevator and an encompassing staircase. Two perimeter staircases are located at the west and east wing of the building (*Fig 3.1*). The site cast panels, roof screen system and the gable roof of the lobby were prefabricated adjacent to the site to be erected into place using a single crane (*Figs 3.2, 3.3*).

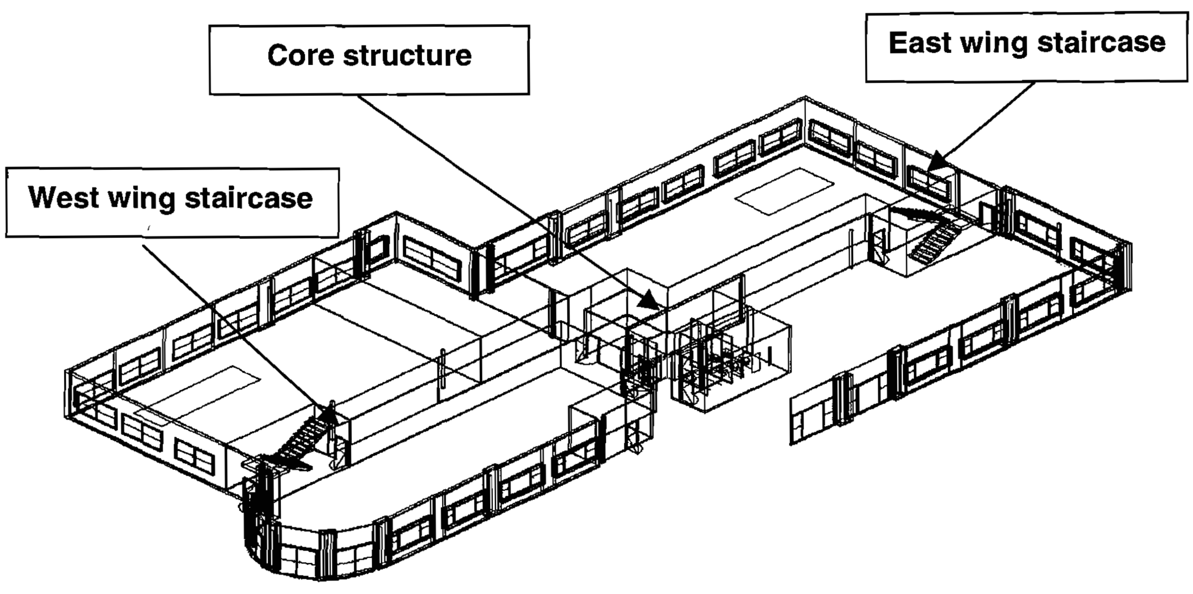

Fig 3.1 1st floor SW isometric view

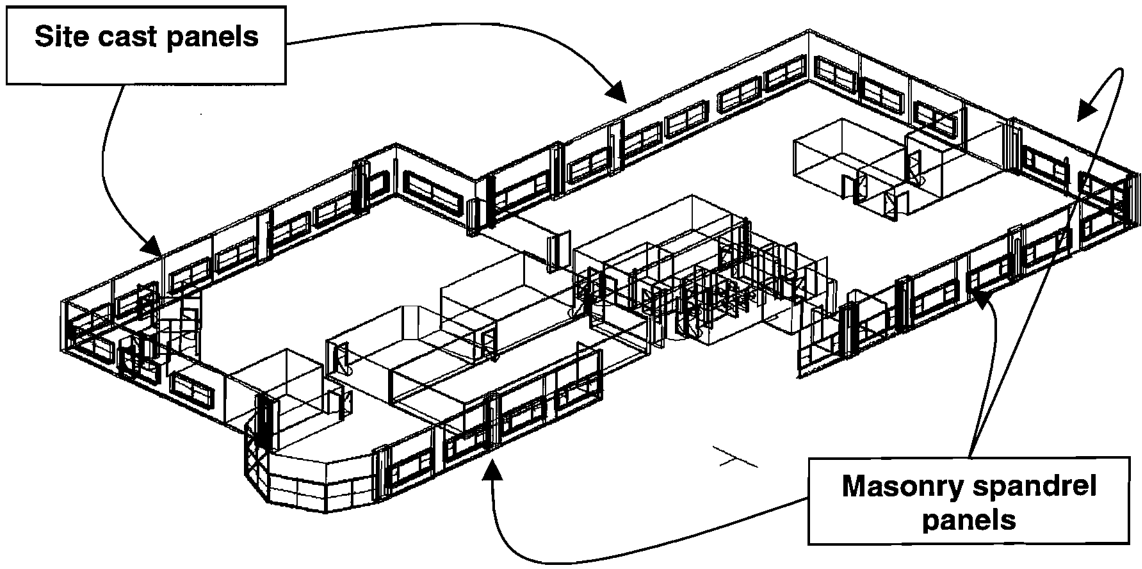

Fig 3.2 2nd floor SW isometric view

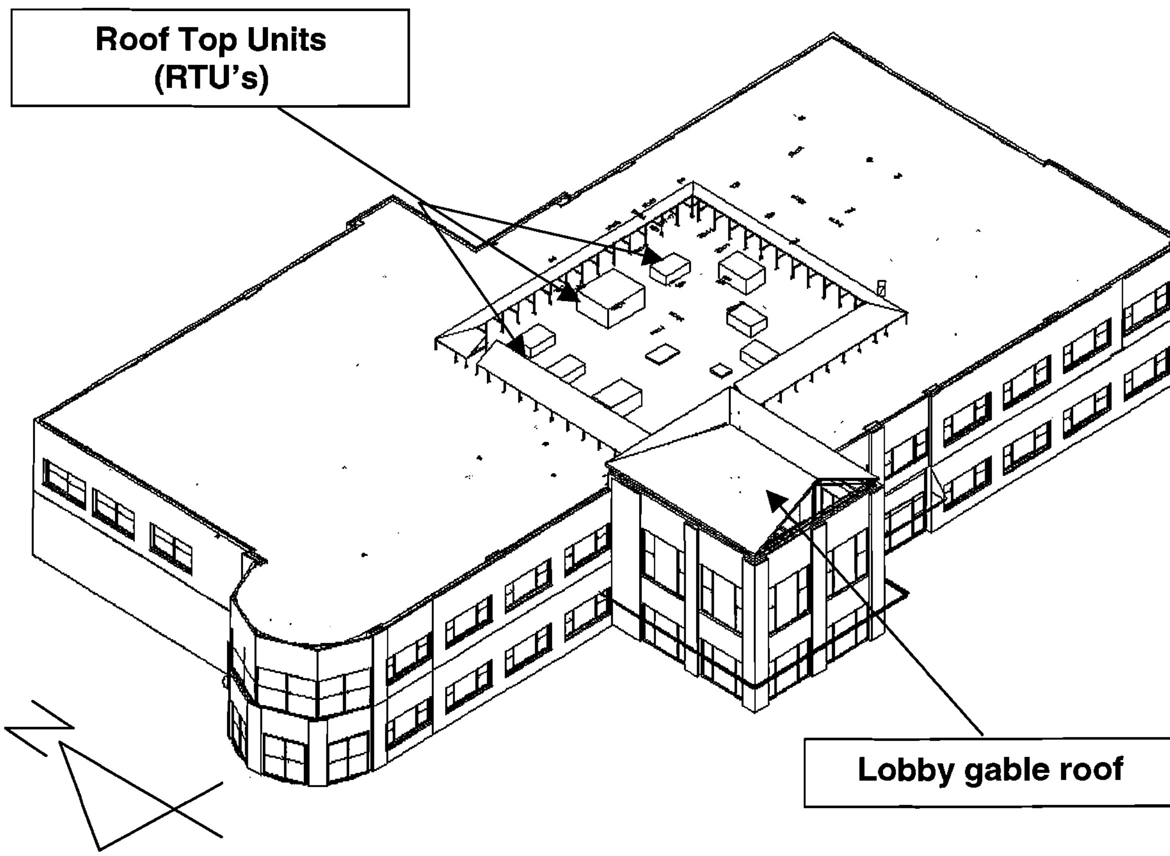

Fig 3.3 3D rendering of FDC Office building

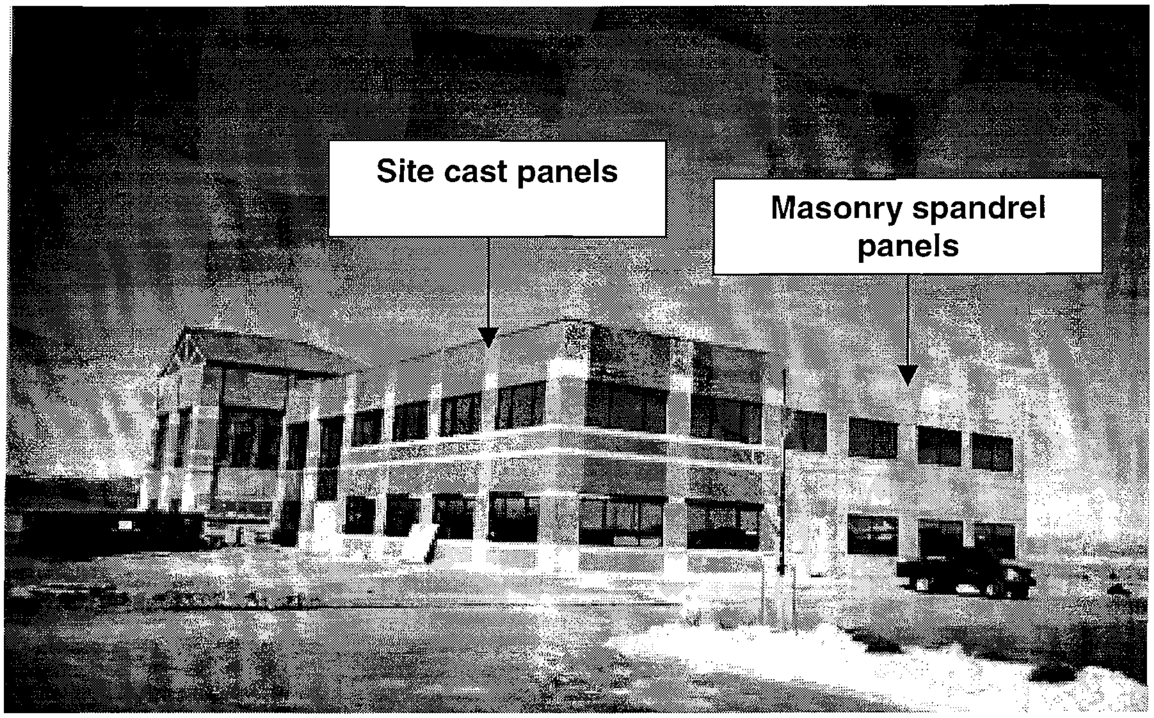

Fig 3.4 SE view of FDC Office building

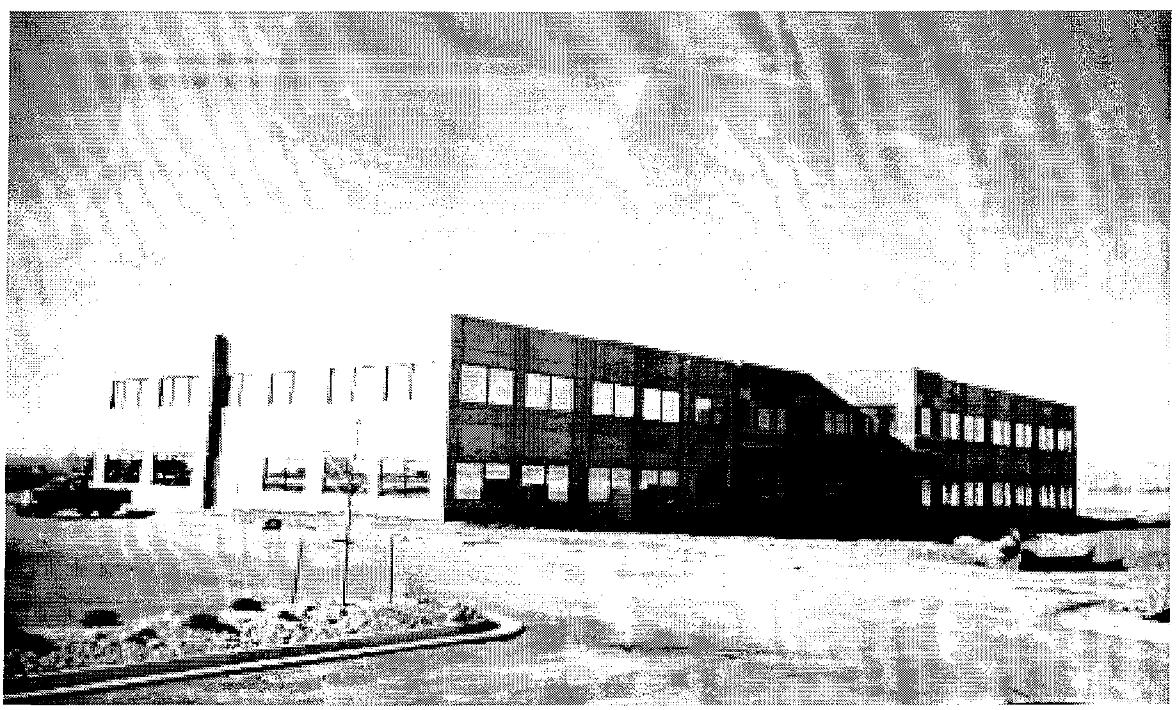

Fig 3.5 NE view of FDC Office building

3.3.3 Schedule Analysis

Schedule description (view Appendix A: Master schedule)

As the objective of our research was to detect potential problems in the overall project, we elected to use the master plan schedule. This schedule would allow us to view the major exterior components (i.e. exterior walls, structural frame, 2nd floor and roof slab & truss) and interior Mechanical, Electrical and Plumbing (MEP) systems in the final 4D model.

The level of detail shown in the master schedule was appropriate in conveying the overall progression of the project (approximately 300 activities). The master schedule shows activities representing exterior components in the first segment and the activities for interior MEP systems in the following segments. The project managers organized the activities for the interior MEP systems into their appropriate phases (refer to *Fig 3.4, 3.5 and Appendix A*). However, a notable disparity existed between the level of detail with respect to the exterior and interior work. The activities representing the exterior components were not divided enough to represent the sequences of the foundation and exterior framing of the building. On the other hand, the schedule went into much more detail in describing the interior installations in the building.

During interior work, several subcontractors typically have to work concurrently in the same or adjacent limited workspaces in order to shorten the overall project schedule. To minimize the potential conflicts among the subcontractors while still providing them with a continuous flow of work throughout the project, the project managers divided the workspace into five major sections on each floor. As shown in the floor phasing plans (*Figs 3.6, 3.7*), the building was partitioned into 11 separate sections (phases 1 to 9 plus phases T and C). Subsequently, the project managers configured the schedule to reflect these subdivisions. They also coordinated all the subcontractors so that the minimum number of subcontractors would be working on a section at the same time.

The project managers did not sequence the three sections on the first floor (*Fig 3.6*) because these sections were not leased and the owner had not yet decided upon the type of installation. Interior work for phase 2 of the first floor began concurrently with the placement of the second floor slab.

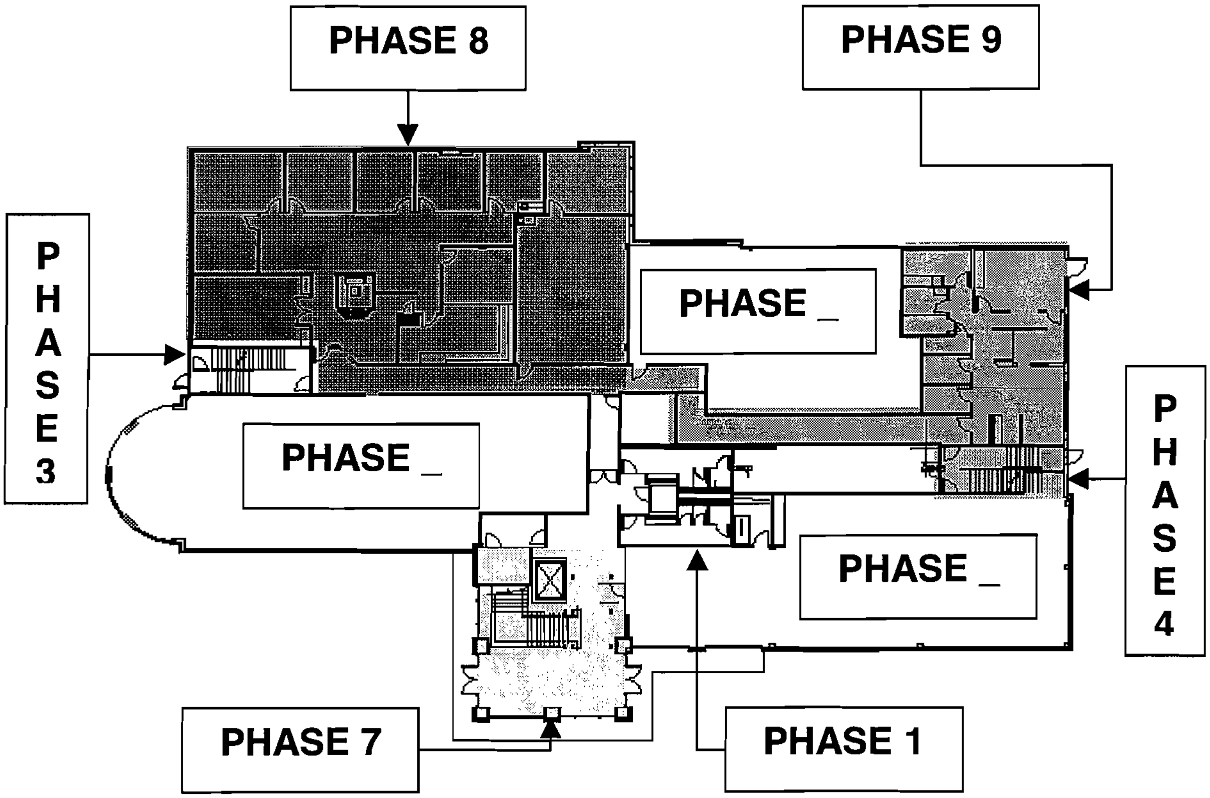

Fig 3.6 1st floor phasing plan

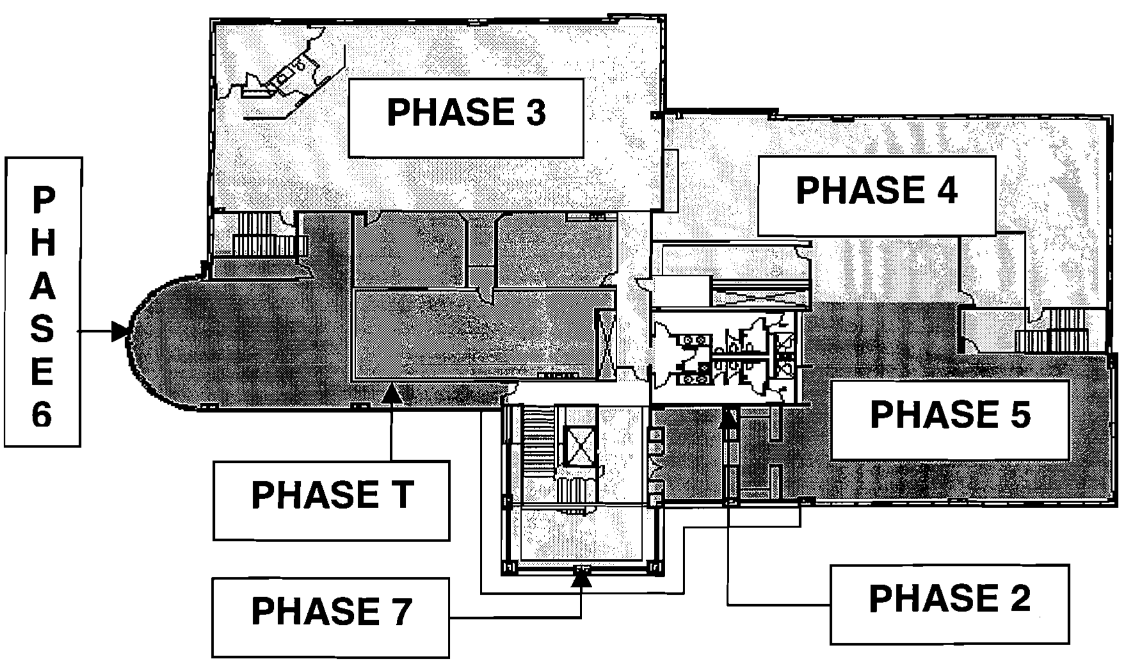

Fig 3.7 2nd floor phasing plan

Initial evaluation of schedule

The research participants found it difficult to understand the logic of the schedule by itself. By correlating the schedule with the 2D drawings and floor phasing plans, we were able to interpret the construction process in our minds. However, it was difficult to decipher whether the logic of the schedule made sense or not. Although all the members of our research team were relatively inexperienced, we discovered that each individual member had a different interpretation of what the schedule conveyed. However, such differences in the interpretation of the schedule also promoted further discussion resulting in a better understanding of the overall project sequence. Individual disparities enforced our initial assertion that a 4D model accurately depicting the project sequence was required to eliminate both misinterpretation and miscommunication.

Due to the failure of reaching a consensus on a single interpretation of the schedule, we could not detect any potential problems whatsoever. There was no way of really detecting any time-space conflicts or constructibility issues based on the master schedule.
Even simple omissions of components that became obvious once viewing the 4D model could not be detected while viewing the schedule. We discovered that without first agreeing upon a concrete interpretation of the schedule, the next step of analyzing the schedule for problems or conflicts was not possible.

The bar chart/CPM schedule's usefulness is restricted as a guideline or timetable. Although a good schedule is effective in conveying sequence information, it is limited to expressing such information and does not convey any other type of information.
The 4D model also reflects the logic of the schedule. However, in addition to conveying project sequence, the 4D model provides the basis for detecting problems in the schedule and thereby evaluating the schedule. The 4D model is not limited to conveying sequence information. By showing potential conflicts and problems not anticipated in the schedule, the 4D model can be used as an evaluation tool of the original schedule.

3.4 Development of the 4D model

The following section discusses the efforts and resources required in building the 4D model and emphasizes the limitations and encumbrances encountered during the 4D model building process.

3.4.1 Criteria Assessment

Before any 3D modeling in support of 4D modeling can be started, the level of detail to be drafted in the 3D model must be determined in correlation with the level of detail shown in the schedule. The user must ensure that all of the building components represented in the 3D model can be associated with an activity in the schedule. This preliminary decision is essential, as it will determine the value of the information the final 4D model provides to the user. The 4D model can be modeled at both the master plan level and at more detailed levels limited to partial phases of the project (McKinney et al. 1998). Project-level based 4D models can be valuable in visualizing the overall sequence of the project. 4D models based on more detailed schedules can be used to clarify specific coordination problems or where the design and schedule are highly complex. Therefore the level of detail of the 3D model must be determined according to the type of problem that the user wants to resolve through the 4D model. Also, the development of the 3D model is the most labor-intensive and time-consuming part of the whole procedure, and it can be cumbersome to make changes to the 3D model once it has been drafted.

The distinction between a product model and a process model also provides the criteria for which components should be included in the 4D model. A *product model* is a conceptual structure used to organize and communicate building design and product information among project participants. A *process model* represent important steps throughout a project's life cycle (Stumpf et al. 1996). Most product modeling efforts are not developed to the level of detail considered useful for construction process designers developing practical applications specifically in the domain of construction control. A process model must include temporary (e.g. scaffolding, formwork etc.) and destructive (e.g. demolition of prior structure etc.) activities relating to components that may not be part of the final structure, but are still crucial in conveying the construction sequence. For example, the installation of a roof system can be represented in the product model by consecutively displaying the components *metal deck, insulation* and *roof tile* on top of one another. However, in the process model the roof system is represented by the activities *install metal deck, install insulation, erect scaffolding* and then *install roof tiles.* It will be sufficient to include the actual components in the 4D model to convey the logic of the sequence, but to detect possible time-space conflicts, the activity *erect scaffolding* must also be represented in the 4D model.

For the 4D model to convey the sequence of construction and also show potential time-space conflicts, the user must decide to what degree of detail such activities in the process model must be shown or depicted. Again the level of detail should be determined to comply with the purpose for which it is being built.

3.4.2 Relating Activities with Components

The first half of the research group analyzed the activities of the schedule to assess which components were required to be drafted in the 3D CAD model and how these components should be subdivided and categorized. The schedule is the basis for how the 3D CAD model is to be built. Without first assessing how and what activities the schedule sequences, there is no way of determining what components should be drafted and how those components should be divided. For example, in the schedule most MEP systems of the FDC building are divided into rough-in (start) and trim (finish) activities. Therefore the MEP components have to be drafted in the 3D CAD model in a manner that will distinguish the individual activities of the schedule. This emphasizes the fact that whilst using today's commercially available simulation tools, a complete schedule is essential for the 4D model process to work. However, most project level schedules do not go into great detail and many issues are incomplete. For example, the master schedule of our project has several activities that encompass a wide spectrum of individual components. The activity *erect structural steel* actually relates to the structural beams and columns of the entire building and also the trusses and frames of the second floor and roof.

Creating a detailed schedule requires the consideration of many factors (such as coordination between subcontractors, resolving time-space conflicts, etc.) which are often left unresolved while generating the master schedule, only to be later dealt with by the subcontractors during actual construction. However, the processes involved in generating the 3D model forces its developers to resolve many of these problems beforehand (Collier et al.1995). An incomplete schedule followed by an insufficient analysis of the schedule activities can lead to redundant components being drawn or conversely, essential components being omitted in the 3D CAD model.

Component Breakdown (view Appendix B-1, B-2:Component breakdown)

Activities in the master schedule were divided into *i) activities that did not have a corresponding component*, and *ii) activities that did have a corresponding component.* The categorization of these activities allowed us to determine which components should be drafted in the 3D CAD model and also how these components should be divided and modeled in the 3D CAD package to support visualization of the schedule as a 4D model.

i) Activities not having a corresponding component

Some of the activities did not have a corresponding component. Activities representing administrative procedures (such as *receive permit, place phone order*) and sitework (such as *earthwork, clear and grub*) did not have a related building component. As the final 4D model was to focus primarily on the sequencing of the building itself, these activities could not be referred to a specific component and thus were discarded. However, activities such as *paint* and *hang sheet rock* did not have a corresponding component but it was still necessary to show them in the 4D model. Such activities would show what work was being done in that area and would be important in conveying potential time-space conflicts. Therefore these activities could not be ignored and methods to represent them in the model had to be devised.

ii) Activities having a corresponding component

For activities that did have a corresponding component, these activities could be linked to the corresponding component in the 3D CAD model. However, this apparently simple process proved to be more difficult than initially presumed. The problem in this case was that a single component in the 3D CAD model was installed in partial sections of the building at differing installation times. Therefore such components needed to be divided to reflect the construction sequence in the schedule.

To organize the components in respect to their relation to the activities of the schedule, the components were categorized as follows:

i) *one to one relationship*: components which could be related to a single activity in the schedule

ii) *one to many relationship*: components which were related to two or more activities in the schedule

Components with *one to one relationship* were those which could be drawn as a single graphical object (layer) in the 3D CAD model and required no further division. For example, the graphical object *box* representing the elevator jack hole component in the 3D CAD model could be related to the activity install *elevator jack hole* in the schedule. However, components with *one to many relationships* required to be divided into several sub-components in order to convey the schedule sequence. For example, in the original 2D drawing, the component *HVAC system* is graphically represented by ducts linked across the entire second floor. (*Fig 3.8-1*) In the schedule, however, the HVAC system is not installed all at once. Each HVAC system of a section is installed at differing times (represented by phases), and also installed in two stages (i.e., rough-in and trim) for each section (*Fig 3.8-2*). To reflect this sequence in the schedule, the HVAC systems component had to be divided into sub-components representing their appropriate sections (*Fig 3.8-3*), and each of these sub-components had to be further divided into rough-in and trim components.

In the 3D CAD model, this division was accomplished by assigning different layer names to each rough-in and trim sub-component of every section. This allowed each activity in the schedule to be linked to a single layer in the 3D CAD model. Only through such divisions could the construction sequence be shown in the 4D model (*Fig 3.8-4*). As a result, the component HVAC system for the second floor had to be divided into 14 individual sub-components and each given a distinct layer name (*Fig 3.9*).

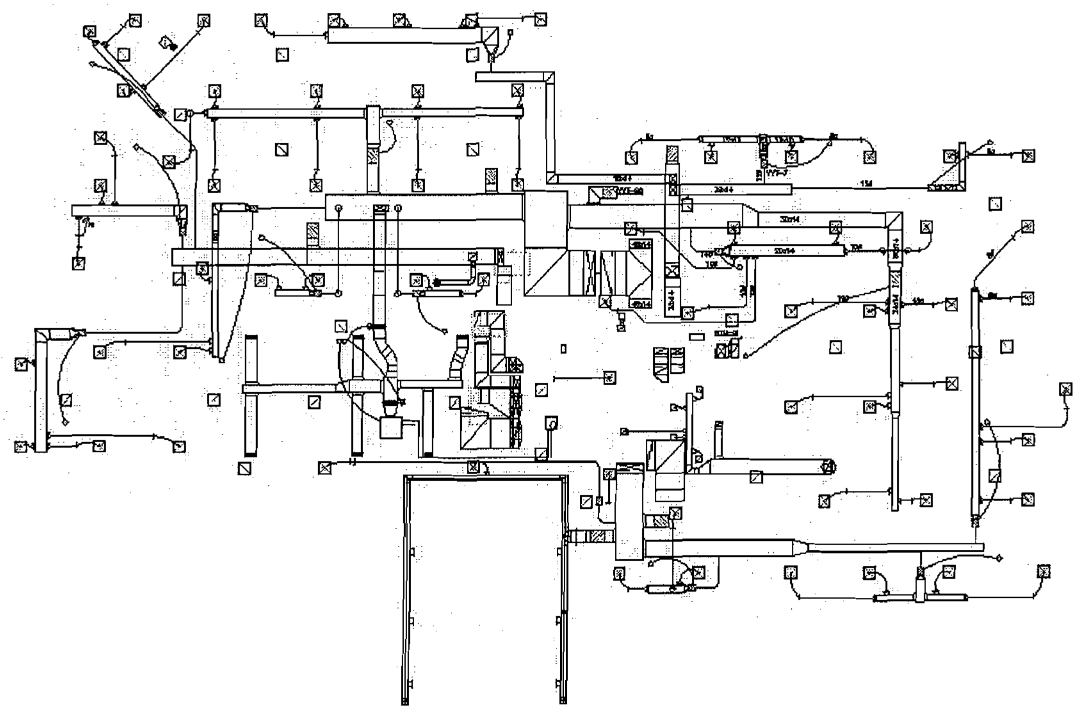

Fig 3.8-1 HVAC system layout of 2nd floor

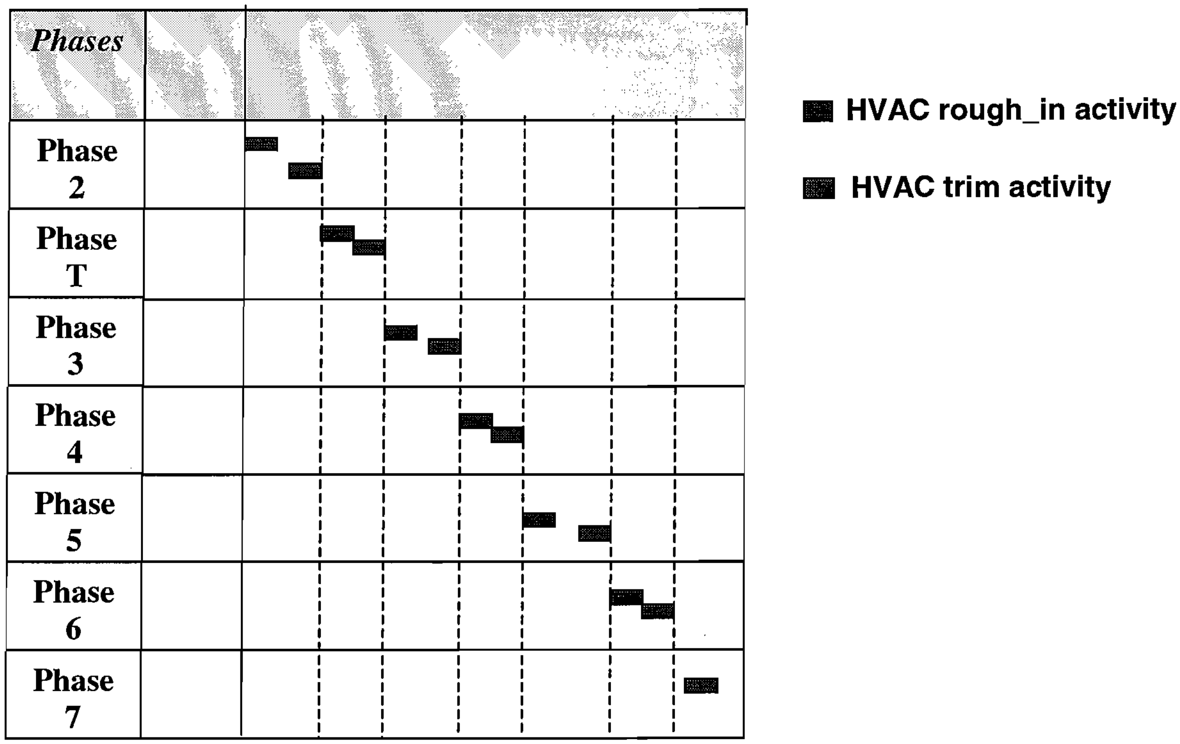

Fig 3.8-2 HVAC system installation sequence depicted by phases and rough-in & trim activities

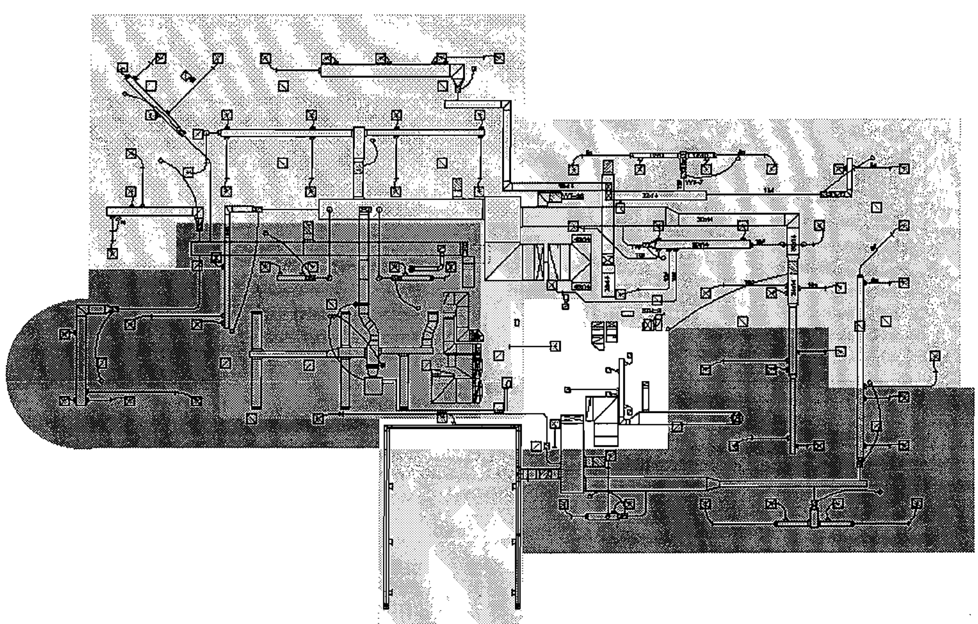

Fig 3.8-3 HVAC components divided into sub-components according to their sections

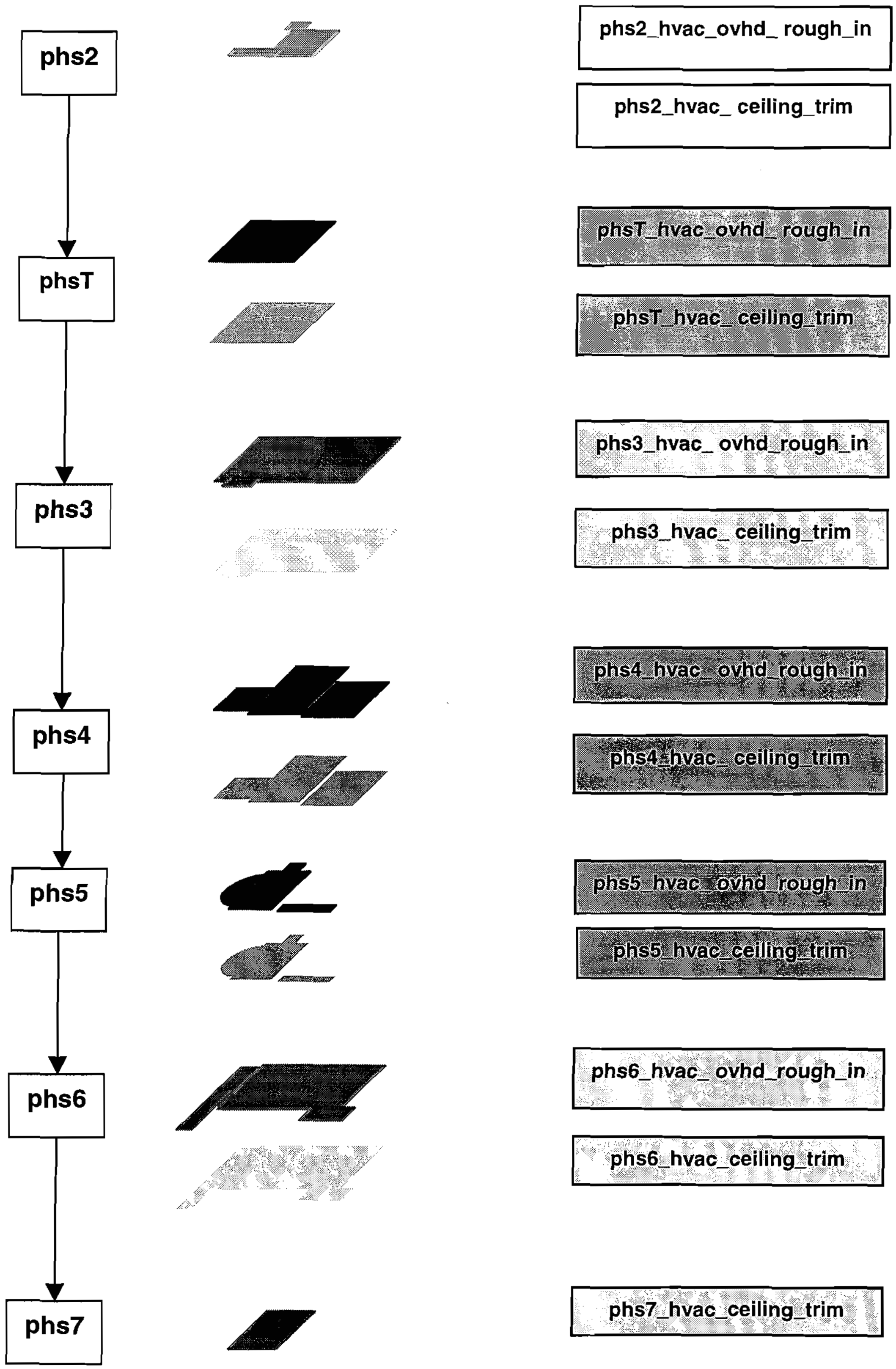

Fig 3.8-4 Each sub-component divided into rough-in(r) and trim(t) sub-components which can then be viewed in the 4D model according to the installation sequence.

Whereas most of the components pertaining to the exterior walls and structural frame of the building were represented in the schedule by a single activity (*one to one relationship*), most of the components for the interior MEP system were represented in the schedule by multiple activities (*one to many relationship*). Therefore the components representing the MEP systems had to be divided into sub-components and given corresponding layer names in a manner similar to the components of the HVAC system.

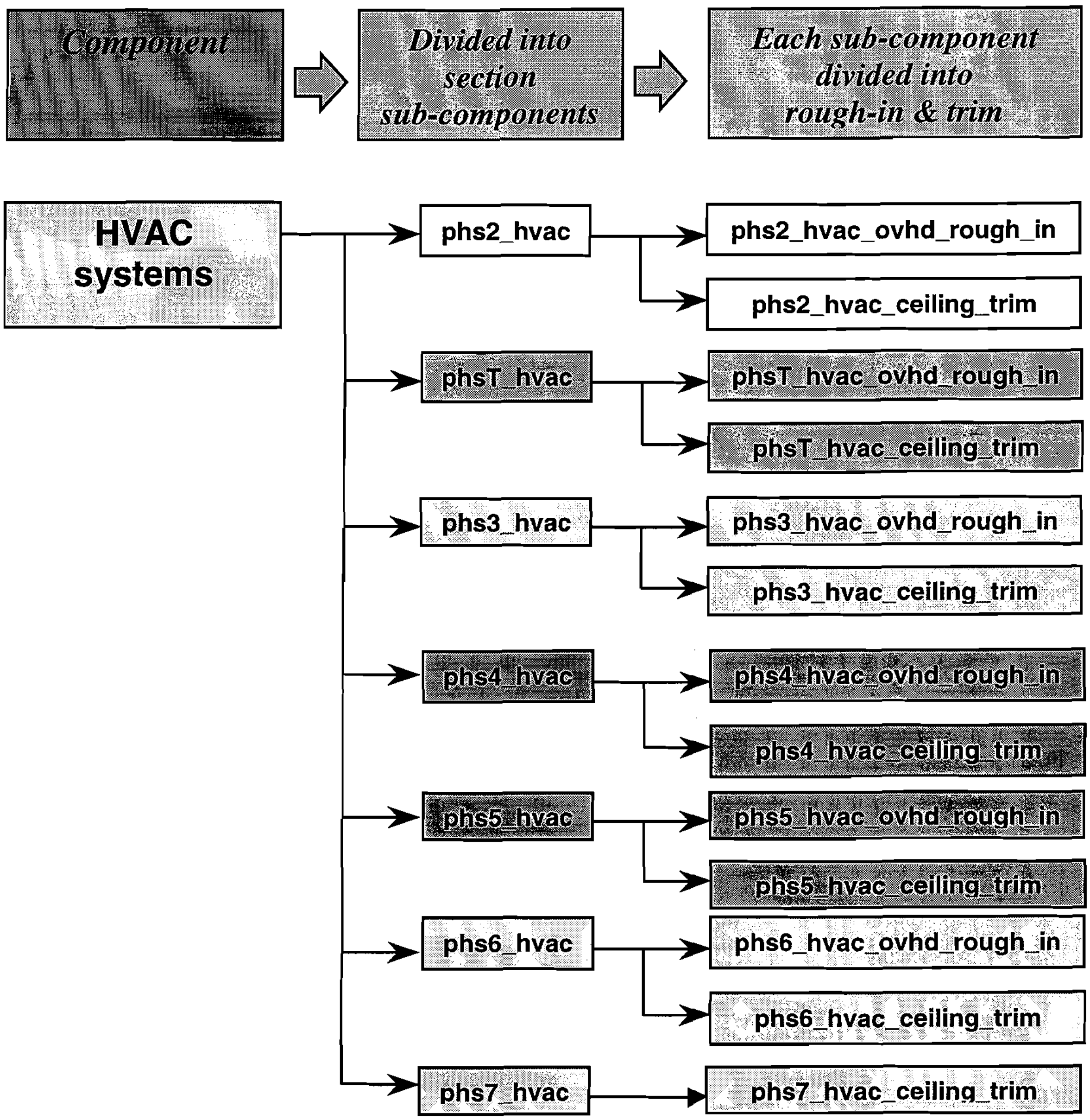

Fig 3.9 2ndfloor HVAC system component breakdown diagram and their layer names

After all the activities of the schedule had been accounted for, the activity names in the schedule were changed to match the layer names in the 3D CAD drawing (e.g., activity ID 115: *core plumbing rough in*, was changed to *phs1_plumb_core_ rough_in*). This facilitated creating the relationship between the component and its activity in the 4D-simulation application.

3.4.3 3D CAD model drafting

Up to this point we had decided upon the level of detail that we want the 4D model to show and as a consequence determined what components should be drawn in the model. We had also determined how components should be broken down to reflect the sequence of the activities in the schedule and by doing so predefined the layer names to be used in the 3D CAD model. The next step involved building the 3D CAD model under these guidelines that we have established.
The 2D drawings were converted into 3D drawings using Autodesk's AutoCAD R14 and the application software ArchT from Ketiv. The latter members of our group were able to work on separate drawings and then combine the drawings using AutoCAD's connect reference (xref) function.

The building was drafted in eight separate CAD files:

1) first floor exterior walls and inner partitions
2) second floor exterior walls and inner partitions
3) second floor slab, frames and trusses
4) roof floor slab, frames and trusses
5) first floor MEP systems (HVAC, Electrical, Plumbing)
6) second floor MEP systems (HVAC, Electrical, Plumbing)
7) roof equipment (RTU's)
8) lobby walls, staircase, and elevator

One of the immediate problems discovered were activities in the schedule that did not have a specific corresponding component, but had to be represented in some fashion in the 4D model. This was a problem recognized while relating the activities to their components and had to be resolved while building the 3D model. As previously stated, these activities cannot simply be ignored if potential problems such as time-space conflicts are to be identified in the 4D model.
The core of the problem is that entirely distinct activities in the schedule had to be represented by a single graphical object (component in the 3D CAD model). For

example, in the 3D model there was only one *wall* graphical object. However, in the schedule, the activities *frame wall, paint,* and *hang sheet rock* were work all being performed on the same wall (*Fig 3.10*).

This problem should not be confused with components that were related to several activities (*one to many relationships*) and therefore had to be divided into sub-components. In that case dividing the component into multiple sub-components allowed the activities to be represented. Also the activities were all representing the same component but only conveyed differing installation times. For the present problem, the wall graphical object cannot be divided to represent distinct activities *frame wall, paint* and *hang sheetrock.*

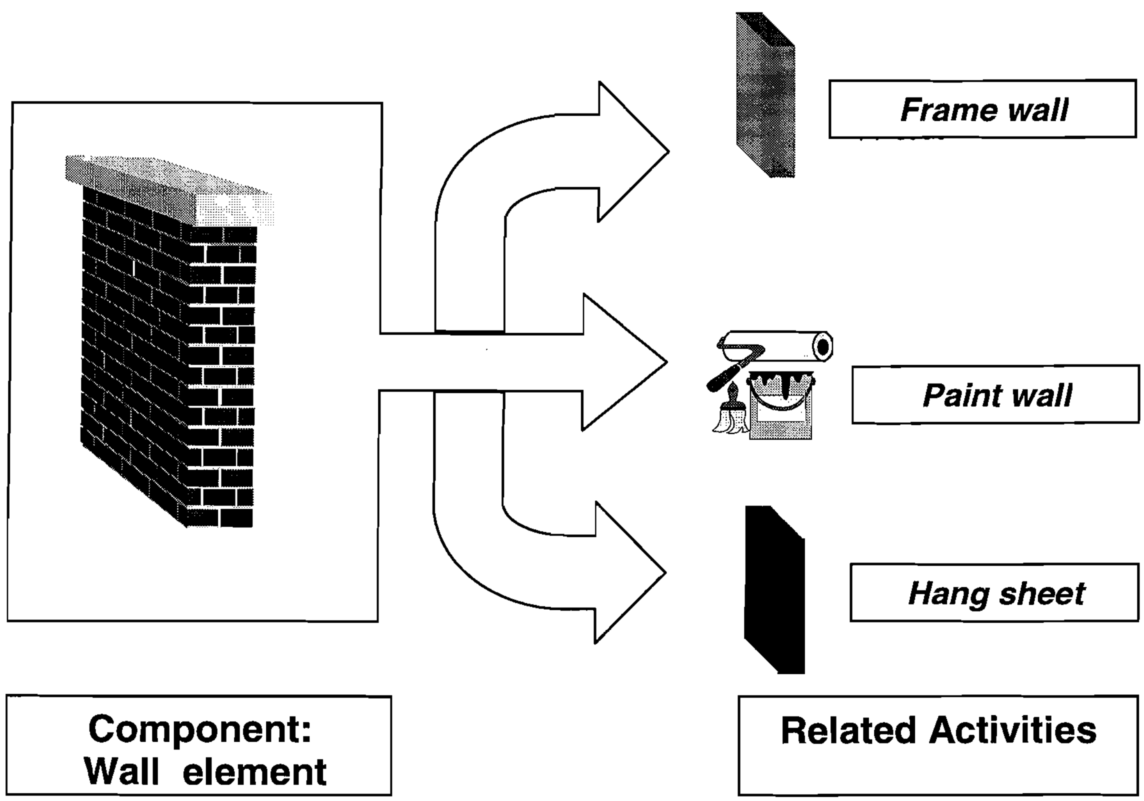

Fig 3.10 Single graphical object representing several activities

Several solutions were suggested to resolve this issue:

i) Draw symbolic representations for the components that do not have a corresponding activity. For example, a drawing of a small paintbrush in the 3D CAD model could represent the activity *paint.*

ii) Draw duplicate graphical objects or CAD entities for a component and give them separate names. For example, if there are four activities related to the wall component, four duplicate walls could be drawn to relate each activity to each component.

iii) Use color code sequencing in the 4D-simulation application.

iv) Attach all related activities to the same graphical object and when the 4D simulation is played out, follow the progression of the 4D model with the original schedule to keep track of which activity is being executed on that component. For example, the wall graphical object was labeled *wall_element* to represent the activities *wall framing, paint* and *hang sheet rock.*

Solutions i) and ii) make the CAD file larger and cumbersome to handle. Solution iii) is not feasible because the simulation application does not support assigning several colors to a single graphical object (component). Solution iv) was elected as the most realistic alternative as it did not require any alterations to the 3D CAD model and did not rely on the functionalities of the 4D-simulation application.

3.4.4 Plantspace 4D Visualization Toolkit and Plantspace Schedule Simulator

Using Plantspace 4D Visualization Toolkit (Jacobus Technologies Inc.), we were now able to import the schedule and CAD data into a single application to create the 4D simulation and view it for evaluation. The following section describes the procedures involved in using the application and identifies present encumbrances of the application.

Overview of application

The Plantspace 4D Visualization Toolkit is a 4D-simulation application which allows the user to visually evaluate project schedules by running the schedule and watching the sequence of the activities' progress over time in conjunction with the building components in the 3D CAD model. The Toolkit imports external data (i.e., CAD files and schedule files) and converts them into Jspace Object Model (JSM) file format.

The Toolkit consists of two types of applications. The first type, *Plantspace Integration Tools* is not an end-user application, but a set of data integration tools used to structure the data of the CAD and schedule JSM files into an object-oriented framework. The integration tool consists of the *JSpace Class Editor*, which defines and edits classes and class libraries, the *JSpace Object Engine,* which generates and runs command queue files, and the *JSpace ODBC Connection,* which imports entire external databases.

Using the *JSpace Class Editor*, we created a new class library based on the standard JSpace class library JCLASS. LIB and added to this library a class for the CAD data (SCHED_GROUP) and another class for the schedule data (P3_ACTIVITY). The SCHED_GROUP class allowed each 3D CAD entity with unique properties in the 3D CAD model to be instanced (created) as an individual object in the CAD JSM file. The P3_ACTIVITY class allowed each activity in the schedule to be instanced as an individual object in the schedule JSM file.

Using the *JSpace Object Engine*, we prepared a command queue file which, when run, created the objects in the schedule and CAD JSM files in accordance with the newly created class library.

The other type of application is a set of end-user application products, the *Plantspace Schedule Simulator,* and the *Plantspace Enterprise Navigator.* These two tools are used to link CAD and schedule objects in the JSM files and simulate the building process by running the 4D model.

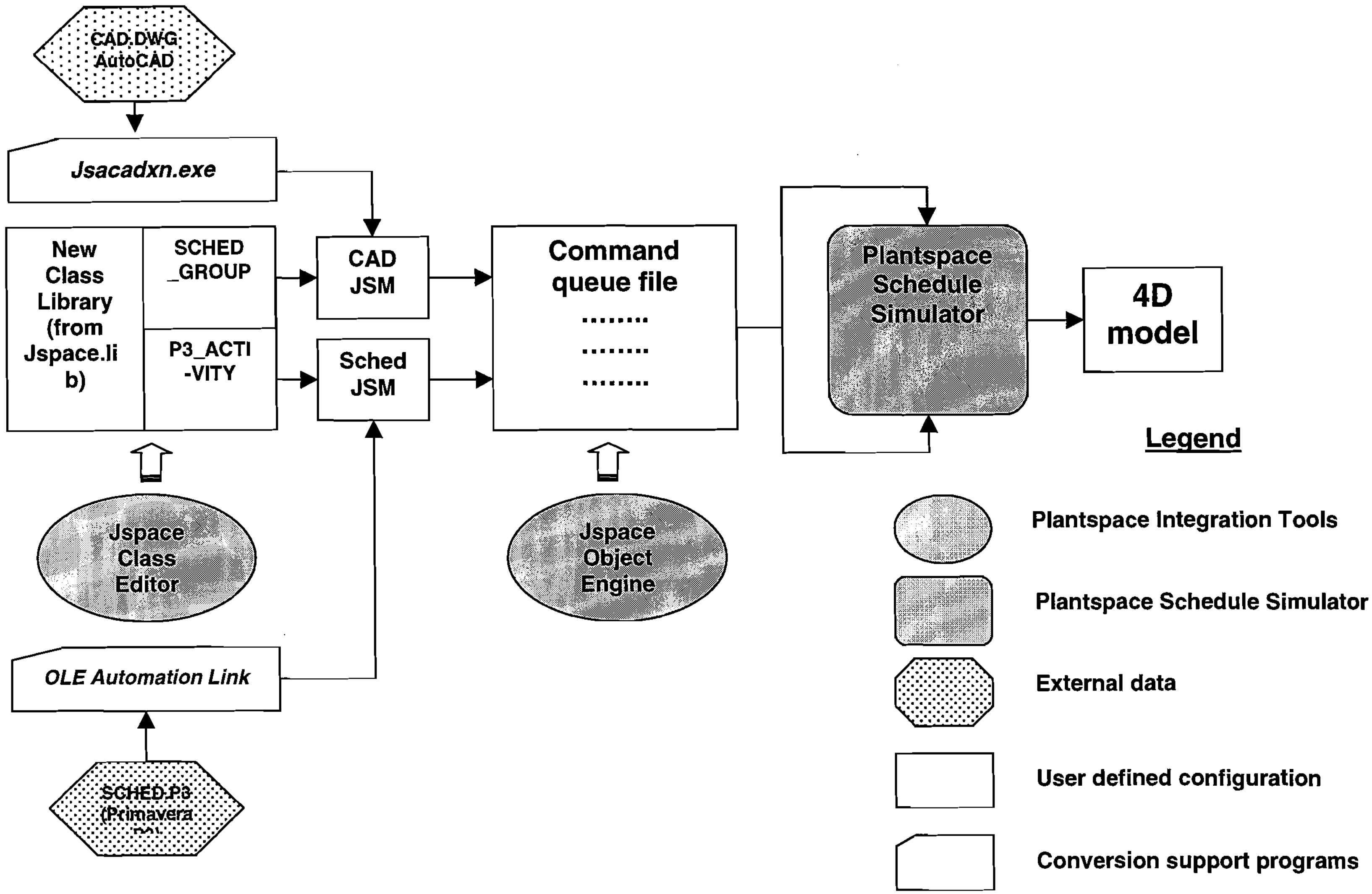

Fig 3.11 Overview of Plantspace 4D Visualization Toolkit's system architecture

Preparing the CAD data

i) Compatibility amongst application software

Incompatibility between Autodesk's AutoCAD and Jacobus' 4D-simulation application delayed the progress of converting the 3D CAD model to the CAD JSM file format. Although Jacobus supplied an execution program (*jsacadxn.exe*) to automatically convert the CAD files to JSM format, this program was only compatible with earlier versions of AutoCAD and not AutoCAD R14 (release version 14). Therefore CAD files drafted in AutoCAD R14 had to be saved as an R12 file, and then reopened in AutoCAD R13 to be converted into JSM file format. In consequence, both versions 13 and 14 of AutoCAD had to be installed on the same computer. To create a single CAD JSM file (there was a total of eight CAD JSM files), two identically large CAD files (R12 and R14) had to be created in order to create an even larger CAD JSM file. For example, the file sizes for versions 14 and 12 of the AutoCAD files representing the lobby components (or CAD file no. 8) were 2.37MB and 795KB respectively (refer to section 4.2.1). The size of the corresponding CAD JSM file was 1.86MB. All three files had to be stored in the computer hard drive in case later alterations to the components needed to be made. All these problems contributed to wasting valuable disk space and slowing down the processing time of the computer. ♦

ii) Grouping CAD Objects

By running a command queue file in the *JSpace Object Engine,* the user can group multiple objects of the same properties (in our case the same layer names) into single group entities. This allows multiple 3D CAD entities (graphical objects) with the same layer names to be maneuvered as a single component that allows easier manipulation of objects in the Plantspace Schedule Simulator. However, the user must refrain from

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♦ Computer configuration : *processor:* Intel 300MHz Pentium II microprocessor, *memory:* 128MB RAM, *HD:-* 4GB, *OS:* Windows NT v4.0
Minimum recommended configuration: a) because several applications (AutoCAD r13&14, Plantspace Visualization Toolkit) need to be opened at once, I recommend 64MB RAM as minimum memory.
b) because large CAD files and JSM files need to be duplicated, I recommend 4GB as minimum HD.

grouping too many objects as this could inhibit the level of detail to be shown in the 4D model.

For example, 3D CAD entities with the layer name *site cast panels* can be grouped to be manipulated as one component which can then be included or excluded from the 4D model as the need arises. On the other hand, this prohibits the *site cast panels* from being divided and shown in accordance to the phases of construction.

An inverse relationship exists between the facilitation of 4D model component manipulation and the degree of detail that can be shown in the 4D model. The user must determine the optimum level of grouping CAD objects with respect to these two factors.

iii) Methods of importing CAD data into JSM file format

Two alternative methods can be used to import the CAD data into the JSM file format. As stated in section 3.4.3, the building was drafted in eight separate CAD files.

a) The eight separate CAD files can be referenced into a single CAD file in AutoCAD R13 to be converted into JSM file format (*Fig 3.12-A*). However, using a single CAD file severely restricted manipulation of the CAD model in the Plantspace Schedule Simulator application. With a single JSM file, all the components of the building would be in view in the 4D model. Specific portions of the building of special interest to the viewer cannot be isolated and viewed separately. Viewing the building as a single entity proved to be too complicated to allow any clear comprehension of the project sequence.

b) The second method is to import the separate CAD files into eight separate JSM files (*Fig 3.12-B*) and subsequently merge these files in the simulator application. This allows the user to view specific portions of the building and isolate specialty subcontractor work as desired.

This points out that the level of manipulation of the 4D model in the simulation application is dependent on how the CAD files are drafted during 3D CAD model drafting. Because we drafted the MEP systems separately from the other building components and also for each floor (section 3.4.3), this allowed us to view the first and second floor MEP systems separately in the 4D model without the other building components.

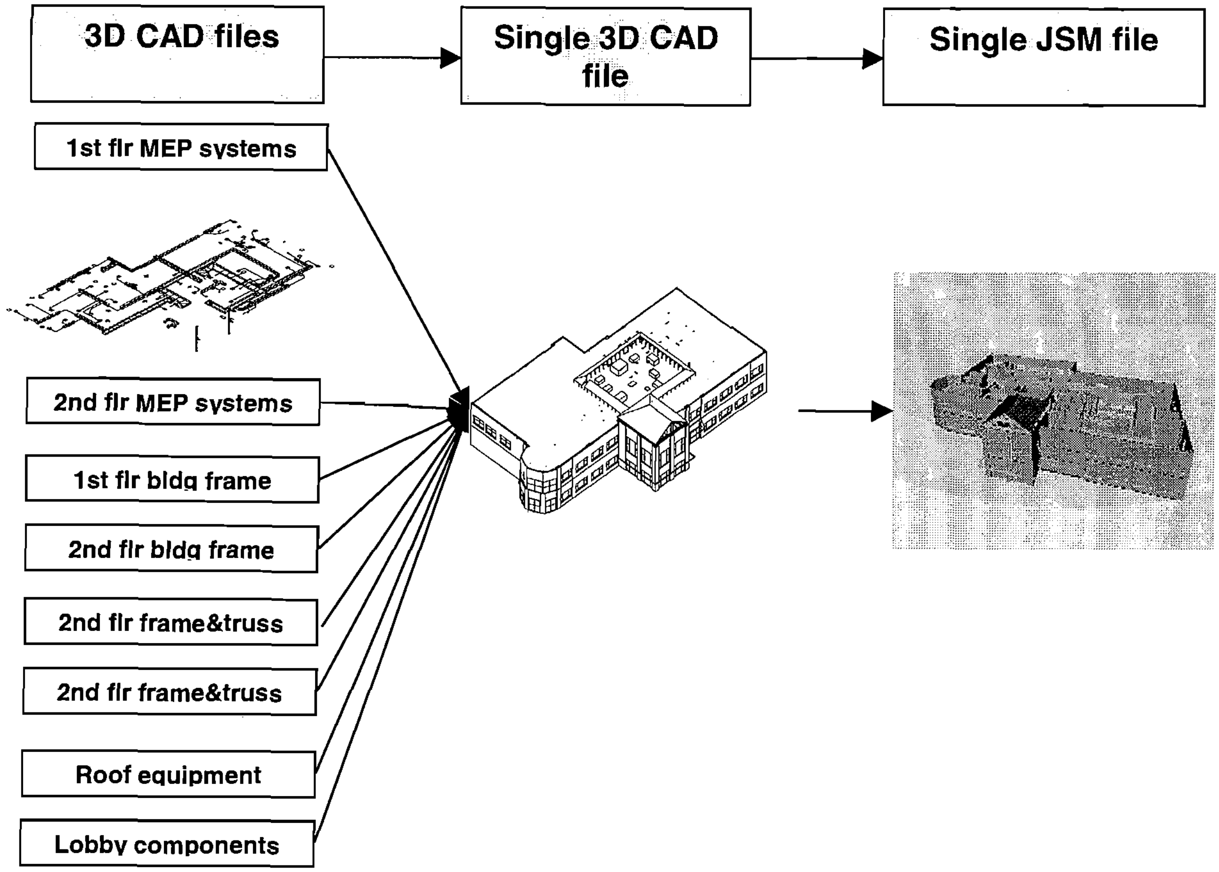


Fig 3.12-A Importing CAD files into a single 3D CAD file and importing it into the Plantspace Schedule Simulator

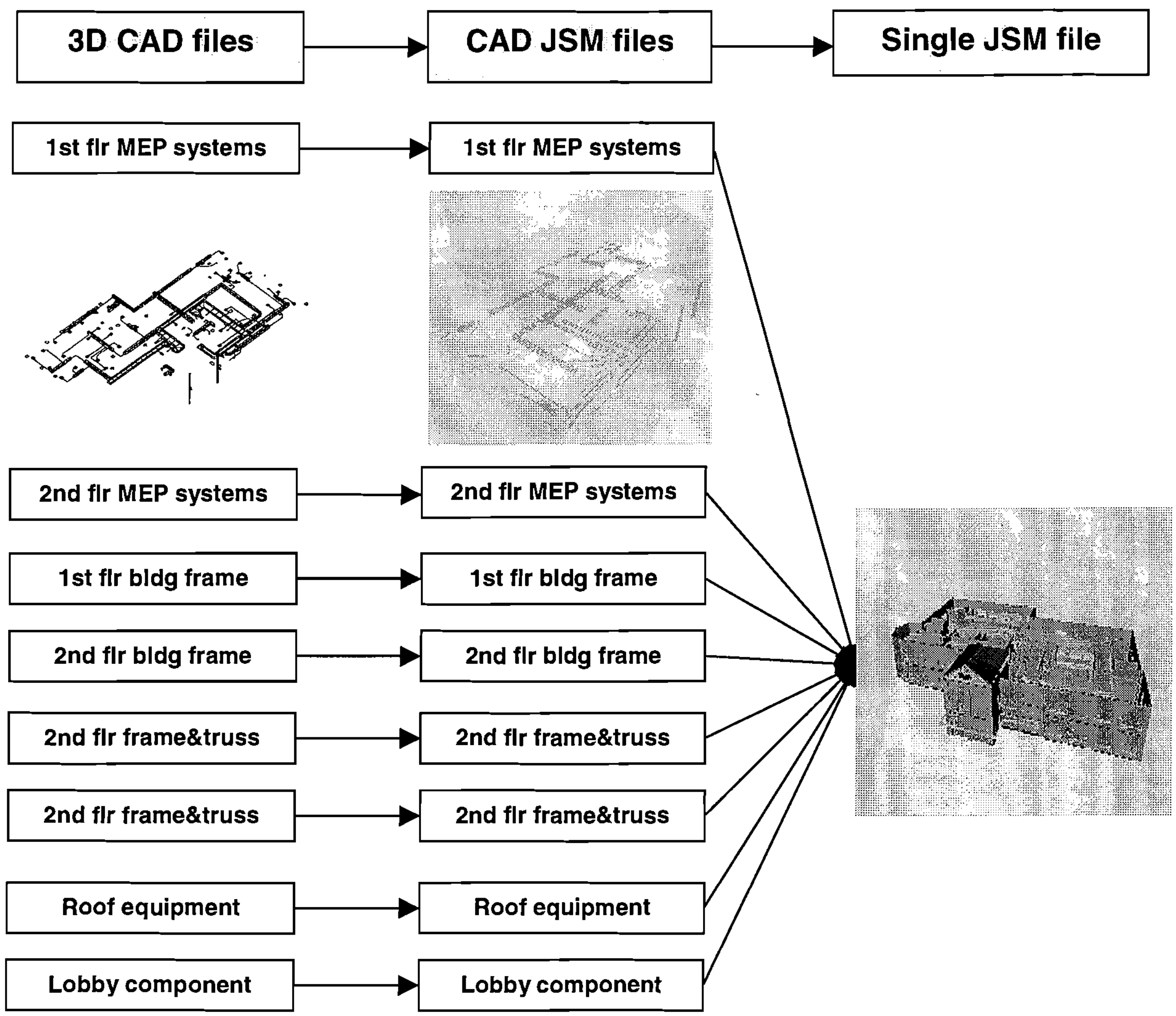


Fig 3.12-B Importing CAD files into JSM files and merging them in the Plantspace Schedule Simulator

Preparing the Schedule data

The schedule data was converted into JSM file format using the OLE (Object Linking and Embedding) Automation Link, a feature of the PlantSpace Schedule Simulator application. This capability allows the user to directly import and update a Primavera or MS Project schedule by either creating objects in a new JSM file or updating the object's properties in an existing JSM file. For example, if the schedule needs to be updated by adding new activities or changing the sequence of existing activities, the user can make these changes by inputting the duration, Early Start (ES) and Early Finish (EF) dates, and sequence information directly in the JSM file without having to make changes in the original schedule. If the original schedule has been changed in the schedule application, the existing JSM file can be updated by importing the updated schedule through the OLE Automation Link without having to create a whole new schedule JSM file.

Establishing relationships between CAD objects and Schedule objects

Once the CAD model data and schedule activity data have been imported into Jspace objects and exist in their respective JSM files, relationships or associations must be formulated between them. The relationships can be automatically created using rule-based batch processes if each component is associated to a single schedule activity (one to one relationships). However, the relationships had to be created manually to associate components representing more than one activity (i.e. one to many relationships).

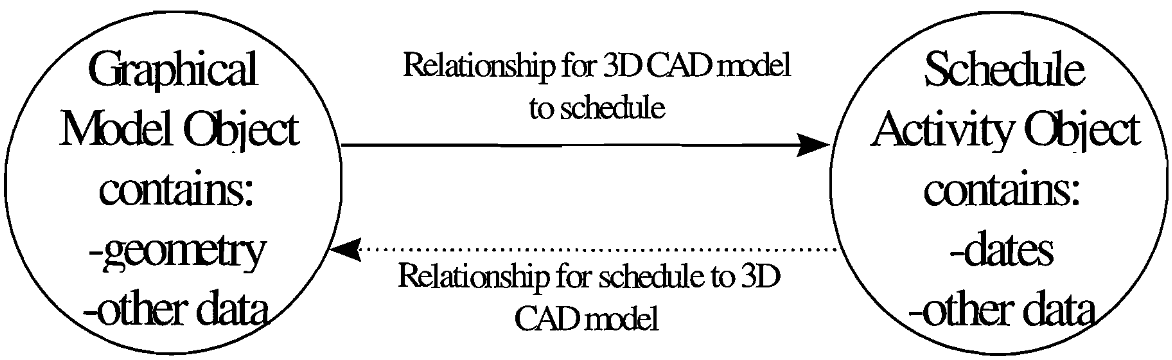


Fig 3.13 Schedule Activity ~ 3D CAD component diagram

Because we had changed the activity names in the schedule to match the layer names in the 3D CAD drawing (section 3.4.3), creating the relationships manually did not take up much time.

Setting different activity types

The Plantspace Schedule Simulator application allows the user to assign the following four activity types to the simulation:

a) *Constructive* - Most activities in a schedule are constructive in nature. In other words, components that are not initially present on the project site must be constructed, and then they remain in place as fixed elements of the facility. These are components that are not present at the start of simulation, then are constructed during the activity and then remain on site.
b) *Destructive* - activities that demolish and remove components from the site. These are components that are present at the start of the simulation, then are demolished and removed during the activity.
c) *Permanent* - activities that perform work on or with permanent features of the facility. These are components present at the start of the simulation, then work is performed on or with them during the activity, and they remain on the site.
d) *Temporary* - activities that require the use of components that are on the site for only a limited period of time. These are components not present at the start of the simulation, then work is performed on or with them during the activity, and then they are removed from the site.

This allows the user to distinguish the different nature of the activities in the schedule, which can be reflected by the components in the 4D model. This feature can also be used to "clean up" the 4D model by removing components from view once they have been built, thus providing a clearer view of the rest of the components in the 4D model. For example, the activity representing the installation of the component *gable roof* of the lobby was assigned activity type "temporary" which made it disappear from view after it had been built. The removal of these components provided a substantially improved view of the interior component construction.

Creating and running alternative sessions

Once we had established all the relationships between the activities and their corresponding components, we ran the Plantspace Schedule Simulator to view the schedule sequence. Viewing all the components of the building proved to be effective in showing the overall sequence of the project. However, having all of the components remain in the 4D model after they had been built resulted in obscuring the view of succeeding activities. Whilst evaluating the 4D model to recognize the logic of the schedule, isolating specific components allowed the sequence to be viewed with less confusion. For example, after the second floor slab was placed, work was still being done on the first floor. Components on the first floor were blocked from view because of the second floor slab. This forced us to halt the progression of the simulation and alter the viewpoint. By preparing a separate session which did not include the second floor slab, the first floor components could be clearly viewed in the 4D model. Subseqeuntly, the sequence of the activties representing the first floor components could be better understood by viewing this session.

Viewing partial sections of the building through different sessions allowed us to comprehend the logic of the schedule faster and also to view portions of the schedule where the logic was unclear. Once we became familiar with the logic of the schedule, we referred back to the overall 4D model to detect potential conflicts in the schedule. As a consequence four scenarios were prepared to show specifc components being built at specific time frames.

a) *Session 1* - The first 4D model included all the components and activities of the building. This scenario allowed us to view the overall progression of the project, but was not conducive in recognizing the logic of the schedule and detecting specific problems.
b) *Session 2* – We omitted the roof truss, roof top units (RTU's), second floor slab and truss from the first model. The removal of these components provided a substantially improved view of the interior component construction.
c) *Session 3* - The third model showed the sequence of the exterior building frame.

d) *Session 4* - The last model only showed the components of the interior MEPsystems (HVAC, electrical, plumbing, sprinklers etc). This scenario clearly conveyed to us the time in which specialty subcontractors needed to install their respective equipment.

We generated the sessions by referencing specific CAD JSM files to a new JSM file (a dummy JSM file). We could have alternatively generated the sessions by deleting the component–activity relationships of the components we wanted to remove. This method would show in the 4D model only the components that were linked to an activity. However, if we needed to see the removed component, we would have to reestablish the link. Therefore it was better to leave the original relationships intact, and isolate specific components by referencing specific CAD JSM files to a dummy JSM file.

The flexibility of generating alternative sessions is predetermined by how the 3D CAD model is drafted in AutoCAD and also by how that data is grouped and imported into the JSM file format. This reemphasizes the importance of careful preplanning of the 3D CAD model construction. For example, if the CAD data were imported into the JSM file as a single file, it would not be possible to isolate specific components to generate alternative sessions in the simulator application.
Isolating specific components to view (i.e. *Sessions 2, 3, and 4*) facilitated the comprehension of the schedule logic. This in turn allowed us to become familiar with the project sequence. However, to identify potential conflicts amongst the various specialty subcontractors working on the project, all the components had to be considered. As a result, *Session 1* was used to detect potential problems in the project sequence.

By viewing the sessions we created, we were able to detect problems previously overlooked in the original schedule (section 3.5). Once these problems were identified through the 4D model, we altered the sequence of the activities of the original schedule in an attempt to minimze the conflicts detected. Then we created a final 4D model that showed the sequence of the new schedule. To modify the schedule sequence, the original

Primavera schedule had to be altered. Once the activity sequences were changed, the JSM schedule data could be updated using the OLE Automation link.

3.5 Problems Detected

The following section describes the problems that were discovered through the analysis of the 4D model conducted by our research team. I have also listed possible solutions to these problems.

3.5.1 Lack of detail in master schedule

There was not enough detail for the exterior elements of the building in the master schedule to show a clear view of how these elements were actually built. The activity *erect structural steel* provided a good example. This single activity represented the structural beam and columns of the entire building, the frame and truss of the second floor and the roof. All of these components were represented in the master schedule by a sinlge activity that has a duration of 15 days. The result was all these components appearing concurrently on the 4D model. The situation was similar for the site cast panels and the exterior stud panels. The site cast panels were cast atop the foundation of the building so that once fully cured, they could be tilted up into their position on the wall. This was an innovative method incorporated by the project manager to reduce transporting and installation time of the site cast panels. In the schedule, casting the site cast panels was again represented as a single activity (*site cast panels*) with a duration of nine days and their installation was represented by another activity (*erect site cast panels*) with three days of duration. The erection of exterior stud panels was also represented as a single activity with a duration of ten days.

As a result, the 4D model does not convey the installation of the exterior components of the building in a sequential fashion, but rather these components are grouped together and installed concurrently.

The lack in the detail of activities with respect to these exterior components made it difficult to relate some of these components to their correct activity and resulted in establishing bogus relationships. These bogus relationships became apparent by viewing the initial 4D model and had to be changed. For example, the initial 4D model showed the four walls of the building being installed prior to structural steel erection. If the four walls were installed first, there would be no access to the inside of the building to erect the structural steel. The reason turned out to be our misinterpertation of the schedule, which was due to the lack of detail in the activities of the schedule. We initially thought that all the four walls were site cast panels. The erection of the site cast panels are represented by a single activity (*erect site cast panels*) which precedes the activity *erect structural steel.* Therefore we had assigned all the four walls of the building to this single activity.

By consulting the project managers, we discovered that whereas the three sides of the wall (north, east and west) were erected using site cast panels, the south side of the wall was erected using masonry spandrel panels (*Fig 3.4*). After the site cast panels were erected, the structural steel was installed, which was followed by the erection of the south masonry spandrel panels which closed out the building. We further discovered that the activity representing the masonry spandrel panels in the schedule was the activity *erect exterior stud panels*. Therefore we needed to change the relationship so that the components for the south side of the wall (i.e. masonry spandrel panels) were linked to the activity *erect exterior stud panels*.

By viewing the 4D model, we were able to seek out the incorrect relationships and modify them to reflect the proper project sequence.

Recommendations

More detail is required to convey the construction of the exterior components. The structural steel frame, truss and frame of the second floor and roof should all be represented by separate activities. The installation sequence of the site cast panels and the masonry spandrel panels should also be represented by more detailed activities. The current level of detail is not sufficient in describing the sequence of how these exterior components were actually built.

3.5.2 Omission of activities in the schedule

There were certain components in the 2D drawings whose installation was not represented in the master schedule. The doors of the interior partitions and portions of electrical fixtures (furns, fix-strips, cable trays) were not given activities in the schedule although there were components in the 2D drawings (*Fig 3.14*). When we viewed the 4D model, we were able to see that these components did not have any activities to link them with. The 4D model is a good way to check that everything in the design (i.e., 2D drawings) is related to an activity in the schedule, providing an easy visual check that the schedule does indeed include activities for the whole scope of the project as represented in the 2D and 3D CAD models.

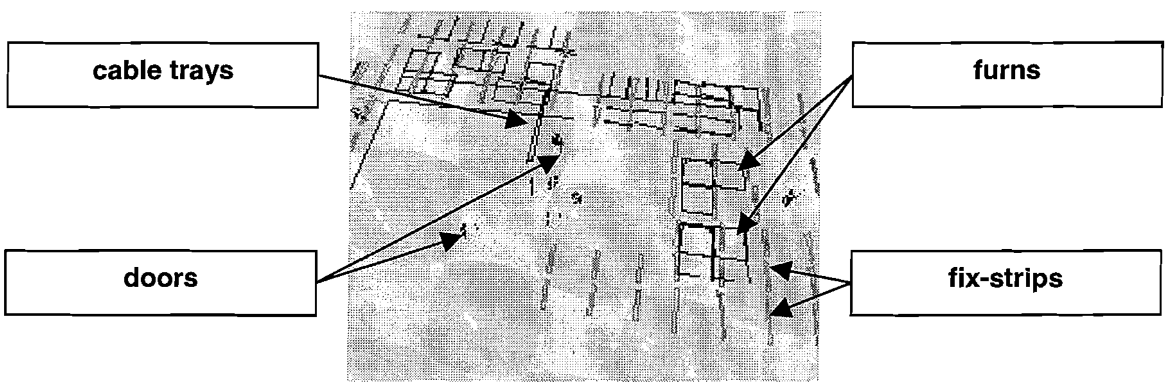


Fig 3.14 4D model showing components which were not related to activities in the master schedule

Recommendations

The activities for these components needed to be added to the master schedule. The project managers acknowledged these omissions in the schedule and notified us of when the components had actually been installed. The doors were installed after each phase of the MEP systems was completed. The electrical fixtures were installed at the same time the electrical overhead components were being installed for each phase.

3.5.3 Problems related to the logic of the schedule

a) There were errors in the logic of the schedule that clearly manifested themselves once the schedule sequence was viewed via the 4D model. For example, the overhead HVAC system for phase 2 was scheduled to be installed before the second floor slab and truss frame was completed. There would not have been a platform on which the workers could work. As the roof frame had not been installed, there would not have been support from which to hang the HVAC ducts.

Recommendations

This is an obvious lapse of logic in the schedule, and activity *phs2_hvac_overhead* needs to be delayed until the second floor slab and truss frame is installed and also the roof frame is installed.

b) The HVAC and Electrical subcontractors are working on phase T of the second floor while the roof is still being installed and there is no protection from the weather. Because roof installation is not completed, there is no protection for phase T work from the weather even when the execution dates are in the winter season (from December 8^{th} to the 15^{th}). In view of the fact that the site is located in Loveland, Colorado, it is crucial for the work to have weather protection. Conversely, whilst installing the roof slab and truss frame, no other work is done in other phases apart from the lobby (phase 7) and phase T of the second floor. No work is being done on the first floor, which does have coverage from the weather.

Recommendations

Adjust the schedule so that the HVAC and Electrical subcontractors can work on the first floor instead of phase T of the second floor.

3.5.4 Problems related to time-space conflicts

While most of the interior specialty work has been scheduled sequentially, the activities *electrical rough in, overhead HVAC rough in* and *plumbing rough in* of phase 1 have been scheduled concurrently. This could potentially disrupt the individual subcontractors leading to delays.

3.5.5 Problems concerning accessibility

We detected a possible accessibility problem in the lobby area. The lobby stairs were installed during the early stages of construction, most probably to provide access for construction of the second floor. However, the subcontractors would not be able to access through the lobby stairs while the activity *lobby stained concrete* was performed (*Fig 3.15*). The potential conflict could cause delays for both the second floor subcontractors and the workers installing the stained concrete in the lobby.

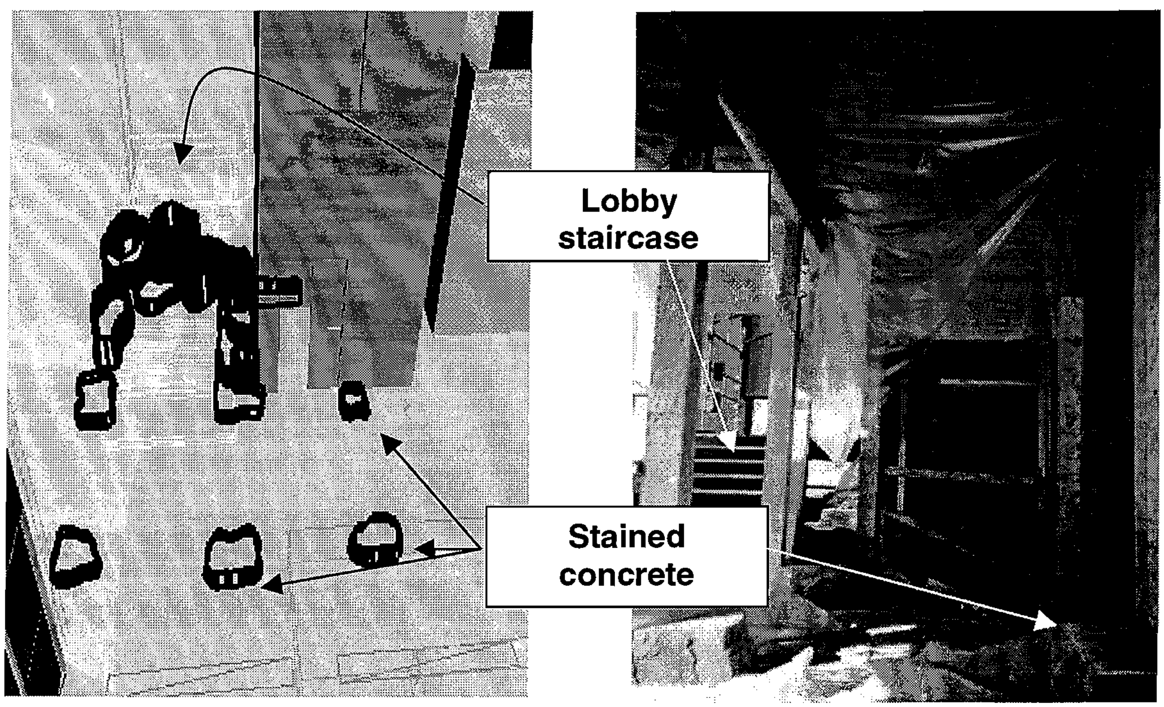


Fig 3.15 4D model and picture showing possible accessibility problems due to early installation of stained concrete

Recommendations

A possible solution would be to reroute the second floor workers to access through the perimeter staircases. In the original schedule, the perimeter staircases are installed after most of the lobby components are installed. Therefore a solution would be to install the perimeter staircases at the east and west wing earlier than shown in the original schedule and before the second floor work begins.

3.6 Actual problems encountered during construction

After viewing the 4D models to evaluate the schedule and detect potential problems in the schedule sequence, we consulted the project managers and asked them about the actual problems they faced during construction. This enabled us to compare the problems they faced as a result of using the original schedule to the problems that were detected through the 4D model.

3.6.1 Congestion in lobby work area

One of the significant problems that the project managers encountered was the congestion in the lobby area. The project managers installed the lobby stairs early in the project to provide access for the subcontractors working on the second floor. However, the subcontractors could not use the stairways while the stained concrete in the lobby was being installed. Scaffolding erected in the lobby area to provide footing for the paint subcontractors further compounded the problem. The congestion resulted in lower productivity rates for the subcontractors affected causing considerable delay to the rest of the project.

3.6.2 Imbalance of work for interior phases

Another problem was the imbalance of work that was scheduled for each phase. The project managers predicted that the time required for the subcontractors to install their work would be similar for each phase of the project. However, the amount of time required for each phase turned out to be quite different for each subcontractor. This resulted in some subcontractors having no float between their work whereas other subcontractors had surplus float. Both cases resulted in reducing the efficiency of the subcontractors affected.

3.7 Limitations of the 4D model

3.7.1 Conveying information

Although viewing the 4D model allowed us to follow the construction sequence with easier perception than the original bar chart schedule, we still needed to run the simulation several times before understanding the progression of the project. It was difficult to keep track of the components currently being built by the 4D model alone. It became necessary to follow the progression of the 4D model simultaneously with the activities of the schedule.

As noted in the initial schedule analysis (section 3.3.3), it was nearly impossible to detect any problem whatsoever. Compared to the conventional bar chart, the 4D model conveyed a plethora of information. The 4D model allowed us to become familiar with the logic of the schedule, which in turn made it easier to detect omissions or contradictions in the sequence logic (section 3.5). It also helped in detecting several accessibility issues. We were able to detect the congestion in the lobby area which impeded access to the second floor through the lobby stairs. In contrast to our expectations, however, we found it was difficult to detect potential constructibility issues or time-space conflicts. We were not able to detect the imbalance that existed amongst the interior specialty work. This is mainly due to the lack of information that the current 4D model conveys. To discern whether constructibility issues or time-space conflicts exist, many other parameters not shown in the model must be considered. For example, to determine whether a time-space conflict exists in a specific area, factors such as crew size, productivity, equipment size, and safety zones must also be addressed. The current 4D model does not show this kind of information. Yet another problem is that today's schedules often show time windows during which an activity should happen and do not show the exact expected activity duration and time. This further compounds the problem of detecting actual time-space conflicts.

3.7.2 Flexibility of the 4D model

Initial decisions concerning component configuration and schedule detail all contributed to the quality of the final 4D model. For example, the lack of detail in the exterior component phases of the schedule resulted in all four faces of the exterior walls appearing concurrently. Also the absence of activities representing temporary work and equipment made it difficult to decipher whether space restrictions would exist. On the other hand, importing separate CAD files into individual JSM files facilitated the manipulation of the CAD objects when isolating the construction of certain components in the 4D model. The flexibility of the 4D model depends on the initial decisions made by the user. However, it is difficult to make such decisions in anticipation of how the 4D model will be used. Because of its dependence to initial design decisions, the 4D model is built at a single level of detail and currently does not support the seamless aggregation and refinement of model detail (Aalami et al. 1996).

Once the purpose of the 4D model has been decided and is built according to this objective, it is very difficult to assess other information that the user may want to derive from the 4D model. For example, if the project manager wanted to use the 4D model to show the sequence of the project to his or her client, he/she will most probably focus on creating the actual components of the building. The project manager later may wish to use the same 4D model to detect time-space conflicts or other issues more valuable to him or herself. However, because temporary components such as scaffolding were not included in the initial model, the 4D model cannot be used for such analysis.

3.7.3 Generating alternative scenarios

It is also difficult to make certain alterations to the 3D CAD model and the schedule once the 4D model has been completely built. The 4D-simulation application makes it relatively easy to alter the duration of the existing activities (say for example, to reflect different crew sizes). This can be achieved directly in the application. However, if the sequence of the original schedule needs to be changed, or new activities need to be added, it is difficult to make such changes directly in the application. Although the Plantspace Schedule Simulator does allow the user to create new activities directly in the application, the user needs to see the overall schedule to determine how these new activities would be sequenced and which activities would be affected by the changes. Therefore, changes such as sequence alterations, or addition of activities, should rather be done in the schedule application. The altered schedule can then be re-imported and converted into the JSM file format using the OLE Automation link, which will update the additional activities and sequence changes into the original schedule JSM file. OLE Automation link allows users to use existing original links between the unaffected activities and their related components without having to reestablish these relationships every time a change is made. However, newly added activities must be linked to their corresponding components, which must be added into the 3D CAD model.

To alter or add components to the 3D CAD model, the only method is to go back and start again from the 3D CAD model drafting stage using AutoCAD. If users wish to alter a component (e.g., move a wall 2 feet from its original location), they must draft the changes in the 3D CAD model and update the existing CAD JSM file by overwriting it. By overwriting the existing CAD JSM file instead of creating a new JSM file, users can save disk space and more importantly, use the originally established link without having to repeat the linking of every component to its related activity. If users wish to add new components, this must also be done in the 3D CAD model. In this case, users must run the command queue file once more so that the added components can be recognized by the Plantspace Schedule Simulator, overwrite the existing JSM file, and link the new components with the new activities updated through OLE Automation link. To prevent re-linking unaffected components with their related activities every time a change is made, users must constantly overwrite the former JSM file whenever they wish to make alterations to the components of the 4D model.

Although altering activity duration of existing activities can be done in the Plantspace Schedule Simulator application, it is difficult to add new activities or CAD components directly in the application. Such alterations must be done separately in their respective applications. This makes creating alternative scenarios time consuming and cumbersome. It also prevents the user from associating the schedule and CAD information in a single environment.

3.8 Future improvements

Future improvements, such as extending the functionalities of the 4D-simulation application and extending the 4D model's applicability, will allow the benefits to outweigh the encumbrances encountered during the development and analysis of the 4D model.

3.8.1 Functional improvements

Users can distinguish critical and non-critical activities by assigning one color for critical activities and another for current activities. However, such limited color-coding does not allow users to represent activities that do not have a corresponding component (e.g., paint wall, remove debris, etc.), or temporary components (e.g., scaffolding, formwork, etc.). Because these activities could not be represented in some way in the 4D model, we had to keep track of the 4D model's progress on the screen and the schedule on a separate spreadsheet to determine which activities were being executed at certain intervals. Methods to represent such activities must be devised and incorporated into the 4D tool.

Network schedules and component lists should be shown together with the 4D model to make comprehension of project sequence easier and faster. Also annotation tools can improve the analysis of the 4D model by emphasizing points of import and describing the assumptions that were made in developing the original schedule.

The progression of the 4D model should be accompanied by a schedule embedded in the application. This schedule can show the progression of the activities as the components are being built in the 4D model. Such a schedule would obviate the tedious task of having to relate the 4D model on the screen with the schedule sheet. These issues are addressed in this section together with the introduction of possible solutions.

i) representing temporary components in the 4D model

Symbolic representations of activities (in the form of symbols or miniature clip art) in the 4D model could be useful in identifying activities that do not correspond to specific components. For example, a miniature paintbrush could represent the activity *paint*. These symbols or clip art could also represent certain components that do not need to be drawn to exact geometric configurations. Instead of having to revert back to the 3D CAD drawings to add components in the 4D model, symbolic representations could be added in the 4D model directly in the simulation application. For example, scaffolding is not part of the actual building and does not always have to be drawn accurately, but does need to be depicted to detect possible time-space conflicts or accessibility problems. Therefore a simplified frame could be added in the 4D model directly in the simulation application to represent the activity *install scaffolding*.

ii) displaying schedule and 4D model concurrently

The 4D–simulation application, Plantspace 4D Visualization Toolkit, which we used for our 4D model development and analysis does not support this functionality. A 4D tool developed by the Bechtel Corporation, the 4D-Planner™, allows users to view the progression of the 4D model in conjunction with the schedule activities. While one half of the screen shows the 4D model, the other half of the screen shows a network schedule diagram plus the ID, dates and duration of the activities currently being executed. This allows better scenario analyses, quicker understanding of the impact of changes, and improved understanding of the project execution plan by non-technical project participants (Williams 1996).

iii) adding a component list to the 4D model

Another useful feature would be for the 4D tool to produce a list of the components that are being currently built by the model and display that list on the screen. The list could notify users of the components whose related activities are on the critical path in the schedule, and also the components whose activities are not critical but are being concurrently executed.

Although adding a schedule and component list would limit users from viewing the 4D model on the entire screen, viewing the 4D model alone without schedule and component information makes it difficult for users to follow and comprehend the construction sequence. This in turn limits the potential of the 4D model, as users will not be able to detect potential problems if they cannot fully comprehend the project sequence. This brings up the limitations of the current monitor- and keyboard- interface (or desktop engineering environment) in viewing the 4D model. These issues are discussed in detail through the introduction of alternative interfaces in chapter 4.

iv) inserting annotation tools in the 4D tool

Annotation tools could greatly improve the quality of information that is represented through the 4D model. As the 4D model shows the components that are being built for each day of the project, the project manager could jot down the points he/she wants to emphasize for that day. These points could be then related directly to other subcontractors by viewing the same 4D model and taking note of the points made. The project manager could also make notes of the reasons for sequencing the activities in a certain order, which will help others following the logic of the schedule. The project manager could use the annotation tools to describe why certain changes in the installation of a component may affect other components leading to cumulative delays.

3.8.2 Applicability of the 4D model

With the functional restrictions of today's commercial 4D tools, it is crucial for the users developing the 4D model to have a concrete view of the model's objective in the early stages of development. Initial decisions concerning the purpose of the 4D model must be formulated to reflect the results that the user wants to detect. However, such decisions restrict users from viewing the 4D model at multiple levels of detail. If the 4D model is built at an abstract level (high level) of detail, the model may not show any construction problems other than reflecting the schedule sequence. On the other hand, if the 4D model is built at a much greater level of detail (low level of detail), the viewer may get confused by not being able to see the forest for the tree. Whereas clients, general contractors, and subcontractors and vendors may use the 4D model for individually different purposes and thus require different levels of detail, current 4D tools are not flexible enough to support multi-leveled 4D models.

The goal is to develop a dynamic model that can be useful for multiple purposes and satisfies the needs of these individual participants. A possible scenario would be to initially build the 4D model at the highest level of detail and add on components and their related activities as the need arises. For example, an initial 4D model would only have the major components and activities of a building (e.g. wall, structural frame and roof and certain major equipment, etc.). This 4D model could be used to present the project to the client. If a problem is detected from this model, and more detail is required to analyze the problem, users should be able to divide the components into further detail and split the related activities to properly represent the project sequence. To make multi-leveled 4D models possible, users should be able to represent CAD components at multiple levels of detail or various scales (i.e., multi-representation of CAD components), and automatically generate the activities to represent these components in the schedule. Such issues will be further discussed in chapter 4.

3.9 Summary

Current 4D models provide a wealth of both qualitative and quantitative information unavailable in conventional bar charts. The 4D model allows the viewer to recognize contradictions in the logic of the schedule, detect omissions of activities in the schedule, uncover accessibility issues, and perform other computer based analyses. In this respect, the 4D model is a valuable tool for evaluating conventional project schedules. However, there are also aspects of 4D models and 4D tools which limit their usefulness; the encumbrances in generating the model, limitations in discovering constructibility and time-space conflicts, current functional limitations, and restricted reusability at multiple levels of detail. These limitations prevent users from easily generating 4D models and conducting effective 4D model analyses.

Future improvements that address these issues are essential for the 4D model to overcome its limitations. The next chapter introduces current research that has addressed some of these issues, and suggests additional improvements for future research. New interfaces, which allow easier interaction with the 4D model and collaboration amongst design participants, are also discussed.

Chapter 4. Current and Future Research

4.1 Introduction

This chapter summarizes the limitations that were discovered through the case study and presents additional issues that have previously been discussed in literature associated with 4D CAD research. Current 4D tools require users to invest significant amounts of time and effort in generating 4D models but provide limited functionality or support for manipulating the 4D model and conducting 4D model analyses. Therefore improvements of 4D tools must be made which can accelerate the generation of 4D models, increase the flexibility of the developed 4D model, and enhance the 4D tool's ability to detect and convey potential planning problems to users.

In response to these limitations, I will propose possible solutions and also introduce several applications that are being investigated by the CIFE community. To expedite the 4D model development process, 4D tools need to support users in preparing the schedule data, and better CAD tools need to be developed to expedite 3D CAD model generation. To increase the flexibility of the 4D model, the CIFE community has developed a research prototype "Collaborative 4D CAD" (Mckinney et al., 1996) which allows users to rapidly generate alternative scenarios by manipulating the schedule and CAD data in a single application. The Construction Method Modeler (CMM) (Aalami et at., 1996), another CIFE project, can be used in conjunction with 3D porduct models to generate multi-leveled 4D models.

To support users in detecting potential problems during 4D model analysis, the CIFE community has explored the use of knowledge-based systems together with semantic 4D models to recognize potential conflicts and relay this information to users (McKinney et al., 1997).

Finally, I will introduce alternative interfaces such as the Responsive Workbench (RWB) (Krueger, 1993) and the Information Mural (IM) (Winograd and Hanrahan, 1997) which can create a realistic collaboration environment for the construction planning team by escaping the desktop engineering paradigm.

4.2 Limitations of current 4D models and 4D tools

Aspects of current 4D models that need improvement can been found in the 4D model's development process; the 4D tool's flexibility in manipulating the 4D model; the ability to convey information concerning potential problems; and functional improvements required to facilitate communication of planning information.

4.2.1 Development of 4D content

Developing the 4D content – 3D CAD component geometry, schedule information, and their associations – can be a time-consuming and labor-intensive process. Construction planners may resist using 4D models as a planning tool because of their reluctance to spend the significant amount of hours required in generating the 4D model. As time is a critical factor in construction and to the project's planners, the efforts required in developing the 4D content have been quantified by documenting the amount of hours that were spent in building the 4D model for the McWhinney project.

Table 4.1 shows the hours of work that were input by the four research participants in generating the 4D model.♦ The table not only shows the time invested in the construction of the 4D model, but also hours required in preparing the schedule data (i.e. breaking down the components in relation to their associated schedule activities), setting up and creating alternative sessions to elucidate the viewing of the simulation, and analyzing the final 4D model to detect problems in the original schedule. This notifies the reader of the actual time a construction planner or general contractor would need to generate a 4D model, and more importantly, the time required to derive substantial benefits by detecting

♦ The recorded hours are accumulated hours amongst the four participants and not individual hours of each participant. The research participants had no initial training in using the Plantspace 4D Visualization Toolkit and were very new to the entire 4D model development process. A few of the students were proficient in converting the 2D drawings into 3D CAD models and had some background in Object Oriented Programming (OOP) methodologies.

potential problems through the simulation. Table 4.2 shows the hours required in drafting the individual 3D CAD models from 2D drawings in relation to the square feet area for each section of the building, and the number of 3D CAD components or entities which constitute that section.

Development Stages	***Hours of work input***
Preparing the schedule data (Component breakdown)	12hrs
3D CAD model drafting (24,360 3D CAD entities): *view Table 4.2 for details*	69hrs
Plantspace 4D Visualization Toolkit	
• *Comprehending the simulation application*	8hrs
• *Setting up classes and libraries*	5hrs
• *Converting external files (CAD & schedule files) into JSM files*	7hrs
• *Establishing relationships between CAD objects and Schedule objects*	3hrs
• *Creating alternative sessions (total of 4 sessions)*	7hrs
4D model analysis	15hrs
Total hours	**126 hrs**

Table 4.1 Hours input in developing 4D model for the McWhinney project

The hours of work depicted in Table 4.1 provide a guideline to which aspects of 4D model development need improvement and automation to ease the burden for project planners or contractors, who cannot afford to invest a lot of time in generating the model. Proper preparation of the schedule data is critical for the final 4D model to achieve its desired purpose. As the 3D CAD model drafting stage is the most time-consuming process, better CAD tools must be developed to make the 3D modeling process easier and faster. A significant stage requiring improvement is developing alternative scenarios in the 4D model. This requires the easy manipulation of the 4D content (refer to *manipulation of 4D content: section 4.2.2*). Furthermore, functional improvements must be made to allow easier detection of potential problems in the construction sequence while conducting 4D model analysis (refer to *detection of potential problems: section 4.2.3*).

3D CAD files	***Square foot of each floor area***	***File size (AutoCAD r14 file)***	***No. of 3D CAD entities***	***Hrs of work input***
1. First floor exterior walls and inner partitions	22,875sf	771kb	1,893	11hrs
2. *Second floor exterior walls and inner partitions*	22,875sf	710kb	1,142	10hrs
3. Second floor slab, frames and trusses	22,875sf	690kb	2,798	13hrs
4. Roof floor slab, frames and trusses	22,875sf	320kb	1,136	8hrs
5. First floor MEP systems (HVAC+Electrical +Plumbing)	47,006sf (22,875+22,875+1,256)	1,365kb (521+624+220)	1,092 (854+228+10)	7hrs
6. Second floor MEP systems (HVAC+Electrical +Plumbing)	47,006sf (22,875+22,875+1,256)	1,827kb (898+724+205)	3,138 (1,354+1,770+ 14)	13hrs
7. Roof equipment (RTU's, Mechanical screen)	3,657sf	591kb	608	4hrs
8. Lobby walls, staircase, and elevator	1,301sf	2,426kb	3,853	15hrs
Total	**373,470sf**	**8,700kb**	**24,360**	**69hrs**

Table 4.2 Hours of input required in drafting 3D CAD models from 2D drawings

From table 4.2 we can see that the time required in building the 3D CAD model is not necessarily in proportion to the square foot area of the section, but to the number of CAD components or entities that need to be drafted for that section of the building.

i) Preparation of schedule data

As depicted in Table 4.1, the actual building of each individual 3D CAD model is the most time-consuming element of creating the 4D model. However, this can be misleading as it can imply the 3D CAD model drafting stage as to be the most important part of the development process. Just as importantly, the quality of the final 4D model is also determined by the initial decisions made in the preparation of the schedule data. Whereas the user may wish to rush into drafting the 3D CAD model, hasty decisions concerning which components should be included in the model can result in the 4D model not achieving its proposed purpose. Time initially invested in performing component breakdown and preparing the layer names for the components of the 3D CAD model can save time in the later stages of model development.

Solution

To expedite the preparation of schedule data and at the same time assure that all activities are properly represented by their component, I propose the following steps to be taken. Based on the experience gained from the case study, I have listed the steps required for preparing the schedule data in the most efficient way possible (refer to *Appendix A,B-1, B-2*), which can be used as a guideline and prevent future users from reinventing the wheel.

1) *Step 1*

   Decide on the purpose or objective of the 4D model. This decision will naturally determine the level of detail of the 4D model and must be established as most current 4D tools only support the construction of single leveled 4D models at one level of detail (refer to *generating multi-leveled 4D models, section 4.2.2*).

2) *Step 2*

   Create a schedule in accordance to the level of detail. If a schedule has been provided, check that the level of detail is appropriate and make adjustments. (e.g., split activities which encompass too many components, or group activities if schedule is too detailed). These adjustments will allow a uniform level of detail of the activities and indicate the level of detail to which components need to be drafted in the 3D CAD model.

3) *Step 3*

   Create a checklist of the activities in the schedule. This can be done by importing the activity ID, activity name, and duration fields in the schedule to a spreadsheet application. Creating a separate list for these fields allows users to reorganize and categorize the activities of the schedule.

4) *Step 4*

   In a column of the spreadsheet, create a new field 'Related Component.' Users can use this field to input the name of the related component of each activity.

5) *Step 5*

   Using the related components' names field, categorize the activities into the following three categories (refer to *section 3.4.2*):

   - *activities not having a corresponding component*
   - *activities with one to one relationship*
   - *activities with one to many relationships*

   Users can determine which components need to be drafted and whether they need to be divided into sub-components to represent their related activities.

6) *Step 6*

   Create a list of the layer names that are to be used for the names of the 3D CAD components, and replace the activity names in the schedule with these layer names. This will speed up linking relationships (between components and their activities) in the 4D-simulation application.

Preparation of the schedule data is a stage in the 4D model development process where human interpretation and decisions have a large impact on the outcome, and yet these decisions have been left to the total discretion of the user. Future applications need to be developed to automate these steps and aid the user in making the right decisions.
One type of research could be the development of an application that determines the level of detail of the 4D model in consensus with its proposed objectives. There are several parameters that determine the level of detail of the 4D model. The level of detail will

vary according to the viewer of the 4D model, scope of the 4D model, the type of problems that need to be detected, and the existence of temporary components in the 4D model (see *Fig 4.1-A*). By asking users about their preference for each of the parameters, the application could, e.g., assign a set of predefined weight factors for each response. By considering these parameters together with the duration of the project and number of activities of the original schedule, the application could determine the best level of detail for the proposed purpose. The application could set the maximum and minimum duration for each activity best suited for that particular level of detail (or ask users to input the durations they prefer). The application could then go through the activities of the schedule to detect which activities need to be adjusted to fit the duration boundaries. Subsequently, it could ask whether the user would want to split an activity whose duration has exceeded the maximum limit, or group certain activities whose duration is less than the minimum limit (*Fig 4.1-B*).

Another improvement could be to automatically generate a checklist and allow users to manually categorize the activities within the 4D-simulation application instead of using an external spreadsheet application.

Lessons learned

Careful consideration of component decomposition determines the quality of information that can be derived from the final 4D model. The list provided can serve as a guideline for future users, which can aid in accelerating the 4D modeling process and guarantee the final 4D model's output. Future research should be done to streamline (automate) this process which can reduce the need to rely solely on human interpretation and aid in minimizing mistakes.

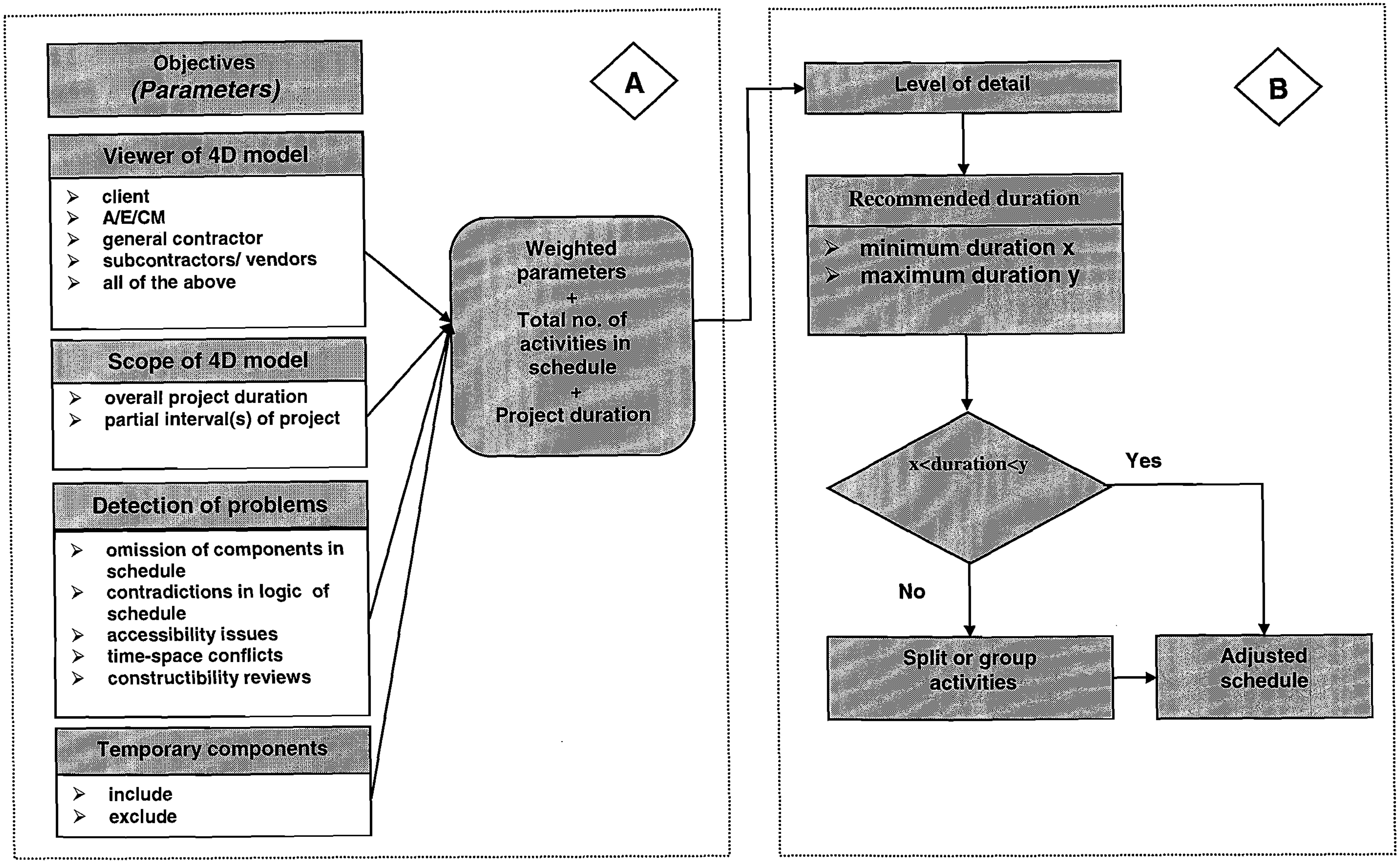


Fig 4.1 Flowchart showing automation process of schedule detail evaluation

ii) generation of 3D CAD models

The amount of time required in generating the 3D CAD model is a significant drawback. The general contractor or construction manager cannot afford to allocate all of his time sitting in his office or trailer building a 4D model. Indeed, due to the frequent changes that exist in construction, the 4D model may be outdated as soon as it is built. Current 4D tools require the 3D CAD model and the schedule to be produced separately, without the benefits of the shared insights that a 4D model can provide for design and construction planning.

Solution

Functional improvements of current CAD tools and drafting 3D CAD models in the design stages of the project (as to the planning stages) can both contribute in expediting the 3D CAD modeling process.

Functional improvements need to be made in converting components in the 2D drawings into 3D components to accelerate 3D CAD model generation. Whilst converting the 2D drawings of the FDC Office building into 3D CAD models, we used 3D templates preset in Ketiv's ArchT application for some components that did not require to be drawn in geometric accuracy. We selected a template that was most geometrically similar to the original component instead of using the components in the 2D drawings to convert into 3D. For example, when inserting perimeter windows inside the site cast panels, we chose a window template from the 'windows' library in ArchT, and inserted it into the site cast panel to represent the original component. The use of such templates expedited the 3D CAD model generation process, and its use was acceptable as the primary purpose of the 4D model (for our case study) was in detecting potential constructibility and time-space conflicts. However, this 4D model would not be acceptable for analyses where exact geometric configurations must be represented in the 3D CAD model (e.g., structural analysis).

To extend the applicability of the 4D model for various analyses, exact geometric configuration must be represented in the 3D CAD models. In cases where templates cannot be used and geometric precision is of utmost priority, all components of the 3D

CAD model need to be drafted from its original 2D drawings. However, drafting all components of the 3D CAD model using the original components in the 2D drawings can be time-consuming. This is because components of a building drawn in separate 2D drawings, different scales, and individual viewpoints must be imported and merged into a single 3D drawing. For example, if we had used the original 2D drawing when inserting the windows into the site cast panels, the scale and viewpoint of the window drawing would have to be changed to insert it into the site cast panel. Repetition of such a process for each component of a building can be very time-consuming and labor-intensive work. Future CAD tools should allow users to predefine the scale and viewpoint of the 3D CAD model and automatically convert imported components into these settings. These functionalities will allow users to view and manipulate the components in the 2D drawings at the same scale and viewpoint and manually insert all components into a single 3D CAD model. Saving customized components as templates in the template library of ArchT could also allow users to store geometric information of components and use them easily for future uses or for alterations to the 3D CAD model. Such improvements will allow easier generation of 3D CAD models using original components in the 2D drawings.

Another method of facilitating 3D CAD model generation would be to build the 3D CAD model in the design stages of the project (Collier, 1995). If the designers built the 3D CAD model as part of the design, they would benefit from having the model to design with, as well as providing a tool for the general contractor and other subcontractors during the building of the structure. Furthermore, the designers would become thoroughly familiar with the 3D aspects of the design and building the 3D CAD model together with the construction planners could eliminate unrealistic design issues.

Lessons learned

As the 3D CAD model drafting stage is the most time-consuming process, better CAD tools must be developed to make this process easier and faster. With current CAD tools, users can expedite the 3D CAD model generation process by using preset templates to represent components in the 3D CAD model. However, for the 4D model to be used for a wide range of analyses, exact geometric configuration of the components need to be drafted. Therefore it is important for users to decide upon the purpose of the 4D model as it dictates the level of geometric accuracy of the 4D model's components.

Future CAD tools should allow users to automatically convert all 2D drawings into a uniform scale and viewpoint and also customize and save certain components as templates. These improvements can enable users to build the 3D CAD model using accurate geometric configuration of the components and at the same time reduce the amount of work-hours.

Building the 3D CAD model in the design stages of a project can allow faster generation of the schedule for construction, enhance collaboration between designer and planner, ultimately resulting in a more realistic and feasible design.

4.2.2 Manipulation of the 4D model

i) Manipulating 4D content in a single environment

The 4D tool does not allow the 4D content to be manipulated in a single environment. To make changes either in the 3D CAD model or the schedule, the user has to go back to the schedule application or AutoCAD drafting tool to make alterations (section 3.7). This makes it difficult to associate the 3D CAD component and the related schedule activities as they have to be configured individually in separate applications.

Current 4D tools do not allow the planner to interact with both the CAD and schedule information within one 4D environment. This in turn makes it cumbersome and time consuming to generate alternative scenarios by adding components to the 3D CAD model or activities to the schedule.

Solution - Collaborative 4D CAD

The 4D model for the case study was constructed using an existing 4D tool (Plantspace 4D Visualization Toolkit) to associate the temporal aspects (sequenced construction activities) with the spatial aspects (3D CAD components or entities) of construction and thereby visually simulate the project sequence. The resulting 4D model has been cited as *Visual* 4D CAD (McKinney et. al, 1996) by the Center for Integrated Facility

Engineering (CIFE) community at Stanford University. Thus far, two distinct generations of 4D CAD have been defined – Visual 4D CAD and Collaborative (or CIFE) 4D CAD. The first generation encouraged further exploration and helped to formulate objectives for the current Collaborative 4D CAD effort.

The research prototype *Collaborative* or *CIFE* 4D CAD, allows planners to 'interactively' generate CAD, schedule, and 4D content within one environment. This prototype is built on AutoCAD and linked to a knowledge-based engineering system, Design++ (Design Power 1995). The CIFE 4D CAD prototype links a 3D graphical model in AutoCAD to a symbolic model in Design++. The planner can open and edit the 3D CAD model, generate or edit the schedule information, and associate CAD entities with construction activities within the CIFE 4D CAD environment. Consequently, the planner has access to all of the 4D content, the 3D CAD geometry, the schedule information and their associations, within one 4D environment. With CIFE 4D CAD, the planner can redesign, re-sequence, or re-associate CAD geometry with construction activities to quickly develop alternative design and construction sequences (McKinney et. al, 1996).

Lessons learned

Collaborative or CIFE 4D CAD allows the user to manipulate the 4D content in a single application which obviates the need for external data to be imported into a 4D simulation application. This allows users who are familiar with CAD drafting techniques to generate 4D models by learning additional functionalities directly in AutoCAD, instead of having to learn a completely new application. With CIFE 4D CAD, users can generate alternative 4D scenarios by adding CAD components in the 3D CAD model or activities in the schedule directly in the AutoCAD application.

ii) Generating multi-leveled 4D models

Another limitation restricting the flexible use of the 4D model is the 4D tool's inability to generate multi-leveled 4D models. The 4D tool (Plantspace 4D Visualization Toolkit) our research team used, allowed us to build 4D models that represented only one perspective of the project. Consequently, we needed to coordinate the level of detail of the design and schedule before the 4D model was built. Other 4D tools, such as the 4D Planner developed by the Bechtel Corporation (Williams, 1996), allow users to create 4D models at two separate levels of detail by breaking up each activity into sub-activities and asking users to choose the display detail. However, in a construction project, it is more than likely there will be more than two participants who need to view the 4D model at different levels of detail. Because current 4D tools only build 4D models at one or two levels of detail, this hinders the collaboration of general contractors and subcontractors, who work towards the same goal, but at different levels of detail.

A good example is the response of the project managers after they had viewed the final model of the McWhinney project.♦ The project managers had initially requested the 4D model to focus on the interior components of the building, so they would be able to detect possible problems and avoid them when constructing the two later buildings.

Thus, they had provided us with a master schedule that had placed more emphasis (i.e., greater detail) in the MEP systems. However, the project managers also wanted to use the model to show the exterior components' sequence to their client. Because the 4D model reflects the detail of the schedule, it did not adequately show the sequencing of these exterior components (section 3.7). To convey the sequence to the client, the level of detail for the exterior components would have to be changed, which means that the 3D CAD models would have to be redrafted, the components re-linked to their activities, and the schedule activities re-sequenced.

The project manager's response to the final 4D model not only reemphasizes the importance of initial decisions made during the 4D model's development process, but also shows the difficulty in generating multi-leveled 4D models through current 4D tools.

Solution

A method of developing multiple levels of detail for a single 4D model must be developed so that multiple participants of a project can use the model to mutually

♦ Our research team sent the JSM files to the project managers of the McWhinney project via e-mail. They were able to set up and view the 4D model through the same 4D-simulation application installed on their computers. This allowed our team to communicate with the project managers through telephones while simultaneously viewing the 4D model from separate locations.

collaborate, and also use the model for individually different purposes.

To generate multi-leveled 4D models, 4D tools need to support multi-representation of 3D CAD entities (i.e, representing a 3D CAD component in multiple levels of detail) in the 3D CAD model, and also support the generation of schedules at multiple levels of abstraction. The next two sections address how the research participants of the CIFE community have approached these two issues.

i) generating multi-leveled product models (multi-representation of 3D CAD entities)

One scenario of developing multi-leveled 3D CAD models would be for the participants of a project to build separate 3D CAD models at various levels of detail and subsequently 'merge' these models into a single 3D CAD model. For example, the construction planner or general contractor breaks the building into several packages (e.g, foundation, structural steel, roof etc.). Each subcontractor responsible for a specific package would be supplied with the relevant design documentation to build his or her own 3D CAD model. While the construction planner may represent the roof of a building by a single surface entity (at high level of detail), subcontractors may represent the roof in greater detail by modeling the roof as a combination of sheet metal, insulation, and stucco CAD entities (at lower levels of detail). The 3D CAD models constructed by the individual subcontractors can then be merged into the project 3D CAD model built by the construction planner.

Generating and coordinating multi-representations of CAD-based planning information requires 'mating' mechanisms (Nnaji et.al 1993) to semantically relate one feature of a component to another feature of a component. Such mating mechanisms could manage the coordination and 'merging' of the individual 4D models.

Such a 3D CAD model will allow the viewing of 3D CAD entities at multiple levels of detail or at various viewing scales. For example, a component in the 3D CAD model may be represented as a single entity in 1:100 scale, and represented as multiple entities at 1:20 scale.

Mckinney et. al (1996) refer to this representation of multiple forms of a building component as *multiple domain-specific views*.

ii) generating hierarchical process models (Construction Method Modeler)

Researchers at CIFE have developed a computer-aided process planning system (CPPS), Construction Method Modeler or CMM. CMM generates process acitivities by employing a hierarchical construction planning process. The hierarchical construction planning process uses computer-interpretable construction method model templates (CMMT) that capture and formalize general construction planning knowledge (Fischer and Aalami 1996). To create a construction schedule or process model, users select the methods that apply to their project from CMM's method library. CMM then applies the selected methods to the design-centric product model and generates the activities specified in the method models, sequences the activities, and links them to their corresponding components in the product model. By choosing further methods, these activities can also be elaborated (refined) into more detailed (lower level) activities, which are again sequenced and linked to their corresponding components of the product model. The interaction at different levels of detail of the construction method model and the product model generates a hierarchical process model, which allows activity networks (schedules) to be generated at multiple levels of detail.

CMM supports the dynamic transition between levels of abstraction of product, process, and method models. They enable the generation of schedules in early project phases when only a schematic product model is available and in later phases when more detailed project descriptions are available. Methods, schedules and 4D models developed in the early phases are thus reusable and form the basis for later schedules. A scheduler simply adds construction method models at the desired level of detail.

Lessons learned

Current 4D tools do not support the generation of multi-leveled 4D models which restricts their usability to a specific class of project members. To generate multi-leveled 4D models, 4D tools must be developed which allow the viewing of multi-leveled components at differing scales and which support the generation of schedules at various levels of detail.

3D CAD and product modeling tools must be developed which can 'merge' 3D CAD models individually developed by the general contractors and subcontractors and support multiple domain-specific views.

CMM allows schedules to be generated at multiple levels of detail by producing a hierarchical process model through the information gained from the product model and related method models. By using CMM, users can transform a design-centric product model into a production-centric 4D model.

4.2.3 4D Model analysis

i) Limitations in detecting potential problems through 4D model analysis

In our case study, we detected several problems not anticipated by the project managers when they were creating the schedule. We detected the lack in the detail of the schedule to adequately portray project sequence, the omission of components that existed in the 2D drawings but were not explicitly scheduled for installation, contradictions in the logic of the schedule, and accessibility issues.

Although significant problems in the schedule, such as these, can be detected through Visual 4D CAD, the problems can only be detected by the viewer. In other words, the problems detected are likely to vary according to the level of expertise and experience of the individual viewer. Visual 4D CAD places the burden of recognizing a potentially troublesome situation entirely on the viewer (McKinney et al. 1998).

Functionality improvements of current 4D tools can promote the detection of problems in the 4D model. The inclusion of the original bar chart schedule has been implemented in other 4D tools, such as the 4D Planner by the Bechtel Corporation (Williams, 1996). The 4D Planner allows users to better follow the simulation of the construction sequence (refer to section 3.8). Annotation tools can allow planners to mark points of emphasis in the 4D model and relate the information to viewers of the 4D model. Although such functional improvements do support the viewer in detecting potential problems, it still requires the user to infer and detect these problems.

Solution

The next step in the development of 4D tools is to enable 4D tools to 'recognize' problems in the construction sequence and relay this information to the viewer. A knowledge-based system must be developed so that 4D tools can reason whether there exist omissions of components or contradictions in the schedule and alert users of these problems. For 4D tools to conduct such analyses, 4D tools must be able to recognize the attributes and behaviors of the individual components of the 4D model. In other words, a knowledge-based 4D tool must be able to recognize the characteristics (e.g., its name, length, width, material etc.) of the components, recognize the relationships components have with other components (e.g., supported by, connected to, etc.), and subsequently reason whether these relationships are logically sound. This in turn means that each component of a 4D model must be assigned their individual attributes and behaviors (i.e., a semantic 4D model must be generated).

For example, how would next generation 4D tools recognize that the HVAC ducts in phase 2 have been sequenced too early in the schedule because the ducts do not have any support from which to hang on (refer to section 3.5)?

The knowledge-based system needs to recognize the ducts' attributes i.e., its name, length, diameter, etc. It must also recognize the ducts' relationship to other ducts, the roof and other related components of the building. It must also recognize whether the duct needs support or can support other components. In this case, the knowledge-based system must infer that the ducts need support. To do this, the duct component must be assigned as its behavior (or relationship) that it requires support (or hanging-from relationship). The system must then look for components whose function is to support other components, e.g., in our case the roof from which the HVAC ducts hang from. The 4D tool can then notify viewers that a contradiction in the logic of the schedule exists by having conducted such analysis. Therefore the characteristics of a component (or the component type) of a semantic 4D model must include its attribute or form (i.e., length, height, etc.), and its behavior or relationship (i.e., supported by, connected to, etc.) with other components.

As can be seen from the example, each component in the semantic 4D model needs to be assigned their attributes and behaviors for 4D model analyses to be conducted. However, assigning components for an entire construction project can add an extraordinary amount of work in building the 4D model. Future research needs to focus on developing methods of assigning attributes to each component of a 4D model (i.e., standard representation of 4D components), improving functionalities for acquiring and representing behaviors (or relationships) between components, and developing an inference engine to reason the relationships between components.

One solution being explored by the CIFE community is by using standard building components (such as Industry Foundation Class (IFC) standard building components) which uses pre-defined attributes of standard components. Based on these components, the CIFE community is investigating methods to acquire relationships between components through the use of and inference engine, through geometric and knowledge-based reasoning, or through manual assignment of the relationships.

Lessons learned

Users need to detect potential problems in the construction sequence by viewing the 4D model. However, current 4D tools place all the burden of detecting these problems to the user. Although functional improvements can elucidate construction sequence and thereby facilitate the detection of problems, it still requires users to consciously look out for problems without the aid of any computer-based analysis. Next-generation 4D tools need to recognize problems/conflicts and relay the information to users. For 4D tools to conduct such analyses, a semantic 4D model needs to be developed by assigning attributes and acquiring relationships to each component in a project. Future research must focus on developing a knowledge-based system that can acquire relationships between standard building components, and convey the hidden conflicts by deciphering incorrect component relationships.

ii) Limitations in detecting time-space conflicts and recognizing cost and productivity issues

Although Visual 4D CAD allows users to detect some time-space conflicts (section 3.5), again the burden of detecting such problems is placed on the viewer. Furthermore, other parameters such as crew size, equipment size, workspace requirements and safety zones must also be considered for such analyses, which makes it difficult to detect time-space conflicts by viewing the 4D model alone. Without careful consideration of time-space conflicts, project managers risk the danger of producing optimistic schedules by sequencing activities concurrently, or generating cost estimates based on too high productivity rates. Because CIFE 4D CAD captures knowledge about building components and schedule activities, the resulting symbolic or intelligent 4D model forms a basis for cost and productivity analysis. If properly represented, the information necessary to build a 4D visualization could support cost estimating and many other kinds of analyses of a design-build scenario. (Akinci et al. 1997).

Solution

Researchers at CIFE have built on CIFE 4D CAD to develop the 4D Work Planner. The 4D Work Planner 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. Akinci et. al have expanded the capabilities of existing 4D tools (Plantspace Schedule Simulator) by graphically and symbolically representing workspace requirements to support the user in identifying time-space conflicts for each activity. The 4D Work Planner system consists of two distinct parts: (1) 4D Simulator and (2) Productivity Modifier and Cost Calculator. Using project specific information (3D model and CPM schedule) together with workspace requirements and 4D interference-checking algorithms, the 4D Simulator identifies the time-space conflicts of activities existing in the schedule. The 4D Simulator highlights the conflict areas while simulating the construction of the 3D model over time. Once conflicts have been detected, the user has the option of changing the schedule duration or modifying the productivity rates for the conflicting activities. The Productivity Modifier and Cost Calculator makes cost calculations and schedule adjustments by utilizing a crew database, productivity modifier matrix, and productivity modifying algorithms.

Lessons learned

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. 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.

4.3 Introduction to Alternative interfaces

The desktop engineering interface (i.e., monitor- and keyboard-based interface) through which the 4D model is viewed does not provide a suitable environment for enhancing collaboration amongst multiple participants. Viewing the 4D model through the desktop environment restricts the simultaneous participation of a project team. Only one member of the team can manipulate the 4D model while others have no access to the model and therefore become passive spectators rather than active participants.

After our group had decided on a change to the 4D model, we needed to refer back to both the schedule and the 3D CAD files in their separate applications to update the changes. Also, if we had several alternatives for a particular problem, each alternative scenario had to be painstakingly built one at a time and these alternatives could only be compared after every alternative had been remodeled. Such restrictions in the generation of alternative scenarios limited our ability to evaluate the problem, discuss alternatives and formulate the best solution by viewing these alternatives through the 4D model. For the 4D model to be used as a collaboration tool amongst multiple participants in a meeting environment, users must be able to rapidly generate and view the various alternative solutions.

Multiple participants of a project use several domain-specific applications to generate discipline-related documentation and evaluate alternatives. While each of these documentations and evaluations have been generated by a stand-alone computer program, the team typically does not have access to the software in a single platform or interface which prohibits project participants from making decisions or evaluations with respect to multiple criteria in real time.

The desktop interface also does not provide true 3D rendering (i.e., although the 4D model is built in 3D, it is viewed in a 2 dimensional, non-immersive environment) of the 3D CAD models, and input devices such as the keyboard and mouse does not support intuitive manipulation of the graphical objects.

In response to these limitations, the CIFE community has studied new interfaces, specifically the Responsive Workbench and the Information Mural, in the efforts of developing a virtual production planning environment.

4.3.1 The Responsive Workbench

The *Responsive Workbench (RWB)* is a 3D interactive graphics system with a tabletop metaphor originally developed in 1993 by Wolfgang Krueger and pioneered by GMD.♦ Computer-generated stereoscopic images are projected onto a horizontal tabletop display surface via a projector and mirrors system (*Fig 4.2*). The users of the workbench wear shutter glasses to observe the 3D effect and interact with the 3D object in a semi-immersive environment (*Fig 4.2*). A 6DOF tracking system tracks the users' head, allowing the correct perspective to be used when rendering the environment. A pair of gloves and a stylus, also tracked by the system, can be used to interact with objects in the tabletop environment.

Users can use the Responsive Workbench as an alternative interface to viewing 4D models. The Responsive Workbench can display 3D CAD models in true 3D and also allows the assembly and disassembly through direct manipulation of the components. This functionality offers a good basis for the development of a virtual production

♦ German National Research Center for Information Technology.

modeling environment. The tabletop display allows users to view the construction of the components and the related schedule sequence in one integrated environment. The workbench affords the architect, engineer and construction planner an opportunity where they can interact and communicate their respective knowledge input in a single environment. I have already stated in chapter 2 that the 4D model promotes interaction amongst the AEC members as it forces the designer and construction planner to resolve design and construction issues/conflicts while building the 3D CAD model. Viewing the 4D model through the Responsive Workbench allows them to generate rapid alternatives, immediately detect problems and appreciate the other's perspective. It also provides them with a physically larger space to work on (as compared to the desktop environment), and therefore can view and manipulate the 3D CAD model and schedule bar chart on the table (*Reference*: IEEE Computer Graphics and Applications, *Collaborative Production Modeling and Planning* Fröhlich et al., 1997).

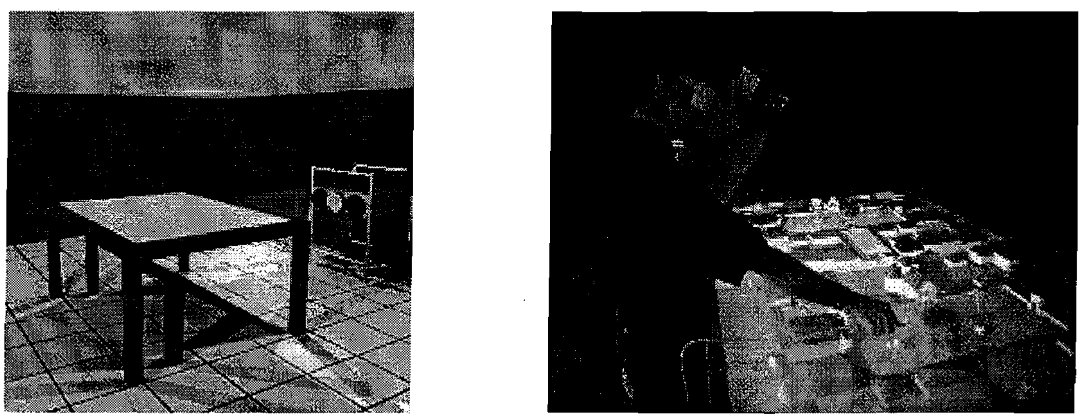


Fig 4.2 RWB system components and picture showing multiple participants interacting through the RWB

4.3.2 Information Mural

The *Information Mural* (*IM*) is a new interface envisioned by the Computer Science Department at Stanford University who have recognized the limitations of the desktop environment in accessing and managing large stores of information, and in supporting the activities of small groups working together. Whereas the first generation of alternative information appliance designs were focused on enhancing the mobility of the appliances (i.e., the rapid development of laptops and personal digital assistants (PDA's)), the next generation of development is focusing on large-format displays embedded in work environments. The Information Mural is a large format, (six by two feet), high-resolution display surface driven by an array of high performance 3D graphics accelerators (*Fig 4.3*). Coupled to this display is a set of laser pointers and other manipulative devices that allow members of a group to directly manipulate the information on the display.

In contrast to most project screens, which require users to view the displayed information at a certain distance from the surface and are thus used mainly as presentation tools, the Information Mural allows the direct manipulation of graphical objects on the display surface because of the high resolution of the display.

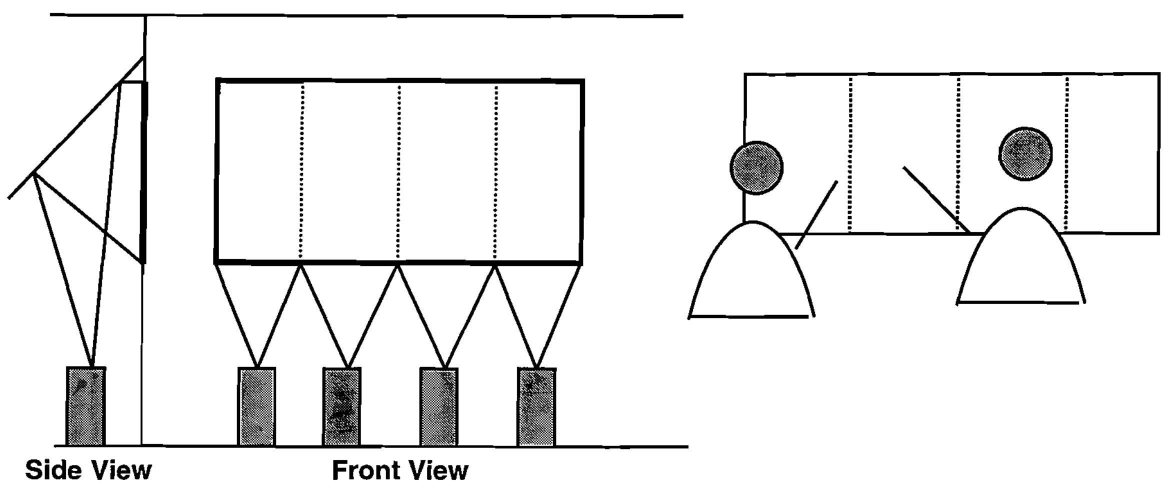


Fig 4.3 Information Mural configuration and multiple participants interacting through the Information Mural

The ability to allow multiple users to work concurrently on a shared scenario makes the Information Mural an ideal interface on which multiple members in a meeting can collaborate and interact (*Fig 4.3*).

The large screen provides an opportune environment for construction design and planning where decisions must be made by multiple people using multiple criteria. The IM allows several views of multiple applications that previously could only be viewed independently, supports intuitive graphical object manipulation, and interaction between the multiple applications.

The CIFE community envisions a virtual project environment where professionals would be able to interact with 3D CAD models on the Responsive Workbench in the center of a room and with other project information on the Information Murals. These interfaces alleviate users from having to view project planning information (such as 4D models, project schedules, resource histograms, organization charts and many other project related documents) and their applications through a single desktop display. Also the participants can view several alternative scenarios concurrently, which allows them to formulate the best scenario by comparing multiple options. The application of the RWB and IM provide a virtual production planning environment where multiple participants can collaborate in a single environment and make design and planning decisions with the benefit of being able to access and manipulate all relevant information.

4.4 Summary

Table 4.3 summarizes the limitations of current 4D tools and reviews the solutions previously discussed in this chapter.

Today's 4D tools require users to invest significant amount of time and effort in generating and analyzing the 4D model, but do not support users in generating alternative scenarios or multi-leveled 4D models. To facilitate the generation of 4D content, I introduced steps that need to be taken to properly prepare schedule data, and also investigated possible methods to automate the process. From our case study, we discovered the 3D CAD model drafting stage to be most time-consuming and labor-intensive. Functional improvements of CAD tools and development of 3D CAD models in the design stages of a project can expedite and facilitate 3D CAD model generation.

Current 4D tools require the schedule and CAD data to be manipulated in separate applications. This makes generation of alternative scenarios cumbersome. The research prototype CIFE 4D CAD allows users to manipulate the 4D content in a single environment whereby facilitating alternative scenario development. Current 4D tools only allow one or two perspectives to be shown through a single 4D model, although multiple participants require the 4D model to be viewed at multiple levels of detail. To produce multiple domain-specific views of the 4D model, mating mechanisms are required which can manage the coordination and 'merging' of individual 4D models. CMM allows schedules to be generated at multiple levels of detail by producing a hierarchical process model through the information gained from the product model and related method models. By using CMM, users can transform a design-centric product model into a production-centric 4D model.

4D models developed with current 4D tools convey spatial aspects of components with the temporal and logical aspects of schedule information. However, these 4D tools place the responsibility of detecting contradictions or conflicts in the schedule on the viewer, and do not convey such problems to the viewer by conducting knowledge-based

		Limitations of Visual 4D CAD & current 4D tools	*Solutions*
Development of 4D content	➢ *Preparation of schedule data*	• Does not support user in data preparation	• Use guidelines • Requires automation
	➢ *Generation of 3D CAD models*	• Requires time-consuming and labor-intensive input from user	• Requires automation of scale and viewpoint conversion, saving customized templates • Generate 3D CAD model in design stage
Manipulation of the 4D model	➢ *Manipulation of 4D content*	• Does not support in manipulating 4D content in single environment	• ***CIFE 4D CAD:*** allows manipulation of 4D content in AutoCAD application
	➢ *Generation of multi-leveled 4D models*	• Does not allow only multi-perspectives of project	• ***Mating mechanisms:*** coordinates 4D models at multiple levels • ***CMM:*** generates multi-leveled 4D production models
4D Model analysis	➢ *Limitations in detecting potential problems*	• Places burden of problem detection on the user	• ***Knowledge based system:*** uses semantic 4D model to infer potential problems and relay information to users
	➢ *Limitations in detecting time-space conflicts and cost & productivity issues*	• Places burden of detecting time-space conflicts on the user	• ***4D Work Planner*:** quantifies impact of time-space conflicts and reflects corresponding impact in schedule and cost estimate

Table 4.3 Limitations of Visual 4D CAD and current 4D tool vs. proposed solutions

computer analyses. The next generation 4D tools must be able to detect potential problems/conflicts in the construction sequence and convey such information to the users. The 4D Work Planner can detect time-space conflicts and based on these findings, conduct cost and productivity analyses. 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.

The CIFE community has explored alternative interfaces such as the RWB and IM to view and manipulate the 4D model. Using these interfaces, the CIFE community envisions a virtual project planning environment where project members can interact and collaborate to make design and planning decisions with the benefit of being able to access and manipulate all relevant information.

Chapter 5. Summary and Conclusions

5.1 Summary

This thesis examined the use of 4D models as an alternative method to CPM networks and bar chart schedules in designing, planning and communicating the schedule sequence of construction projects. The paper addressed the advantages of using the 4D model as an alternative planning tool in the AEC industry and also discussed the limitations of current 4D models and 4D tools in developing and analyzing the construction sequence.
Traditional scheduling tools embraced by the AEC industry produce CPM schedules, which do not effectively convey the various assumptions and thought processes involved in developing them. Because 4D models integrate the spatial, temporal and logical aspects of construction planning information, misinterpretation of the project sequence can be minimized. Better comprehension and communication of the schedule through the 4D model enables project participants to detect unforeseen problems previously overlooked using CPM schedules. By formalizing design and construction information, the 4D model can promote interaction and collaboration between designers and builders. Because the 4D model conveys both geometric and planning information, designers and builders can interact and collaborate through a common medium. The 4D model also allows additional analyses concerning cost, productivity, safety and resource allocation to be conducted which can support the development of realistic schedules and cost estimates.
Developing the 4D model involved categorizing the activities of the original schedule, creating 3D CAD models from 2D drawings, and creating relationships between the schedule activities with the 3D CAD model components in a 4D-simulation application. Through the 4D model we were able to detect various problems unanticipated by project managers who used CPM schedules in their project. However, limitations in the flexibility and applicability of current 4D models and 4D tools restricted the detection and analysis of many other constructiblity issues.

Improvements to current 4D models and 4D tools must be made to expedite the generation of 4D models and to aid users in conducting 4D model analyses. Automating schedule data preparation and building the 4D model in the design stages can expedite 4D model development. Using CIFE 4D CAD and CMM can support the generation of alternative scenarios and multi-leveled 4D models. Functional improvements such as the insertion of CPM schedules, component lists, temporary components and annotation tools can aid users in viewing the project sequence and detecting potential problems/conflicts. The next generation of 4D tools must be able to recognize these problems and convey the information to users. This can relieve users of having to consciously look out for problems without the aid of computer-based analysis tools. The use of alternative interfaces should allow users to view and manipulate multiple discipline-specific applications in a single medium. This, in turn, allows them to resolve problems while considering multiple aspects about a project.

Through this paper I have provided a guideline to the current level of technology available in creating and analyzing 4D models. I have emphasized improvements of 4D CAD that are most critical for it to convey and analyze construction planning information.

The realization of these improvements will allow 4D CAD to evolve into a more economically viable and technically user-friendly tool. This in turn can reduce the reluctance industry members may have towards using 4D models, and authenticate the 4D model's use as a project planning tool in future construction projects.

5.2 Conclusions

Some members of the AEC community may be hesitant in using 4D CAD as a project planning tool. One of the reasons for the initial reluctance could be attributed to the additional up-front costs in developing and analyzing the 4D model. Because of these initial front-end costs, individuals may only feel the need of 4D models for large and complex, high-tech projects, where the overhead costs could absorb these costs as planning costs. The reason behind this perception is that users may view 4D models essentially as presentation tools used for projecting construction sequence to non-professionals such as clients. In our case study, the project managers wanted to use the 4D model primarily as a presentation medium for prospective and current clients. They wished to use the 4D model as a presentation tool rather than a planning tool. Using 4D models as a presentation tool to clients can be a positive first step in raising the awareness of the new technology and allowing the AEC community to gradually accept its usage. However, its usage must not be confined to presentations. The 4D model's true value lies in detecting problems and clearly relaying these problems to project participants. If its usage is restricted to that of a presentation tool, the 4D model will simply remain as a fixed overhead cost and users will not be able to reap its full benefits.

The widespread use of 4D models can also be hampered by the current criteria used in awarding contracts and in selecting subcontractors. Construction contracts are often awarded to the lowest responsible bidder. This practice does not differentiate between subcontractors using innovative technologies and other subcontractors using conventional planning tools. Indeed, the construction methods used for project execution is the contractor's sole responsibility on which clients or A/E's cannot dictate, let alone the project management tools contractors may use. Furthermore, the use of such new technology does not necessarily guarantee the quality or cost savings to the project. However, it is undeniable that using technological innovations such as the 4D model can help in *preventing* unanticipated problems during actual construction, which is one of the main causes for cost overruns and ensuing disputes between clients and contractors. Current contracting practices still place too much emphasis on the lowest cost, and not on who can deliver the best product while ensuring cost, time and quality of the final facility through the use of effective planning tools.
Such contracting practices can result in the selection of individual subcontractors using different project planning tools for the same project. However, for the 4D model to be used effectively, ideally all members (or at least the majority) of the project team must use it as a common medium to generate a uniform and continuous flow of communication. For example, I was involved in another case study which was to

investigate practices used by Nielson & Dillingham Construction co. in managing subcontractor coordination. The project manager of the project, Mark Ebner, wanted to use CAD applications to coordinate with his/her subcontractors, but this was not possible because one or two subcontractors still used paper-based 2D drawings. Therefore when using new technologies, all participants must be able to use it and not just a selected group of participants in the project hierarchy. The lack of consistency in project planning applications amongst participants will prohibit the effective communication and collaboration between them.

The selection criteria for awarding contracts should place more emphasis on the lowest bidder who can also ensure the time, cost and quality of the project. This can be achieved by using 4D models to anticipate problems and minimize the impact of unproductive changes during construction. The incorporation into the selection criteria can encourage contractors to explore new technologies such as the 4D model. Selecting subcontractors enthusiastic about new technology or training them to use 4D models as planning tools is critical for both the proliferation of 4D CAD and also for it to be used effectively.

For all members of the AEC industry to embrace the 4D model in planning and coordinating the project, each discipline professional must be able to benefit from the 4D model in one way or another. For example, designers may be reluctant in taking the responsibility of constructing 4D models or 3D CAD models for the sole purpose of communicating with contractors or for viewing constructiblity issues. However, if the 4D model can also be used to conduct design related analyses such as structural analysis, this would provide the incentive for designers to build the 4D model in the early stages of the project with the collaboration of contractors/planners. The designer can provide the design information and the builder can provide the planning information. This will naturally induce collaboration and feedback between the two entities. All participants involved should benefit from the 4D model by helping in developing and analyzing the 4D model.

As the example shows, the development of the 4D model involves the collaboration between the designers and builders. However, this is in conflict with most project delivery systems used by the AEC industry which is typically characterized by its linear and fragmented facility delivery processes.

In this respect, incorporating 4D models in design-build projects may be the next step in the proliferation of this relatively new technology. Design-build projects allow a single entity to be responsible for the design and construction of a project, thereby reducing the adversarial relationships of the designer and builder. Design-build projects also tend to be place more emphasis on meeting the quality and time requirements of the project. Design-build projects encourage cooperation between designers and builders, and also try to ensure that unforeseen delays are accounted for beforehand. The 4D model seems to be a suitable planning tool for such a delivery system as it must be built together by project participants, and allows better detection of unanticipated problems.

Future improvements of the 4D model and 4D tool alone cannot guarantee its use as the next generation planning tool in the AEC industry. Advocates of this technology must inform the AEC community of its benefits and direct and stimulate research into this area. In response, the AEC community must be willing to accept new innovative technologies and be aggressive in exploring alternatives to conventional planning tools.

5.3 Acknowledgements

We thank research participants Winnie Hung, Steve Long and Randy Wiederhold for helping us develop the 4D model and provide valuable critique for the analysis of the 4D model. Rich Creveling, project manager of the McWhinney project deserves special thanks for providing us with the research material. Finally, we thank the members of the CIFE community for their unbridled support and intellectual insight into our project.

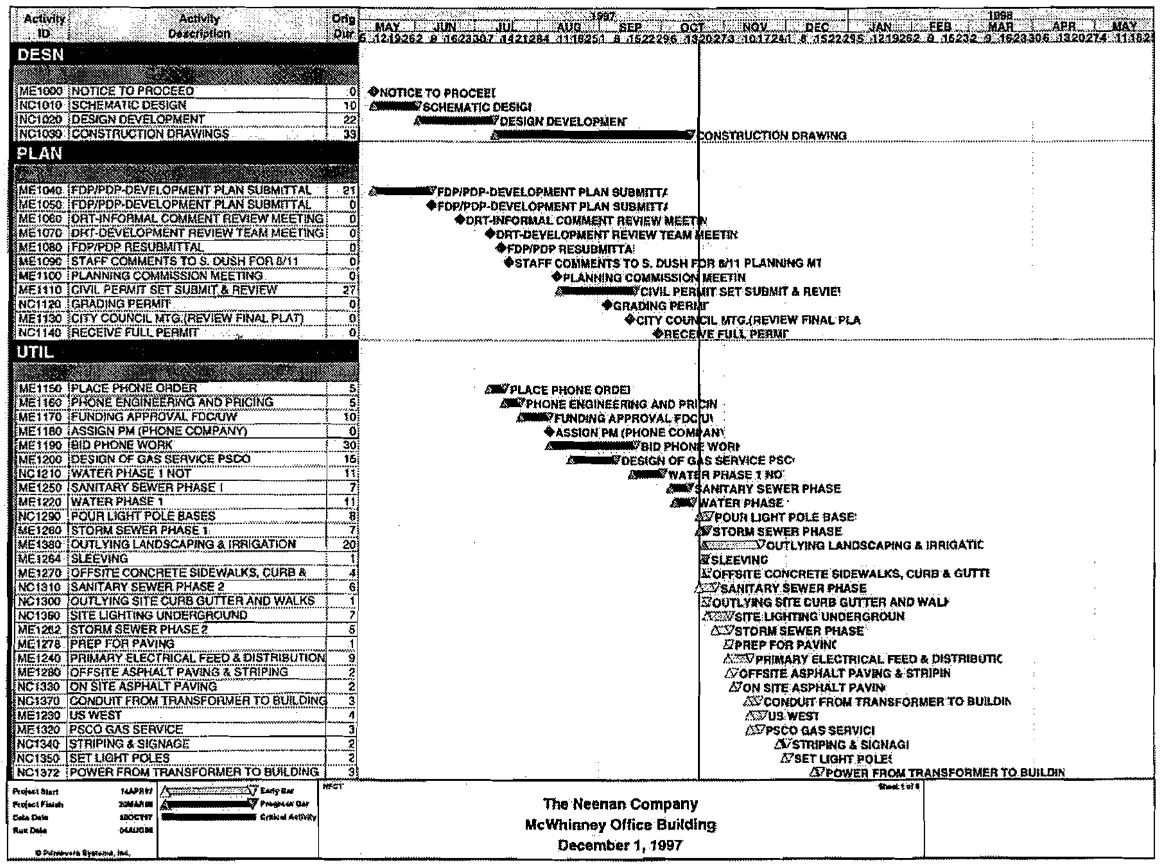
Appendices

Appendix A: Master Schedule

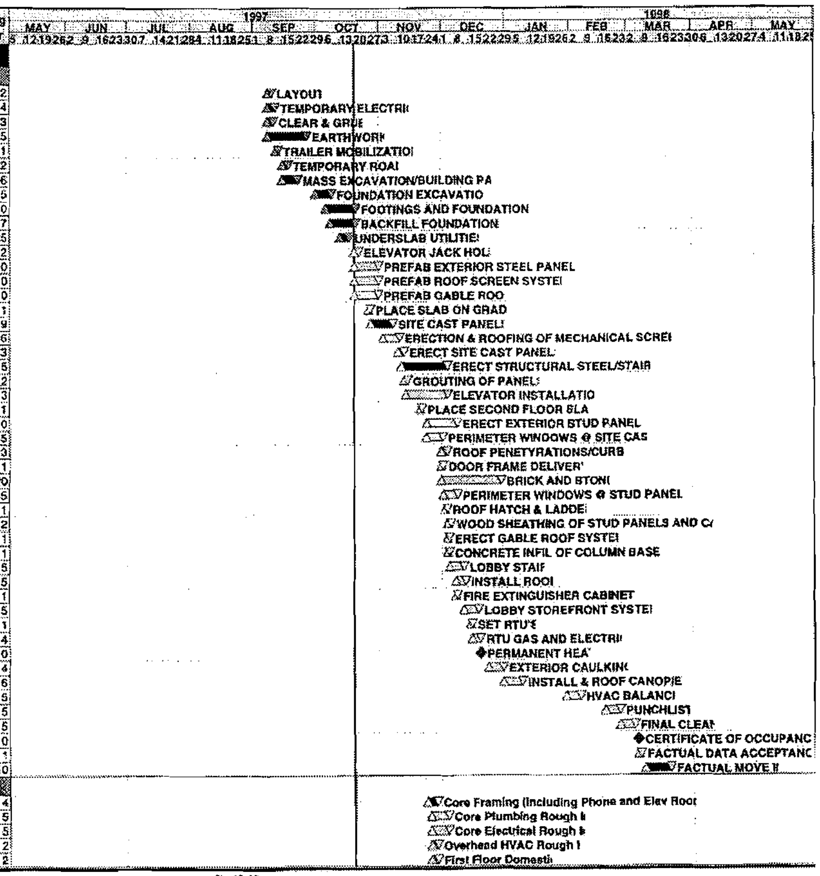
Appendix B-1: Related Component Categorization

Appendix B-2: Component Breakdown

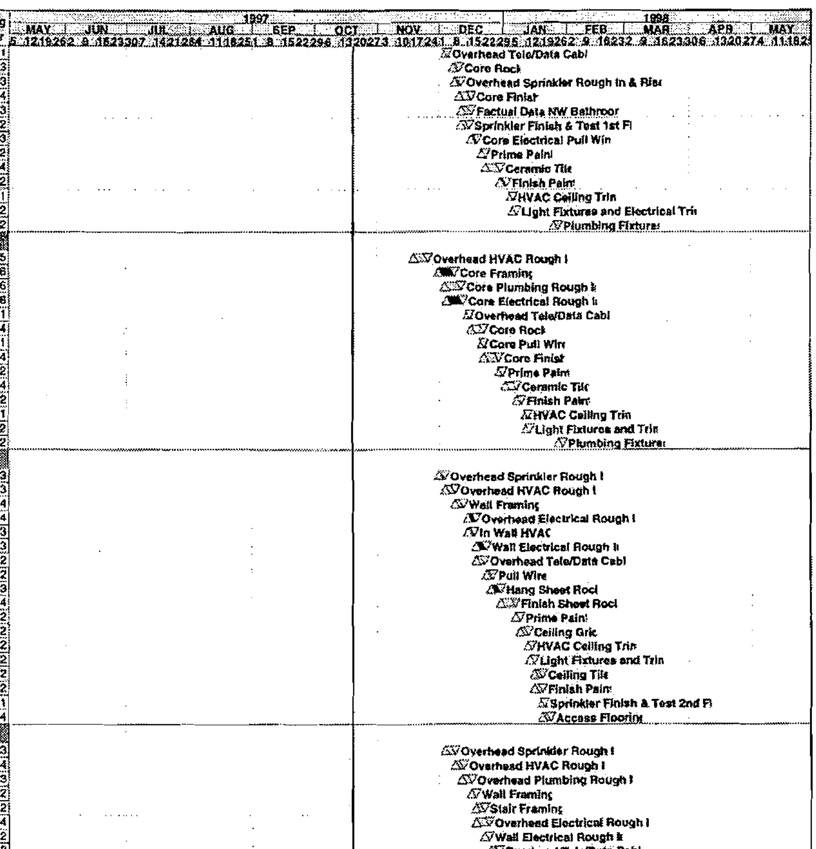
Appendix A: Master Schedule



Activity ID	Activity Description	Orig Dur
BLDG		
CORE		
NC1390	LAYOUT	2
NC1410	TEMPORARY ELECTRIC	4
NC1420	CLEAR & GRUB	3
NC1430	EARTHWORK	15
NC1440	TRAILER MOBILIZATION	1
NC1400	TEMPORARY ROAD	2
NC1450	MASS EXCAVATION/BUILDING PAD	6
NC1460	FOUNDATION EXCAVATION	5
NC1470	FOOTINGS AND FOUNDATIONS	10
NC1510	BACKFILL FOUNDATIONS	7
NC1500	UNDERSLAB UTILITIES	5
NC1490	ELEVATOR JACK HOLE	2
NC1520	PREFAB EXTERIOR STEEL PANELS	10
NC1540	PREFAB ROOF SCREEN SYSTEM	10
NC1530	PREFAB GABLE ROOF	10
NC1550	PLACE SLAB ON GRADE	1
NC1560	SITE CAST PANELS	9
NC1710	ERECTION & ROOFING OF MECHANICAL	6
NC1580	ERECT SITE CAST PANELS	3
NC1570	ERECT STRUCTURAL STEEL/STAIRS	15
NC1590	GROUTING OF PANELS	2
NC1910	ELEVATOR INSTALLATION	13
NC1020	PLACE SECOND FLOOR SLAB	1
NC1650	ERECT EXTERIOR STUD PANELS	10
NC1810	PERIMETER WINDOWS @ SITE CAST	5
NC1610	ROOF PENETYRATIONS/CURBS	3
NC1980	DOOR FRAME DELIVERY	1
NC1700	BRICK AND STONE	20
NC1812	PERIMETER WINDOWS @ STUD PANELS	5
NC1630	ROOF HATCH & LADDER	1
NC1720	WOOD SHEATHING OF STUD PANELS AND	2
NC1660	ERECT GABLE ROOF SYSTEM	1
NC1850	CONCRETE INFIL OF COLUMN BASES	1
NC1900	LOBBY STAIR	5
NC1760	INSTALL ROOF	5
NC2110	FIRE EXTINGUISHER CABINETS	1
NC1814	LOBBY STOREFRONT SYSTEM	5
NC1860	SET RTU'S	1
NC1870	RTU GAS AND ELECTRIC	4
NC1940	PERMANENT HEAT	0
NC1990	EXTERIOR CAULKING	4
NC2030	INSTALL & ROOF CANOPIES	6
NC2260	HVAC BALANCE	5
NC2280	PUNCHLIST	5
NC2300	FINAL CLEAN	5
NC2290	CERTIFICATE OF OCCUPANCY	0
NC2320	FACTUAL DATA ACCEPTANCE	1
NC2330	FACTUAL MOVE IN	10
PHS1		
103	Core Framing (Including Phone and Elev Room)	4
115	Core Plumbing Rough In	5
120	Core Electrical Rough In	5
130	Overhead HVAC Rough In	2
116	First Floor Domestic	2



Activity ID	Activity Description	Orig Dur
140	Overhead Tele/Data Cable	1
104	Core Rock	3
110	Overhead Sprinkler Rough In & Riser	3
105	Core Finish	4
117	Factual Data NW Bathroom	3
170	Sprinkler Finish & Test 1st Flr	2
122	Core Electrical Pull Wire	3
155	Prime Paint	2
164	Ceramic Tile	4
157	Finish Paint	2
175	HVAC Ceiling Trim	1
180	Light Fixtures and Electrical Trim	2
181	Plumbing Fixtures	2
PHS2		
221	Overhead HVAC Rough In	5
203	Core Framing	6
212	Core Plumbing Rough In	6
215	Core Electrical Rough In	8
240	Overhead Tele/Data Cable	1
204	Core Rock	4
216	Core Pull Wire	1
205	Core Finish	4
236	Prime Paint	2
257	Ceramic Tile	4
238	Finish Paint	2
248	HVAC Ceiling Trim	1
251	Light Fixtures and Trim	2
252	Plumbing Fixtures	2
PHST		
T100	Overhead Sprinkler Rough In	3
T110	Overhead HVAC Rough In	3
T120	Wall Framing	4
T130	Overhead Electrical Rough In	4
T125	In Wall HVAC	3
T150	Wall Electrical Rough In	3
T140	Overhead Tele/Data Cable	2
T160	Pull Wire	2
T170	Hang Sheet Rock	3
T180	Finish Sheet Rock	4
T190	Prime Paint	2
T200	Ceiling Grid	2
T220	HVAC Ceiling Trim	2
T210	Light Fixtures and Trim	2
T230	Ceiling Tile	2
T240	Finish Paint	2
T250	Sprinkler Finish & Test 2nd Flr	1
T260	Access Flooring	4
PHS3		
310	Overhead Sprinkler Rough In	3
315	Overhead HVAC Rough In	4
312	Overhead Plumbing Rough In	3
322	Wall Framing	2
100	Stair Framing	2
318	Overhead Electrical Rough In	4
320	Wall Electrical Rough In	2
321	Overhead Tele/Data Cable	2



Activity ID	Activity Description	Orig Dur
319	Pull Wire	2
101	Stair Rock	3
324	Hang Sheet Rock	3
102	Stair Tape & Finish	3
327	Finish Sheet Rock	4
330	Prime Paint	2
336	Ceiling Grid	4
345	Light Fixtures and Trim	3
342	HVAC Ceiling Trim	3
348	Ceiling Tile	4
332	Finish Paint	2
351	Floor Covering	3
339	Sprinkler Finish	2
346	Plumbing Fixtures	2
PHS4		
610	Overhead Sprinkler Rough In (+PHS2)	3
615	Overhead HVAC Rough In	5
612	Overhead Plumbing Rough In	1
623	Wall Framing	3
618	Overhead Electrical Rough In	3
200	Stair Framing	2
620	Wall Electrical Rough In	2
619	Pull Wire	2
621	Overhead Tele/Data Cable	2
624	Hang Sheet Rock	4
201	Stair Rock	3
627	Finish Sheet Rock	4
630	Prime Paint	2
202	Stair Tape & Finish	3
636	Ceiling Grid	4
645	Light Fixtures and Trim	3
642	HVAC Ceiling Trim	3
648	Ceiling Tile	4
632	Finish Paint	2
651	Floor Covering	3
639	Sprinkler Finish	1
PHS5		
510	Overhead Sprinkler Rough In	2
515	Overhead HVAC Rough In	3
523	Wall Framing	3
518	Overhead Electrical Rough In	2
521	Overhead Tele/Data Cable	2
520	Wall Electrical Rough In	2
519	Pull Wire	2
524	Hang Sheet Rock	3
527	Finish Sheet Rock	5
530	Prime Paint	2
536	Ceiling Grid	4
545	Light Fixtures and Trim	3
542	HVAC Ceiling Trim	3
548	Ceiling Tile	4
532	Finish Paint	2
551	Floor Covering	3
509	Sprinkler Finish	1
PHS6		
410	Overhead Sprinkler Rough In	3

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Activity ID	Activity Description	Orig Dur
415	Overhead HVAC Rough In	3
418	Overhead Electrical Rough In	2
423	Wall Framing	3
421	Overhead Tele/Data Cable	2
420	Wall Electrical Rough In	1
419	Pull Wire	2
424	Hang Sheet Rock	3
427	Finish Sheet Rock	4
430	Prime Paint	2
436	Ceiling Grid	4
445	Light Fixtures and Trim	4
442	HVAC Ceiling Trim	3
448	Ceiling Tile	4
432	Finish Paint	2
451	Floor Covering	3
439	Sprinkler Finish & Test 2nd Flr.	1
PHS7		
NC1740	LOBBY ROCK AND STAINED CONCRETE	6
DP7050	frame lobby	4
DP7000	Wall Electrical Rough In	2
DP7005	Pull Wire	2
DP7030	Hang Sheet Rock	3
DP7035	Finish Sheet Rock	5
DP7010	Light Fixtures and Trim	2
DP7015	HVAC Ceiling Trim	2
DP7020	Sprinkler Heads	2
DP7240	Fabricate Steel Handrail/Guardrails	5
DP7040	Prime Paint	4
DP7230	Finish Store Front	1
DP7290	2nd Floor Wood Floor Prep	2
DP7045	Finish Paint	5
DP7220	Stair Treads	4
DP7250	Factual Data Entry Wall	1
DP7210	Elevator Installation	15
DP7260	Store Front Wood Doors/Operators	3
DP7270	Install Steel Handrail/ Guardrail	2
DP7280	Wood Cap at Handrails	4
DP7300	Oak Hard Wood Flooring and Base	4
DP7200	LOBBY STAINED CONCRETE	6
PHS8		
FP8001	Overhead HVAC Rough In	3
FP8003	Wall Framing	3
FP8002	Overhead Electrical Rough In	2
FP8009	Wall Electrical Rough In	1
FP8006	Pull Wire	2
FP8015	Hang Sheet Rock	6
FP8004	Overhead Tele/Data Cable	2
FP8020	Finish Sheet Rock	7
FP8025	Prime Paint	3
FP8030	Ceiling Grid	6
FP8050	Finish Paint	3
FP8035	Light Fixtures and Trim	4
FP8000	Ceramic Tile	3
FP8045	Ceiling Tile	6
FP8040	HVAC Ceiling Trim	3
FP8086	Casework	1

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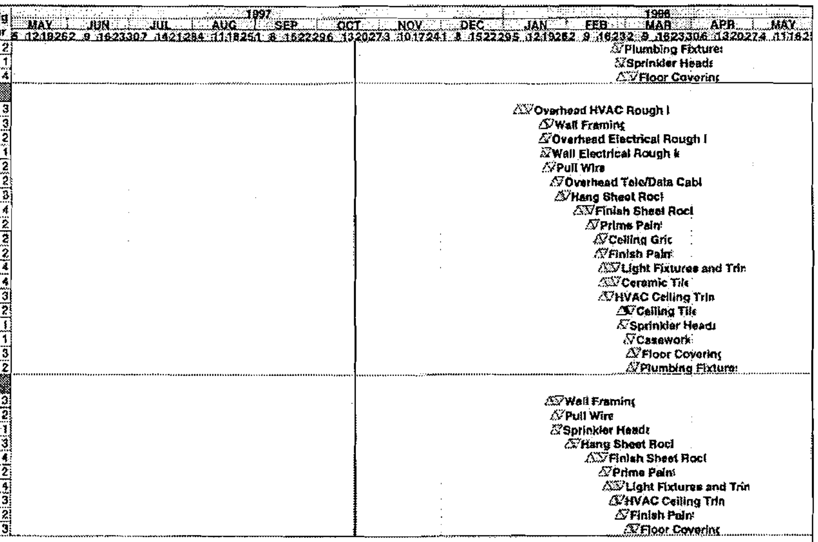
Activity ID	Activity Description	Orig Dur
FP8005	Plumbing Fixtures	2
FP8060	Sprinkler Heads	1
FP8055	Floor Covering	4
PHS9		
GP9030	Overhead HVAC Rough In	3
GP9032	Wall Framing	3
GP9031	Overhead Electrical Rough In	2
GP9034	Wall Electrical Rough In	1
GP9035	Pull Wire	2
GP9033	Overhead Tele/Data Cable	2
GP9003	Hang Sheet Rock	3
GP9004	Finish Sheet Rock	4
GP9005	Prime Paint	2
GP9006	Ceiling Grid	2
GP9010	Finish Paint	2
GP9007	Light Fixtures and Trim	4
GP9000	Ceramic Tile	4
GP9008	HVAC Ceiling Trim	3
GP9009	Ceiling Tile	2
GP9012	Sprinkler Heads	1
GP9023	Casework	1
GP9011	Floor Covering	3
GP9001	Plumbing Fixtures	2
PHSC		
HPC002	Wall Framing	3
HPC010	Pull Wire	2
HPC060	Sprinkler Heads	1
HPC015	Hang Sheet Rock	3
HPC020	Finish Sheet Rock	4
HPC025	Prime Paint	2
HPC035	Light Fixtures and Trim	4
HPC040	HVAC Ceiling Trim	3
HPC050	Finish Paint	2
HPC055	Floor Covering	3



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APPENDIX B-1: RELATED COMPONENT CATEGORIZATION				
Activity ID	Activity description	Original duration	AREA/DEPARTMENT	Related Component
DESN				
ME1000	NOTICE TO PROCEED	0	DESN	
NC1010	SCHEMATIC DESIGN	10	DESN	
NC1020	DESIGN DEVELOPMENT	22	DESN	
NC1030	CONSTRUCTION DRAWINGS	33	DESN	
PLAN				
ME1040	FDP/PDP-DEVELOPMENT PLAN SUBMITTAL	21	PLAN	
ME1050	FDP/PDP-DEVELOPMENT PLAN SUBMITTAL	0	PLAN	
ME1060	DRT-INFORMAL COMMENT REVIEW MEETING	0	PLAN	
ME1070	DRT-DEVELOPMENT REVIEW TEAM MEETING	0	PLAN	
ME1080	FDP/PDP RESUBMITTAL	0	PLAN	
ME1090	STAFF COMMENTS TO S. DUSH FOR 8/11 PLANNING	0	PLAN	
ME1100	PLANNING COMMISSION MEETING	0	PLAN	
ME1110	CIVIL PERMIT SET SUBMIT & REVIEW	27	PLAN	
NC1120	GRADING PERMIT	0	PLAN	
ME1130	CITY COUNCIL MTG.(REVIEW FINAL PLAT)	0	PLAN	
NC1140	RECEIVE FULL PERMIT	0	PLAN	
UTIL				
ME1150	PLACE PHONE ORDER	5	UTIL	
ME1160	PHONE ENGINEERING AND PRICING	5	UTIL	
ME1170	FUNDING APPROVAL FDC/UW	10	UTIL	
ME1180	ASSIGN PM (PHONE COMPANY)	0	UTIL	
ME1190	BID PHONE WORK	30	UTIL	
ME1200	DESIGN OF GAS SERVICE PSCO	15	UTIL	
NC1210	WATER PHASE 1 NOT	11	UTIL	
ME1250	SANITARY SEWER PHASE 1	7	UTIL	
ME1220	WATER PHASE 1	11	UTIL	
NC1290	POUR LIGHT POLE BASES	8	UTIL	
ME1260	STORM SEWER PHASE 1	7	UTIL	
ME1380	OUTLYING LANDSCAPING & IRRIGATION	20	UTIL	
ME1264	SLEEVING	1	UTIL	
ME1270	OFFSITE CONCRETE SIDEWALKS, CURB & GUTTER	4	UTIL	
NC1310	SANITARY SEWER PHASE 2	6	UTIL	
NC1300	OUTLYING SITE CURB GUTTER AND WALKS	1	UTIL	
NC1360	SITE LIGHTING UNDERGROUND	7	UTIL	
ME1262	STORM SEWER PHASE 2	5	UTIL	
ME1278	PREP FOR PAVING	1	UTIL	
ME1240	PRIMARY ELECTRICAL FEED & DISTRIBUTION	9	UTIL	
ME1280	OFFSITE ASPHALT PAVING & STRIPING	2	UTIL	
NC1330	ON SITE ASPHALT PAVING	2	UTIL	
NC1370	CONDUIT FROM TRANSFORMER TO BUILDING	3	UTIL	
ME1230	US WEST	4	UTIL	
ME1320	PSCO GAS SERVICE	3	UTIL	
NC1340	STRIPING & SIGNAGE	2	UTIL	
NC1350	SET LIGHT POLES	2	UTIL	
NC1372	POWER FROM TRANSFORMER TO BUILDING	3	UTIL	
BLDG CORE				
NC1390	LAYOUT	2	BLDG	-
NC1410	TEMPORARY ELECTRIC	4	BLDG	-
NC1420	CLEAR & GRUB	3	BLDG	-
NC1430	EARTHWORK	15	BLDG	earthwork
NC1440	TRAILER MOBILIZATION	1	BLDG	-
NC1400	TEMPORARY ROAD	2	BLDG	temporary roads
NC1450	MASS EXCAVATION/BUILDING PAD	6	BLDG	excavation
NC1460	FOUNDATION EXCAVATION	5	BLDG	fdtn excavation
NC1470	FOOTINGS AND FOUNDATIONS	10	BLDG	footings and foundation
NC1510	BACKFILL FOUNDATIONS	7	BLDG	foundation backfill
NC1500	UNDERSLAB UTILITIES	5	BLDG	-
NC1490	ELEVATOR JACK HOLE	2	BLDG	elev jack hole
NC1520	PREFAB EXTERIOR STEEL PANELS	10	BLDG	(prefab) ^ext. steel panels
NC1540	PREFAB ROOF SCREEN SYSTEM	10	BLDG	(prefab) roof screen
NC1530	PREFAB GABLE ROOF	10	BLDG	(prefab) gable roof
NC1550	PLACE SLAB ON GRADE	1	BLDG	slab on grade
NC1560	SITE CAST PANELS	9	BLDG	site cast panels
NC1710	ERECTION & ROOFING OF MECHANICAL SCREEN	6	BLDG	mechancial screen
NC1580	ERECT SITE CAST PANELS	3	BLDG	(erect) site cast panels
NC1570	ERECT STRUCTURAL STEEL/STAIRS	15	BLDG	(erect struct. steel/stairs
NC1590	GROUTING OF PANELS	2	BLDG	grout panels
NC1910	ELEVATOR INSTALLATION	13	BLDG	(install) elev.
NC1620	PLACE SECOND FLOOR SLAB	1	BLDG	2nd flr slab
NC1650	ERECT EXTERIOR STUD PANELS	10	BLDG	(erect) ext.stud panels
NC1810	PERIMETER WINDOWS @ SITE CAST	5	BLDG	perimeter windows
NC1610	ROOF PENETYRATIONS/CURBS	3	BLDG	roof pentrations/curbs
NC1960	DOOR FRAME DELIVERY	1	BLDG	-
NC1700	BRICK AND STONE	20	BLDG	-
NC1812	PERIMETER WINDOWS @ STUD PANELS	5	BLDG	perimeter windows

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NC1630	ROOF HATCH & LADDER	1	BLDG	roof hatch, ladder
NC1720	WOOD SHEATHING OF STUD PANELS AND CAP	2	BLDG	wood sheathing
NC1660	ERECT GABLE ROOF SYSTEM	1	BLDG	(erect) gable roof system
NC1850	CONCRETE INFIL OF COLUMN BASES	1	BLDG	column basese
NC1900	LOBBY STAIR	5	BLDG	lobby stair
NC1760	INSTALL ROOF	5	BLDG	roof
NC2110	FIRE EXTINGUISHER CABINETS	1	BLDG	fire extinguisher
NC1814	LOBBY STOREFRONT SYSTEM	5	BLDG	lobby storefront system
NC1860	SET RTU'S	1	BLDG	RTU
NC1870	RTU GAS AND ELECTRIC	4	BLDG	gas &electric
NC1940	PERMANENT HEAT	0	BLDG	heat
NC1990	EXTERIOR CAULKING	4	BLDG	caulking
NC2030	INSTALL & ROOF CANOPIES	6	BLDG	roof canopies
NC2260	HVAC BALANCE	5	BLDG	-
NC2280	PUNCHLIST	5	BLDG	-
NC2300	FINAL CLEAN	5	BLDG	-
NC2290	CERTIFICATE OF OCCUPANCY	0	BLDG	-
NC2320	FACTUAL DATA ACCEPTANCE	1	BLDG	-
NC2330	FACTUAL MOVE IN	10	BLDG	-
PHS1				
103	Core Framing (Including Phone and Elev Room)	4	BLDG	framing
115	Core Plumbing Rough In	5	BLDG	plumbing
120	Core Electrical Rough In	5	BLDG	elec
130	Overhead HVAC Rough In	2	BLDG	hvac
116	First Floor Domestic	2	BLDG	?
140	Overhead Tele/Data Cable	1	BLDG	overhead tele/data cable
104	Core Rock	3	BLDG	core rock
110	Overhead Sprinkler Rough In & Riser	3	BLDG	sprinklers
105	Core Finish	4	BLDG	corefinish
117	Factual Data NW Bathroom	3	BLDG	bathroom
170	Sprinkler Finish & Test 1st Flr	2	BLDG	sprinklers
122	Core Electrical Pull Wire	3	BLDG	pull wire
155	Prime Paint	2	BLDG	paint
184	Ceramic Tile	4	BLDG	ceramic tile
157	Finish Paint	2	BLDG	paint
175	HVAC Ceiling Trim	1	BLDG	hvac
180	Light Fixtures and Electrical Trim	2	BLDG	light fixtures and trim
181	Plumbing Fixtures	2	BLDG	plumbing
PHS2				
221	Overhead HVAC Rough In	5	BLDG	hvac
203	Core Framing	6	BLDG	framing
212	Core Plumbing Rough In	6	BLDG	plumbing
215	Core Electrical Rough In	6	BLDG	elec
240	Overhead Tele/Data Cable	1	BLDG	overhead tele/data cable
204	Core Rock	4	BLDG	core rock
216	Core Pull Wire	1	BLDG	pull wire
205	Core Finish	4	BLDG	core finish
236	Prime Paint	2	BLDG	paint
257	Ceramic Tile	4	BLDG	ceramic tile
238	Finish Paint	2	BLDG	paint
248	HVAC Ceiling Trim	1	BLDG	hvac
251	Light Fixtures and Trim	2	BLDG	light fixturesx
252	Plumbing Fixtures	2	BLDG	plumbing fixtures
PHST				
T100	Overhead Sprinkler Rough In	3	BLDG	sprinklers
T110	Overhead HVAC Rough In	3	BLDG	hvac
T120	Wall Framing	4	BLDG	framing
T130	Overhead Electrical Rough In	4	BLDG	elec
T125	In Wall HVAC	3	BLDG	wall hvac
T150	Wall Electrical Rough In	3	BLDG	wall elec
T140	Overhead Tele/Data Cable	2	BLDG	tele/data cable
T160	Pull Wire	2	BLDG	pull wire
T170	Hang Sheet Rock	3	BLDG	sheet rock
T180	Finish Sheet Rock	4	BLDG	sheet rock
T190	Prime Paint	2	BLDG	paint
T200	Ceiling Grid	2	BLDG	grid
T220	HVAC Ceiling Trim	2	BLDG	hvac
T210	Light Fixtures and Trim	2	BLDG	light fixtures
T230	Ceiling Tile	2	BLDG	tile
T240	Finish Paint	2	BLDG	paint
T250	Sprinkler Finish & Test 2nd Flr	1	BLDG	sprinkler
T260	Access Flooring	4	BLDG	flooring
PHS3				
310	Overhead Sprinkler Rough In	3	BLDG	sprinkler
315	Overhead HVAC Rough In	4	BLDG	hvac
312	Overhead Plumbing Rough In	3	BLDG	plumbing
322	Wall Framing	2	BLDG	wall framing
100	Stair Framing	2	BLDG	stair framing
318	Overhead Electrical Rough In	4	BLDG	elec
320	Wall Electrical Rough In	2	BLDG	wall elec

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321	Overhead Tele/Data Cable	2	BLDG	tele/data cable
319	Pull Wire	2	BLDG	pull wire
101	Stair Rock	3	BLDG	stair rock
324	Hang Sheet Rock	3	BLDG	sheet rock
102	Stair Tape & Finish	3	BLDG	stair
327	Finish Sheet Rock	4	BLDG	sheet rock
330	Prime Paint	2	BLDG	paint
336	Ceiling Grid	4	BLDG	grid
345	Light Fixtures and Trim	3	BLDG	light fixtures
342	HVAC Ceiling Trim	3	BLDG	hvac
348	Ceiling Tile	4	BLDG	tile
332	Finish Paint	2	BLDG	paint
351	Floor Covering	3	BLDG	floor
339	Sprinkler Finish	2	BLDG	sprinkler
346	Plumbing Fixtures	2	BLDG	plumbing
PHS4				
610	Overhead Sprinkler Rough In (+PHS2)	3	BLDG	sprinkler
615	Overhead HVAC Rough In	5	BLDG	hvac
612	Overhead Plumbing Rough In	1	BLDG	plumbing
623	Wall Framing	3	BLDG	framing
618	Overhead Electrical Rough In	3	BLDG	elec
200	Stair Framing	2	BLDG	stair framing
620	Wall Electrical Rough in	2	BLDG	wall elec
619	Pull Wire	2	BLDG	pull wire
621	Overhead Tele/Data Cable	2	BLDG	tele/data cable
624	Hang Sheet Rock	4	BLDG	sheet rock
201	Stair Rock	3	BLDG	stair rock
627	Finish Sheet Rock	4	BLDG	sheet rock
630	Prime Paint	2	BLDG	paint
202	Stair Tape & Finish	3	BLDG	stair
636	Ceiling Grid	4	BLDG	grid
645	Light Fixtures and Trim	3	BLDG	light fixtures and trim
642	HVAC Ceiling Trim	3	BLDG	hvac
648	Ceiling Tile	4	BLDG	tile
632	Finish Paint	2	BLDG	paint
651	Floor Covering	3	BLDG	flooring
639	Sprinkler Finish	1	BLDG	sprinkler
PHS5				
510	Overhead Sprinkler Rough In	2	BLDG	sprinkler
515	Overhead HVAC Rough In	3	BLDG	hvac
523	Wall Framing	3	BLDG	framing
518	Overhead Electrical Rough In	2	BLDG	elec
521	Overhead Tele/Data Cable	2	BLDG	tele/data cable
520	Wall Electrical Rough In	2	BLDG	wall elec
519	Pull Wire	2	BLDG	pull wire
524	Hang Sheet Rock	3	BLDG	sheet rock
527	Finish Sheet Rock	5	BLDG	paint
530	Prime Paint	2	BLDG	grid
536	Ceiling Grid	4	BLDG	light fixtures and trim
545	Light Fixtures and Trim	3	BLDG	hvac
542	HVAC Ceiling Trim	3	BLDG	tile
548	Ceiling Tile	4	BLDG	paint
532	Finish Paint	2	BLDG	flooring
551	Floor Covering	3	BLDG	sprinkler
539	Sprinkler Finish	1	BLDG	sheet rock
PHS6				
410	Overhead Sprinkler Rough In	3	BLDG	sprinkler
415	Overhead HVAC Rough In	3	BLDG	hvac
418	Overhead Electrical Rough In	2	BLDG	elec
423	Wall Framing	3	BLDG	wall framing
421	Overhead Tele/Data Cable	2	BLDG	tele/data cable
420	Wall Electrical Rough In	1	BLDG	elec
419	Pull Wire	2	BLDG	pull wire
424	Hang Sheet Rock	3	BLDG	sheet rock
427	Finish Sheet Rock	4	BLDG	sheet rock
430	Prime Paint	2	BLDG	paint
436	Ceiling Grid	4	BLDG	grid
445	Light Fixtures and Trim	4	BLDG	light fixtures and trim
442	HVAC Ceiling Trim	3	BLDG	hvac
448	Ceiling Tile	4	BLDG	tile
432	Finish Paint	2	BLDG	paint
451	Floor Covering	3	BLDG	flooring
439	Sprinkler Finish & Test 2nd Flr	1	BLDG	sprinkler
PHS7				
NC1740	LOBBY ROCK AND STAINED CONCRETE	6	BLDG	LOBBY ROCK/CONCRETE
DP7050	frame lobby	4	BLDG	frame lobby
DP7000	Wall Electrical Rough In	2	BLDG	elec
DP7005	Pull Wire	2	BLDG	pull wire
DP7030	Hang Sheet Rock	3	BLDG	sheet rock
DP7035	Finish Sheet Rock	5	BLDG	sheet rock

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DP7010	Light Fixtures and Trim	2	BLDG	lfght fixtrues & trim
DP7015	HVAC Ceiling Trim	2	BLDG	hvac
DP7020	Sprinkler Heads	2	BLDG	sprinklers
DP7240	Fabricate Steel Handrail/Guardrails	5	BLDG	(fab) steel handrails/guardrails
DP7040	Prime Paint	4	BLDG	paint
DP7230	Finish Store Front	1	BLDG	store front
DP7290	2nd Floor Wood Floor Prep	2	BLDG	2nd flr wood flr prep
DP7045	Finish Paint	5	BLDG	paint
DP7220	Stair Treads	4	BLDG	staitr treads
DP7250	Factual Data Entry Wall	1	BLDG	facual data entry wall
DP7210	Elevator Installation	15	BLDG	elevator
DP7260	Store Front Wood Doors/Operators	3	BLDG	front wood doors
DP7270	Install Steel Handrail/ Guardrail	2	BLDG	(install)stl handrails/grdrails
DP7280	Wood Cap at Handrails	4	BLDG	wood cap @handrails
DP7300	Oak Hard Wood Flooring and Base	4	BLDG	oak hard wood flrg
DP7200	LOBBY STAINED CONCRETE	6	BLDG	lobby concrete
PHS8				
FP8001	Overhead HVAC Rough In	3	BLDG	hvac
FP8003	Wall Framing	3	BLDG	framing
FP8002	Overhead Electrical Rough In	2	BLDG	overhead 'elec
FP8009	Wall Electrical Rough In	1	BLDG	wall elec
FP8006	Pull Wire	2	BLDG	pull wire
FP8015	Hang Sheet Rock	6	BLDG	sheet rock
FP8004	Overhead Tele/Data Cable	2	BLDG	Overhead Tele/Data Cable
FP8020	Finish Sheet Rock	7	BLDG	sheet rock
FP8025	Prime Paint	3	BLDG	paint
FP8030	Ceiling Grid	6	BLDG	Ceiling Grid
FP8050	Finish Paint	3	BLDG	paint
FP8035	Light Fixtures and Trim	4	BLDG	Light Fixtures and Trim
FP8000	Ceramic Tile	3	BLDG	Ceramic Tile
FP8045	Ceiling Tile	6	BLDG	Ceiling Tile
FP8040	HVAC Ceiling Trim	3	BLDG	hvac
FP8066	Casework	1	BLDG	case work
FP8005	Plumbing Fixtures	2	BLDG	plumbing
FP8060	Sprinkler Heads	1	BLDG	spirnklers
FP8055	Floor Covering	4	BLDG	flooring
PHS9				
GP9030	Overhead HVAC Rough In	3	BLDG	overhead hvac
GP9032	Wall Framing	3	BLDG	framing
GP9031	Overhead Electrical Rough In	2	BLDG	overhead elec
GP9034	Wall Electrical Rough In	1	BLDG	wall elec
GP9035	Pull Wire	2	BLDG	pull wire
GP9033	Overhead Tele/Data Cable	2	BLDG	Overhead Tele/Data Cable
GP9003	Hang Sheet Rock	3	BLDG	sheet rock
GP9004	Finish Sheet Rock	4	BLDG	sheet rock
GP9005	Prime Paint	2	BLDG	paint
GP9006	Ceiling Grid	2	BLDG	grid
GP9010	Finish Paint	2	BLDG	paint
GP9007	Light Fixtures and Trim	4	BLDG	Light Fixtures and Trim
GP9000	Ceramic Tile	4	BLDG	Ceramic Tile
GP9008	HVAC Ceiling Trim	3	BLDG	HVAC Ceiling Trim
GP9009	Ceiling Tile	2	BLDG	Ceiling Tile
GP9012	Sprinkler Heads	1	BLDG	sprinklers
GP9023	Casework	1	BLDG	casework
GP9011	Floor Covering	3	BLDG	flooring
GP9001	Plumbing Fixtures	2	BLDG	plumbing
PHSC				
HPC002	Wall Framing	3	BLDG	framing
HPC010	Pull Wire	2	BLDG	pull wire
HPC060	Sprinkler Heads	1	BLDG	sprinklers
HPC015	Hang Sheet Rock	3	BLDG	sheet rock
HPC020	Finish Sheet Rock	4	BLDG	sheet rock
HPC025	Prime Paint	2	BLDG	paint
HPC035	Light Fixtures and Trim	4	BLDG	light fixtures and trim
HPC040	HVAC Ceiling Trim	3	BLDG	hvac
HPC050	Finish Paint	2	BLDG	paint
HPC055	Floor Covering	3	BLDG	flooring

APPENDIX B-2: COMPONENT BREAKDOWN				
1. Activities having a corresponding component				
i) Components with *one to one relationship:*				
components which can be related to a single activity in the schedule				
Footings&foundation				
Foundation_backfill				
Elev_jack_hole				
Prefabext_steel_panels				
Prefab_roof_screen				
Prefab_gable_roof				
Slab_on_grade				
Site_cast_panels				
Mechanical_screen				
Erect_site_cast_panels				
Erect_struct_steel/stairs				
Grout_panels				
Install_elev.				
2nd_flr_slab				
Erect_ ext_stud_panels				
Perimeter_windows				
Roof_pentrations/curbs				
Roof_hatch/ladder				
Wood_sheathing				
Erect_gable_roof_system				
Column_base				
Lobby_stair				
Roof				
Fire_extinguisher				
Lobby_storefront_system				
RTU				
Gas &electric				
Heat				
Caulking				
Roof_canopies				
PHASE1				
1st_flr_bathroom				
Factual_dataNW_bathroom				
PHASE2				
-				
PHASE3				
-				
PHASE4				
-				
PHASE5				
-				
PHASE6				
-				
PHASE7				
Lobby_rock/stained_concrete				
Frame_lobby				
Fabricate_stl_handrails/guardrails				
Finish_store_front				
2nd_flr_woodflrprep				
Factual_data_entry_wall				
Elevator_installation				
Store_frontwood_ doors/operators				
Install_handrails/guardrails				
Woodcap_handrails				
Lobby_stained_concrete				

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ii) Components with *one to many relationship*:
components which can be related to two or more activities in the schedule
These components must be divided into section rough-in &trim sub-components
to represent each corresponding activity

Components	phs_comp	specification	suffix	layer name
Electrical	phs1_elec	core	rough_in	ph1_elec_core_rough_in
(*trim* includes light fixtures)			trim	phs1__elec_core_trim
	phs2_elec	core	rough_in	phs2_elec_core_rough_in
			trim	phs2_elec_core_trim
	phsT_elec	overhead	rough_in	phsT_elec_overhead_rough_in
		wall	rough_in	phsT_elec_wall_rough_in
		overehad/wall	trim	phsT_elec_overhead/wall_trim
	phs3_elec	overhead	rough_in	phs3_elec_overhead_rough_in
		wall	rough_in	phs3_elec_wall_rough_in
		overhead/wall	trim	phs3_elec_overhead/wall_trim
	phs4_elec	overhead	rough_in	phs4_elec_overhead_rough_in
		wall	rough_in	phs4_elec_wall_rough_in
		overhead/wall	trim	phs4_elec_overhead/wall_trim
	phs5_elec	overhead	rough_in	phs5_elec_overhead_rough_in
		wall	rough_in	phs5_elec_wall_rough_in
		overhead/wall	trim	phs5_elec_overhead/wall_trim
	phs6_elec	overhead	rough_in	phs6_elec_overhead_rough_in
		wall	rough_in	phs6_elec_wall_rough_in
		overhead/wall	trim	phs6_elec_overhead/wall_trim
	phs7_elec	wall	rough_in	phs7_elec_wall_rough_in
		wall	trim	phs7_elec_wall_trim
	phs8_elec	overhead	rough_in	phs8_elec_wall_rough_in
		wall	rough_in	phs8_elec_wall_rough_in
		overhead/wall	trim	phs8_elec_overhead/wall_trim
	phs9_elec	overhead	rough_in	phs9_elec_wall_rough_in
		wall	rough_in	phs9_elec_wall_rough_in
		overhead/wall	trim	phs9_elec_overhead/wall_trim
	phsC_elec		trim	phsC_elec_trim
Plumbing	phs1_plumb	core	rough_in	phs1_plumb_core_rough_in
			fixtures	phs1_plumb_core_fixtures
	phs2_plumb	core	rough_in	phs2_plumb_core_rough_in
			fixtures	phs2_plumb_core_fixtures
	no phsT			
	phs3_plumb	overhead	rough_in	phs3_plumb_overhead_rough_in
			fixtures	phs3_plumb_overhead_trim
	phs4_plumb	overhead	rough_in	phs4_plumb_overhead_rough_in
	no phs5			
	no phs6			
	no phs7			
	phs8_plumb		fixtures	phs8_plumb_fixtures
	phs9_plumb		fixtures	phs9_plumb_fixtures
	no phsC			
HVAC	phs1_hvac	overhead	rough_in	phs1_hvac_overhead_rough_in
			ceiling trim	phs1_hvac_ceiling_trim
	phs2_hvac	overhead	rough_in	phs2_hvac_overhead_rough_in
			ceiling trim	phs2_hvac_ceiling_trim
	phsT-hvac	overhead	rough_in	phsT_hvac_overhead_rough_in
			ceiling trim	phsT_hvac_ceiling_trim
		wall	rough_in/trir	phsT_hvac_wall_rough_in/trim
	phs3_hvac	overhead	rough_in	phs3_hvac_overhead_rough_in
			ceiling trim	phs3_hvac_ceiling_trim
	phs4_hvac	overhead	rough_in	phs4_hvac_overhead_rough_in

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			ceiling trim	phs4_hvac_ceiling_trim
	phs5_hvac	overhead	rough_in	phs5_hvac_overhead_rough_in
			ceiling trim	phs5_hvac_ceiling_trim
	phs6_hvac	overhead	rough_in	phs6_hvac_overhead_rough_in
			ceiling trim	phs6_hvac_ceiling_trim
	phs7_hvac	overhead	ceiling trim	phs7_hvac_overhead_ceiling_trim
	phs8_hvac	overhead	rough_in	phs8_ hvac_overhead_rough_in
			ceiling trim	phs8_hvac_ceiling_trim
	phs9_hvac	overhead	rough_in	phs9_ hvac_overhead_rough_in
			ceiling trim	phs9_hvac_ceiling_trim
	phsC_hvac	overhead	ceiling trim	phsC_hvac_overhead_ceiling_trim
Sprinklers	phs1_sprnk	overhead	rough_in	phs1_sprnk_overhead_rough_in
			finish	phs1_sprnk_overhead_finish
	no phs2			
	phsT_sprnk	overhead	rough_in	phsT_sprnk_overhead_rough_in
			finish	phsT_sprnk_overhead_finish
	phs3_sprnk	overhead	rough_in	phs3_sprnk_overhead_rough_in
			finish	phs3_sprnk_overhead_finish
	phs4_sprnk	overhead	rough_in	phs4_sprnk_overhead_rough_in
			finish	phs4_sprnk_overhead_finish
	phs5_sprnk	overhead	rough_in	phs5_sprnk_overhead_rough_in
			finish	phs5_sprnk_overhead_finish
	phs6_sprnk	overhead	rough_in	phs6_sprnk_overhead_rough_in
			finish	phs6_sprnk_overhead_finish
	phs7_sprnk	heads		phs7_sprnk_heads
	phs8_sprnk	heads		phs8_sprnk_heads
	no phs9			
	phsC_sprnk	heads		phsC_sprnk_heads
Tiles	phs1_tile	ceramic	ceramic_tile	phs1_tile_ceramic
	phs2_tile	ceramic	ceramic_tile	phs2_tile_ceramic
	phsT_tile	ceiling	ceiling_tile	phsT_tile_ceramic
	phs3_tile	ceiling	ceiling_tile	phs3_tile_ceramic
	phs4_tile	ceiling	ceiling_tile	phs4_tile_ceramic
	phs5_tile	ceiling	ceiling_tile	phs5_tile_ceramic
	phs6_tile	ceiling	ceiling_tile	phs6_tile_ceramic
	nophs7			
	phs8_tile	ceiling	ceiling_tile	phs8_tile_ceiling _tile
		ceramic	ceramic_tile	phs8_tile_ceramic
	phs9_tile	ceiling	ceiling_tile	phs9_tile_ceramic
		ceramic	ceramic_tile	phs9_tile_ceramic
	no phsC			
Stairs	no phs1			
	no phs2			
	no phsT			
	phs3_stair		framing	phs3_stair_framing
			rock	phs3_stair_rock
			tape/finish	phs3_stair_tape/finish
	phs4_stair		framing	phs4_stair_framing
			rock	phs4_stair_rock
			tape/finish	phs4_stair_tape/finish
	phs7_stair		treads	phs7_stair_treads
	no phs8			
	no phs9			
	no phsC			
Overhead tele/data cable	phs1_cable	overhead	-	phs1_cable_overhead
	phs2_cable			phs2_cable_overhead
	phsT_cable			phsT_cable_overhead

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	phs3_cable			phs3_cable_overhead
	phs4_cable			phs4_cable_overhead
	phs5_cable			phs5_cable_overhead
	phs6_cable			phs6_cable_overhead
	no phs7			
	phs8_cable			phs8_cable_overhead
	phs9_cable			phs9_cable_overhead
	no phsC			
Grid	no phs1			
	no phs2			
	phsT_grid	ceiling	ceiling_grid	phsT_grid_ceiling_grid
	phs3_grid	ceiling	ceiling_grid	phs3_grid_ceiling_grid
	phs4_grid	ceiling	ceiling_grid	phs4_grid_ceiling_grid
	phs5_grid	ceiling	ceiling_grid	phs5_grid_ceiling_grid
	phs6_grid	ceiling	ceiling_grid	phs6_grid_ceiling_grid
	no phs7			
	phs8_grid	ceiling	ceiling_grid	phs8_grid_ceiling_grid
	no phs9			
Pull wire	phs1_wire	core	core_wire	phs1_wire_core_wire
	phs2_wire	core	core_wire	phs2_wire_core_wire
	phsT_wire	pull	pull_wire	phsT_wire_pull_wire
	phs3_wire	pull	pull_wire	phs3_wire_pull_wire
	phs4_wire	pull	pull_wire	phs4_wire_pull_wire
	phs5_wire	pull	pull_wire	phs5_wire_pull_wire
	phs6_wire	pull	pull_wire	phs6_wire_pull_wire
	phs7_wire	pull	pull_wire	phs7_wire_pull_wire
	phs8_wire	pull	pull_wire	phs8_wire_pull_wire
	phs9_wire	pull	pull_wire	phs9_wire_pull_wire
	phsC_wire	pull	pull_wire	phsC_wire_pull_wire
2. Activities not having a corresponding component				
Earthwork				
Temporary_roads				
Excavation				
Fdtn_excavation				
Layout				
Temporary electric				
Clear & grub				
Trailer mobilization				
Underslab utilities				
Door frame delivery				
Brick and stone				
HVAC balance				
Punchlist				
Final clean				
Certicficate of occupancy				
Factual data acceptance				
Factual move in				
ii) Components with *one to many relationship*:				
components which can be related to two or more activities in the schedule				
These components must be divided into section rough-in &trim sub-components				
to represent each corresponding activity				
components	***phs_comp***	***specification***	***suffix***	***layer name***
Framing	phs1_frmg	core		phs1_frmg_core
	phs2_frmg	core		phs2_frmg_core

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	phsT_frmg	wall		phsT_frmg_wall
	phs3_frmg	wall		phs3_frmg_wall
	phs4_frmg	wall		phs4_frmg_wall
	phs5_frmg	wall		phs5_frmg_wall
	phs6_frmg	wall		phs6_frmg_wall
	phs7_frmg	lobby		phs7_frmg_lobby
	phs8_frmg	wall		phs8_frmg_wall
	phs9_frmg	wall		phs9_frmg_wall
	phsC_frmg	wall		phsC_frmg_wall
Paint	phs1_paint		prime	phs1_paint_prime
			finish	phs1_paint_finish
	phs2_paint		prime	phs2_paint_prime
			finish	phs2_paint_finish
	phsT_paint		prime	phsT_paint_prime
			finish	phsT_paint_finish
	phs3_paint		prime	phs3_paint_prime
			finish	phs3-paint_finish
	phs4_paint		prime	phs4_paint_prime
			finish	phs4_paint_finish
	phs5_paint		prime	phs5_paint_prime
			finish	phs5_paint_finish
	phs6_paint		prime	phs6_paint_prime
			finish	phs6_paint_finish
	phs7_paint		prime	phs7_paint_prime
			finish	phs7_paint_finish
	phs8_paint		prime	phs8_paint_prime
			finish	phs8_paint_finish
	phs9_paint		prime	phs9_paint_prime
			finish	phs9_paint_finish
	phsC_paint		prime	phsC_paint_prime
			finish	phsC_paint_finish
Rock	phs1_rock	core	start	phs1_rock_start
			finish	phs1_rock_finish
	phs2_rock	core	start	phs2_rock_start
			finish	phs2_rock_finish
	phsT_rock	sheet	hang	phsT_rock_hang
			fiinsh	phsT_rock_finish
	phs3_rock	sheet	hang	phs3_rock_hang
			fiinsh	phs3_rock_finish
	phs4_rock	sheet	hang	phs4_rock_hang
			fiinsh	phs4_rock_finish
	phs5_rock	sheet	hang	phs5_rock_hang
			fiinsh	phs5_rock_finish
	phs6_rock	sheet	hang	phs6_rock_hang
			fiinsh	phs6_rock_finish
	phs7_rock	sheet	hang	phs7_rock_hang
			fiinsh	phs7_rock_finish
	phs8_rock	sheet	hang	phs8_rock_hang
			finish	phs8_rock_finish
	phs9_rock	sheet	hang	phs9_rock_hang
			finish	phs9_rock_finish
	phsC_rock	sheet	hang	phsC_rock_hang
			finish	phsC_rock_finish
Floor Covering	no phs1			
	no phs2			
	phsT_flrg		access_flrg	phsT_flrg_acces_flrg
	phs3_flrg		flr_covering	phs3_flrg_flr_covering
	phs4_flrg		flr_covering	phs4_flrg_flr_covering

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	phs5_flrg		flr_covering	phs5_flrg_flr_covering
	phs6_flrg		flr_covering	phs6_flrg_flr_covering
	phs7_flrg		OHW_flrg	phs7_flrg_OHW_flrg
	phs8_flrg		flr_covering	phs8_flrg_flr_covering
	phs9_flrg		flr_covering	phs9_flrg_flr_covering
	phsC_flrg		flr_covering	phsC_flrg_flr_covering

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