CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Four-Dimensional Modeling in Design and Construction

By
Eric Collier and Martin Fischer

CIFE Technical Report #101
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STANFORD UNIVERSITY

If you would like to contact the authors please write to:

c/o CIFE, Civil Engineering,
Stanford University,
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020

SUMMARY
CIFE TECHNICAL REPORT #101

Title: **Four Dimensional Modeling in Design and Construction**

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- Name of Agency: Dillingham Construction Company Inc. (A member of CIFE)
- Title of Research Project: *Three Dimensional Modeling and Schedule Animation of the San Mateo County Health Center*

1. Abstract:

Four-dimensional models are three-dimensional graphical computer models that show various stages of completion of a project over time. This report focuses on the modeling of construction projects where the stages of completion correspond to a construction schedule. The report summarizes research work with Dillingham Construction Company showing the San Mateo County Health Center on the computer as it will be constructed from 1994-1999 and discusses the benefits of 3D and 4D computer models. The report also presents potential enhancements and improvements for 4D computing as it becomes an increasingly valuable tool in integrated design and integrated construction.

2. Subject:

- What is the report about in laymen's terms?

  Just as time-lapse photography can be made to show an actual construction process in a short time period, computer animations can show how construction will take place before anything is built but with nearly the same clarity. These animations become a visual set of instructions for construction as useful as step-by-step photographs showing a child how to assemble a tower of blocks.

- What are the key ideas or concepts investigated?

  What advantages do 3D models have over 2D drawings?
  What are the problems that result from communicating designs in 2D?
  How can 3D computer models assist in clarifying design intent?
  How can 4D computer models assist in planning construction?
  What were the results of the 4D modeling of the SMC Health Center project?
  What are the differences in physical 3D models and 3D computer models?
  What are the capabilities of 3D and 4D models that make them cost-effective?
  What are the benefits of 4D models to each member of the construction team?
  How can 4D modeling be used today?
  Why aren't 3D and 4D computer modeling used more today in construction?
  What new technological tools will encourage greater use of 4D modeling?
  What is the future outlook for 3D and 4D computer modeling?

- What is the essential message?

  Four-dimensional computing is a currently available, powerful tool that enables better design and construction through enhanced communications by way of clearer, more complete, and more powerful visual representations of construction projects.

3. Objectives/Benefits:

- Why did CIFE fund this research?
  Out of a recognition of 3D modeling as the core technology for the ultimate realization of the benefits of integrated facility engineering through computers.
- What benefits does the research have to CIFE members?
  It gives a clear example of what can be accomplished with 3D computer models and demonstrates the specific application to construction by way of linking these models to construction schedules to create 4D models.
- What is the motivation for pursuing the research?
  To work closely with industry to show on a very practical level the first steps that can be taken towards using electronic models as a tool in planning and communication on construction projects.
- What did the research attempt to prove/disprove or explore?
  This research sought to understand more completely the realm of 4D computer modeling and its application to design and construction, with the particular emphasis of being able to encourage its immediate wide-spread implementation.

4. Methodology:

- How was the research conducted? Research Assistant Eric Collier worked under the direction of Assistant Professor Martin Fischer in close collaboration with Dillingham Construction's management from the San Mateo County Health Center project including Program Manager Tom Trainor and Project Manager George Hurley. The work was done under the direction of Jack Ritter of Dillingham Construction and Paul Teicholz of CIFE along with assistance from Frank Vaugn of Dillingham, The Ratcliff Group Architects, their consultants, and a small group of Stanford students from Craig Howard's CAD class, Spring 1994.
- Did the investigation involve case studies, computer models, or some other method? This project involved building 3D CAD models in AutoCad on a 386 and then an Intel powered Pentium, linking them to Dillingham's Primavera construction schedules with Jacobus Technology's Construction Simulation Toolkit (a Windows product), and viewing the animation in Bechtel's Walkthru program (distributed by Jacobus Technology) on a Silicon Graphics Iris Indigo Elan.

5. Results:

- What are the major findings of the investigation?
  -The actual creation of the 3D model is the most time intensive portion of a 4D model or any other application that uses the 3D model.
  -To derive the greatest value a 3D model it should be created in the design stage.
  -The power of 4D modeling is so great that it is worthwhile for a contractor to build3D and 4D models even after the design is complete.
  -It is practical to use 3D and 4D modeling today for competitive advantage and enhanced integration in design and construction.

- What outputs were generated (software, other reports, video, other)
  CIFE Video #23 "3D Schedule Animation of the San Mateo County Health Center" 1994, run time 10 minutes. Reports on research in Stanford Campus Report, San Mateo Times, and Architecture (Sept. 1994 issue).

6. Research Status:

- What is the status of the research? Completed.
- What is the logical next step? To integrate this work with other CIFE research.
- Are the results ready to be applied? Yes.

ABSTRACT

This report presents compelling reasons for using four-dimensional modeling in the design and construction industry. I use the term four-dimensional modeling to describe three-dimensional CAD models that can show changes over the fourth dimension of time. Three-dimensional computer models provide the opportunity for individuals to create a complete image of what a structure will look like before it is built. Many issues that can be left unresolved in 2D drawings with the hope that someone will figure them out in the field must be resolved when creating a 3D model.

Today there is software that can create complex construction schedules, showing the interrelationship of activities and the balance of manpower. But all coordination between the schedule and geometric information must take in place the minds of the construction planners. Three-dimensional modeling is a tool that assists in making the geometry clear so that other issues can be considered more carefully. These two tools, the schedule and the model, can be linked together to animate the construction schedule with the objects appearing as they will during construction. Simulating construction with 4D CAD models is similar to having a new 3D computer model for each day of construction.

I present a case study of the actual development and use of a 4D model. Included are images of this work and discussions of the research. This case study is the remodeling and renovation of the San Mateo County Health Center which will take place over the next five years and involves 320,000 square feet of buildings, most of which are new buildings. Using this case study as a backdrop, other issues of 3D and 4D modeling are discussed.

Although many will benefit from using 4D, clients will be especially rewarded. Most clients like to know what will be done during construction and how construction will take place. Clients that ask when the building will be done will be told by the contractor a date that represents the point in time when all work will be completed. What the clients may really want to know is the date by which the doors and windows will be installed so that the building can be heated. By observing the construction schedule created in 4D, they can decide for themselves the answer to their question.

The 4D model gives more explicit explanations of construction operations, enabling the client and others to play a more informed role in design and construction. The major benefit of this will be more satisfied customers who face fewer unexpected surprises during construction, feel more a part of the process, appreciate the complexity and danger of the work, feel that the contractor is taking an active role in helping them meet their goals, and receive more construction value through a higher level of efficiency.

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1 INTRODUCTION

Three-dimensional computer modeling has been available for more than two decades. Even so, it is a technology that continues to quickly change and develop. As 3D computer modeling becomes a more economically viable and powerful tool, few involved in the design and construction of the built environment are realizing the potential that already exists for such technology. For contractors, the key advantage of electronic 3D models is the capability of adding the fourth dimension--that of time. The intent of this report is to emphasize the usefulness of this technology in the construction industry by presenting its conceptual strengths, our experiences in using it on a research project, discussions of potential benefits and current challenges, and projections for future developments.

1.1 3D Computer Graphics

In this age of electronic wonders, people are accustomed to impressive displays of sophisticated computer images. With relatively little effort, anything in the world--any image that one can think of--can be conjured up electronically, displayed, rotated, transformed, and manipulated before one's eyes. Without even realizing it, many people of the current generation probably saw their first 3D computer images as title letters of the evening news rolling through space on their television screen. In the 1970's these images required large, expensive computers on which a simple animation sequence took weeks or months to create. At that time these images had to be used repeatedly so that the cost was justified. Today 3D modeling has reached new levels of capability and affordability. The entertainment industry is now able to create 3D computer models with movements and colors so realistic that they surpass any animation created by camera tricks and 3D "physical" painted models of plastic or wood. But to achieve this, millions of dollars are poured into cinematic morsels with the knowledge that millions of entertainment viewers will pay to consume these visual tidbits.

Although the entertainment industry is currently the most visible in its use of computer models, the rapid development of 3D computer modeling has made it available for use in many segments of the academic, industrial, scientific, and business communities. But it is difficult for a person or an industry unfamiliar with making computer models or movie footage to view displays of 3D graphics and to be able to make good judgments on how much time and money it takes to create the models, or to evaluate the practical potential for 3D computer modeling in one's own segment of the marketplace. This report presents such an evaluation for the architectural and construction industries.

1.2 A Three-Dimensional World

To understand the real potential of 3D computer models in construction, one must first appreciate the value of 3D models as a form of communication. This section discusses the weaknesses and limitations of 2D drawings in conveying information about objects and the added clarity that 3D models provide.

Techniques for two-dimensional drawings have been developed to the point that it is the method most commonly employed for designing objects. Perspectives, isometric drawings, and other methods allow the representation of a 3D object on a flat surface. Designers are able to sketch on any scrap of paper as a way of developing three dimensional ideas. But with the ease of drawing also comes the inherent limitations. Because people must combine information from at least two drawings in their minds (see Figure 1), they must often consult drawings a number of times before they understand the proper 3D information.

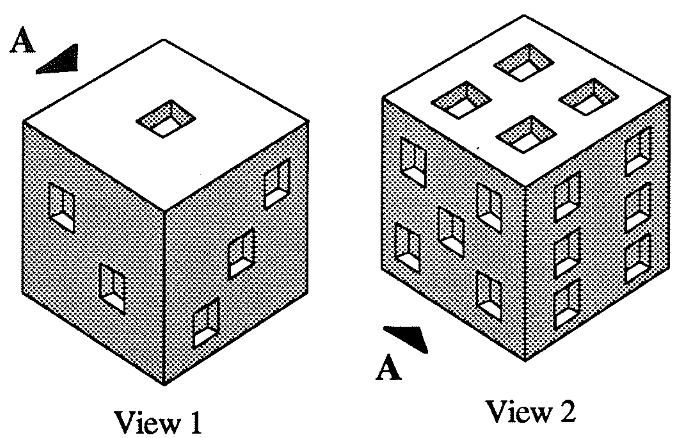


Figure 1 The six faces necessary to understand a cube

The Six-Sided Cube

For example, in Figure 1, to determine if the face on the back of View 1 that is indicated by "A" contains five windows or six, one must turn the image shown in View 2 upside down in one's mind and merge it with the three faces of View 1. Although the "A" in View 2 indicates that it is the face with five windows, one must still go through the exercise in order to actually visualize the five windows on that face. Once you have determined that the side with five windows is the answer, you can begin to look at View 1 and imagine four windows on the bottom, six windows at the back on the right, and five windows at the back on the left. But then if you turn your attention to View 2, you must follow a similar exercise before determining which face contains three windows and which contains two.

The Puzzle of Two Dimensions

Understanding this simple 3D object is similar to understanding a puzzle. The best way to convince someone who, for example, incorrectly perceives that the face with six windows (rather than that with five) would be viewed at position "A" is to build a representative cube or model. Once the proper number of windows is drawn or sculpted on each face, you could look at the model as in View 1, point to the face indicated as "A," and turn the model to view the proper number of windows.

Two Dimensions

The cube drawn in Figure 1 shows multiple faces in a single drawing. Most design documents used for construction represent each face in a separate two dimensional drawing (see Figure 2). Such drawings provide even less 3D information. The proper face for side "A" can be determined from the drawings, but a complete picture of the object is difficult to create and keep in one's mind. For instance, if you had not seen Figure 1, it would have been impossible to understand that the small squares represent depressions rather than raised bumps or holes. One would also need to understand if "North" meant the side seen from the north or the side that one saw when one looked north from the south.

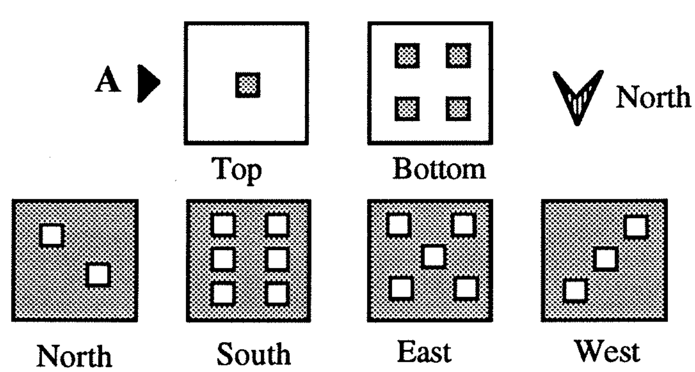


Figure 2 Flat projection drawings of a cube

Anyone familiar with 2D drawings will know that by drawing the cube with its faces as if it had been unfolded on the page will make the pinpointing of side "A" clear. In addition, dashed lines can indicated depressions and thinner solid lines can indicate bumps. With most structures, these methods cannot be used because elevations are often drawn on a separate sheets. But even forming a visual image of a folded up cube requires some skill and practice to actually visualize the final product in one's mind.

The 3D Model as Solution

The underlying weakness of two-dimensional drawings is that information in three dimensions is necessary for the complete perception and construction of the object. Three-dimensional models have been used for centuries to supplement this weakness. Once a model has been constructed, the "puzzle" aspect of understanding the drawings is removed. If I had handed you a model of the cube instead of the drawings and asked you to build it for me, simple questions such as what faces were opposite other faces would be obvious. The discussion could then move quickly into what the purpose of the cube is, how it is to be made, if the depressions are the right size, what color it should be, and so on. Being able to imagine the cube in your mind's eye would also be easier after you held the model of the cube and examined it closely.

1.3 Construction and 3D

The built environment is made up of three-dimensional objects. Using 3D models is the most complete way of conveying information, short of creating an exact duplicate of the object. Before computers the only option for creating a 3D representation was to build replicas of the 3D structure at different scales. The limitations of this method led to the use of 2D drawings to convey geometric design information. This section first introduces the development, the limitations, and the inefficiencies of the current system. A discussion of the benefit of visualizing construction using 3D computer models follows. The last portion of this section defines and discusses the use of 4D computer models.

1.3.1 Current Methods for Visualizing Construction

Architects are familiar with building models. Since they design volumetric spaces bounded by objects which are three dimensional by nature, they understand the limitations of drawings. Architects have traditionally used "study" models of paper and glue in practice as well as in their education, to test out ideas that sketches can only suggest. Sometimes they build an expensive "realistic" scale model of how the project is to look at completion. This model provides everyone involved in the project with an image of what they are working towards, but neither type of model provides enough information to be useful in construction. In this report, I refer to these models as "physical 3D models" or simply "physical models," as one usually makes them by assembling actual physical materials. See Section 3.3.1 for a further discussion of the strengths and limitations of physical models in comparison to 3D CAD computer models.

Development of 2D

Once even the largest structures were built under the direction of a master builder who would personally convey images from his or her head to those involved in the construction. Employing small models or full scale mock-ups would assist in this process. Design would take place during the construction as problems would arise, and people often learned how to do things better by trial and error. Eventually it was found that two dimensional drawings of column grids or basic plans were a good way of representing and planning for the relative size and shape of a structure. As structures became more complex and the cost of construction rose, it became increasingly important to figure out details in advance of construction. Two-dimensional drawings proved to be the most economical method of conveying the graphical information about a structure's geometry.

Different Three Dimensional Images

In general, the use of two-dimensional drawings has provided an acceptable method for the construction of structures not thought possible a few centuries ago. It has allowed for the specialization of skills to the point that a designer is able only to design and a builder can concentrate solely on building. But this method of conveying graphic information in two dimensions is not without its inefficiencies. As part of the design process, designers produce two-dimensional representations of their mind's 3D image of the structure. Everyone involved in design, planning, and construction must look at the 2D graphic representation and build their own mental 3D images. Not only is this a duplication of effort, but it is also quite common for different people to create incorrect or incomplete images (See Figure 3).

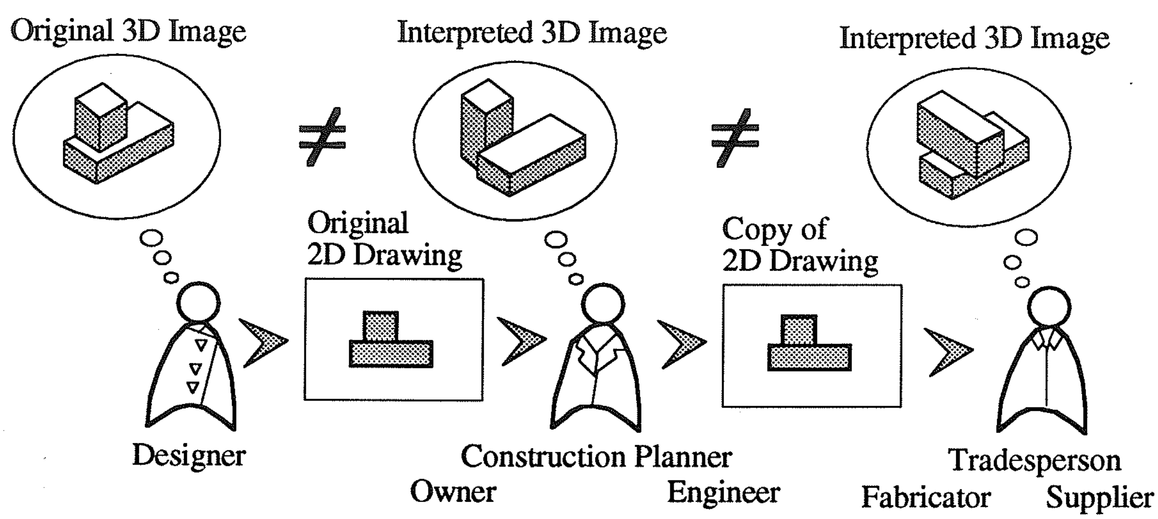


Figure 3 Different 3D Images as a result of misunderstanding the 2D drawings

Just as in the example of the cube , some people may get the image right on one day, only to mentally rebuild it incorrectly another day. Numerous people spend many hours in the design and construction phase of a project studying the 2D drawings trying to imagine what the structure will look like in three dimensions. Everyone from the client to the engineer to the contractor must try to predict what this structure will look like in order to determine the cost and time necessary to build it as well as its potential to meet standards, codes, and requirements. Usually people are only able to spend time visualizing aspects that are most important to them, or those areas where they anticipate problems. In the prevalent design/bid/build approach, many construction companies turn 2D graphic information into a sufficiently complete 3D picture to estimate quantities of materials needed and to develop at least a semi-feasible plan for building the structure. Only the winners of the bid are rewarded for their efforts.

Field Resolution of Conflicts

Because of the difficulty of keeping in mind 3D information that is constructed and reconstructed from 2D information, many conflicts do not manifest themselves until they surface during construction. Sometimes there is an omission by a designer, who falls victim to the abstraction of 2D and fails to resolve enough 3D information. Other times another individual's 3D interpretation turns out to be different from the designer's interpretation. When an error isn't caught before the installation of materials, resolving conflicts can be very costly. Correcting the improper placement of concrete, for example, by jack-hammering it out and pouring new concrete is an inefficient method of solving the inadequacies of poor graphic communication. Even though construction is capital intensive and on-the-job mistakes can be costly, the current trend is to put less money into the design phase and work out the details in the construction phase. One reason for this might be that the designer's solution to providing more information is usually to supply more drawings. More drawings require more mental energy to combine images and organize information.

1.3.2 Communication with 3D Computer Models

Today computer software has made it possible to draw electronic models in virtual 3D space. These objects have coordinates in the X, Y, and Z axes that define the actual shape. This allows the object to be "turned" and viewed from any angle. An electronic CAD model combines the shared understanding that comes from a physical model and the flexibility of electronic communications. Using 3D computer models in the design and construction process has many advantages over traditional methods.

Common geometry

Just as with a physical model, a 3D computer model of construction gives everyone a similar view of the final product. The designer's final image is expressed literally in the 3D model rather than in abstraction as is the case with 2D drawings. Although the model may not show all the material qualities or the effects of weather that the designer may imagine as part of his or her design, the geometry is exact. Each person that sees the model, from the client to the supplier of the smallest item for construction is able to perceive the same object quickly by viewing the 3D model (see Figure 4).

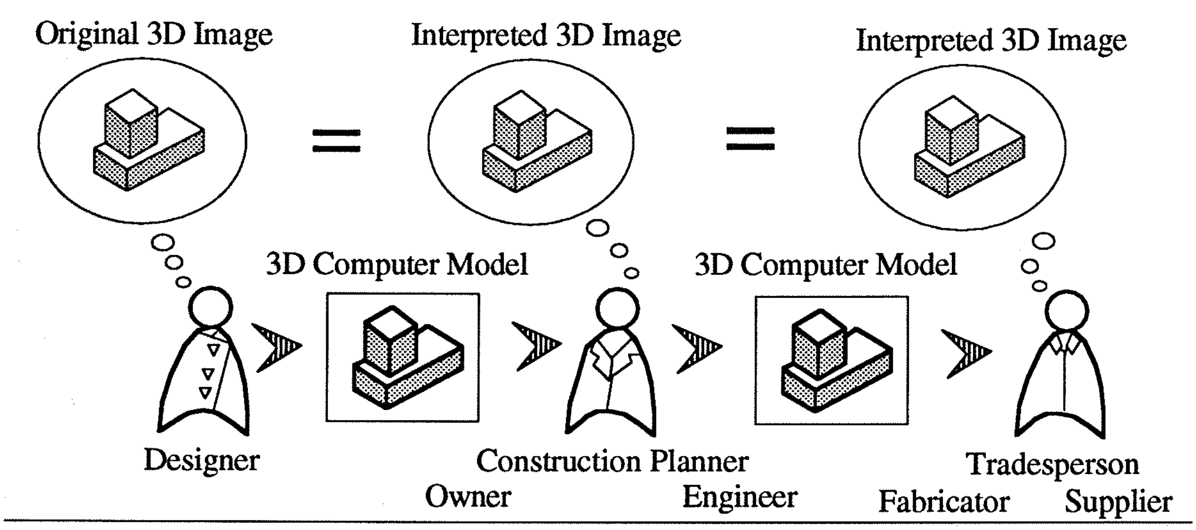


Figure 4 Communication using 3D Model

The Electronic Model

Unlike a physical model, this model can be viewed on individual computers in offices that are remote from one another. Thus, the model can become an object that each individual can study and examine, just as if each person had been able to take home a physical model. As in the example of the cube, having a model to "hold in one's own hand," or at least to rotate around on one's computer, leads to a much more complete understanding of the project. Because the model exists electronically, it can actually become various models at different scales and with different levels of detail which further enhance understanding.

Combined Information

Because of its being a geometric model, information is provided from a single source rather than on multiple drawings that must be combined in one's head. Sometimes referring to a number of drawings is required to understand a certain geometry. If there are disputes over the geometric interpretation, the parties must remember which and what aspects of the drawings led them to their conclusions. With the model, understanding geometry becomes simply a matter of turning the 3D model around enough times to understand it clearly. This requires a person only to remember areas that need to be discussed rather than also having to remember where all the drawings are that explain the geometry. This simplification in 3D also means a reduction in errors resulting from conflicts in dimensions or geometry that appears differently on different sheets, for instance, the foundation drawing and the first floor plan. Dimensions all come from the model, where each dimension is shown just once.

Although the information is put together in the form of a model, one can still view 2D plans, sections, and elevations. Viewing a floor plan from above is the quickest way to see the different functions of the rooms and such things as exit paths, rather than navigating through a model at eye-height. But since the model can be "cut" electronically at any location without changing or duplicating any of the data, two-dimensional views can still be used with all geometry coming from the 3D model. Using this method could virtually eliminate conflicts between plan, section, and elevation.

Getting Past the Puzzle

With all geometric data for construction projects documented in only two dimensions, constant effort is required to remember how all the different images fit together. Just as with the cube in Figure 1, this effort to solve the "puzzle" of 2D is one that is required of each person who works on the project who wants to get an idea of any piece of the structure. Having a 3D model to base discussions on removes the requirement of solving a puzzle. Two people can discuss the materials and methods of a structure while having a clear understanding of the intended geometric outcome.

Designers and contractors develop good puzzle-solving skills by converting 2D drawings into 3D images and built objects. They may even feel that "any good designer should be able to imagine the 3D aspects in their mind," or "3D models are good for people who can't build it in their mind." Although there is certainly a skill involved in understanding drawings, there are many other aspects of construction and design that have to be put aside until the 3D geometry is understood and any conflicts are solved. 3D Modeling is a tool that assists in making the geometry plain so that those involved can consider other issues more completely.

Complex Information

The 3D model allows perception of much greater amounts of information than the mind can easily put together. Imagine trying to create the image of a major city in your mind with just a map and a flat 2D drawing of the skyline. If you were asked to locate the position of the tallest building on the map, it would be quite difficult. If you were provided with a drawing of the skyline of each street, eventually by comparing the various drawings you could complete the task. On the other hand, if you were presented a 3D model of the city, the tallest building would be obvious (see Figure 5). Buildings and other structures are even more complex: understanding them involves more than just understanding the relative height of buildings in a city. Imagine if a contractor is handed a drawing of a building where the ceiling in each room is a different height and is asked to find the tallest ceiling. Again, the contractor would have to consult many 2D drawings to find the information that would be readily apparent in a single 3D model.

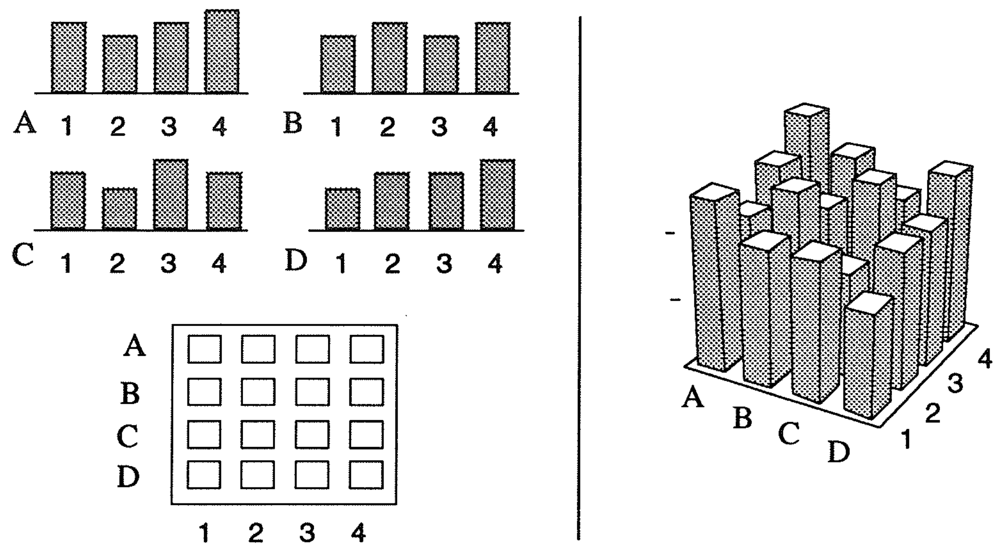


Figure 5   Complex Information Clear in 3D

1.3.3 Construction is 4D

While designers determine where objects should be to create spaces and fulfill requirements, contractors must figure out how and in what sequence to get those objects into position. This means that a contractor works with the added dimension of time. In addition to understanding the final manifestation of a structure, the contractor must plan each step that will be taken to build the project and determine when each activity will take place (see Figure 6). Thus construction deals with four dimensions: the three dimensions of space plus time.

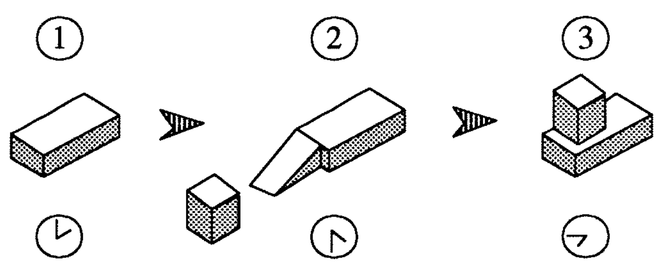


Figure 6   Construction Sequence

The beginning time for each step must be estimated so that the proper materials and the proper work crews show up at the location of construction at the proper time. This requires the sequence of installation to be planned out, as well as estimates for how long each step will take. Projects that have carefully-planned sequences and accurate time estimates have substantially better outcomes than those less carefully planned. But once the plans have been made, they can only be effective if they are communicated to those involved in the construction process.

Current Methods of Communicating the Construction Schedule

Today the common method of documenting the construction schedule is with a two dimensional bar chart (See Figure 7). This information, just like 2D drawings, is incomplete by itself. Although one can understand from it an activity such as "build ramp," there is no information about the proper placement of the ramp, how long it needs to be, and so on.

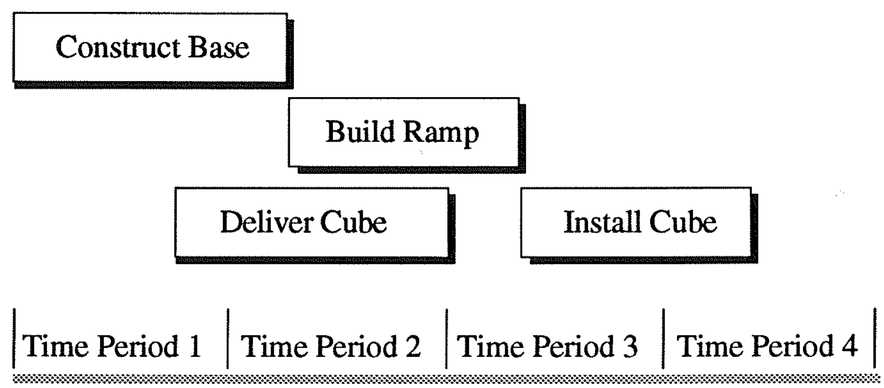


Figure 7 Construction Schedule

These schedules have been developed to the point where they can contain information such as identifying the critical activities to keeping the job on schedule, the effect of different crew sizes, and so forth. But all coordination with geometric information must take place in the heads of those planning construction. There is usually so much information for the different subcontractors who perform different parts of the work that they only try to understand their own small piece of the work. It is then up to the project team supervising construction to coordinate the integration of the different work forces.

Construction Planning with 4D Computer Models

When the design of a structure is communicated with a 3D model, there is the potential to turn it into a 4D model for construction planning. Because 3D computer models can easily be taken apart and put back together, one can model and show the construction sequence over time (see Figure 8). The construction planner can develop a sequence of construction and estimate the duration of activities and then simulate it by having the model appear on the computer screen as it is to be built. Such a display shows not only the time frame for each activity in the construction schedule, but also all geometric data about the object itself and its location relative to other objects.

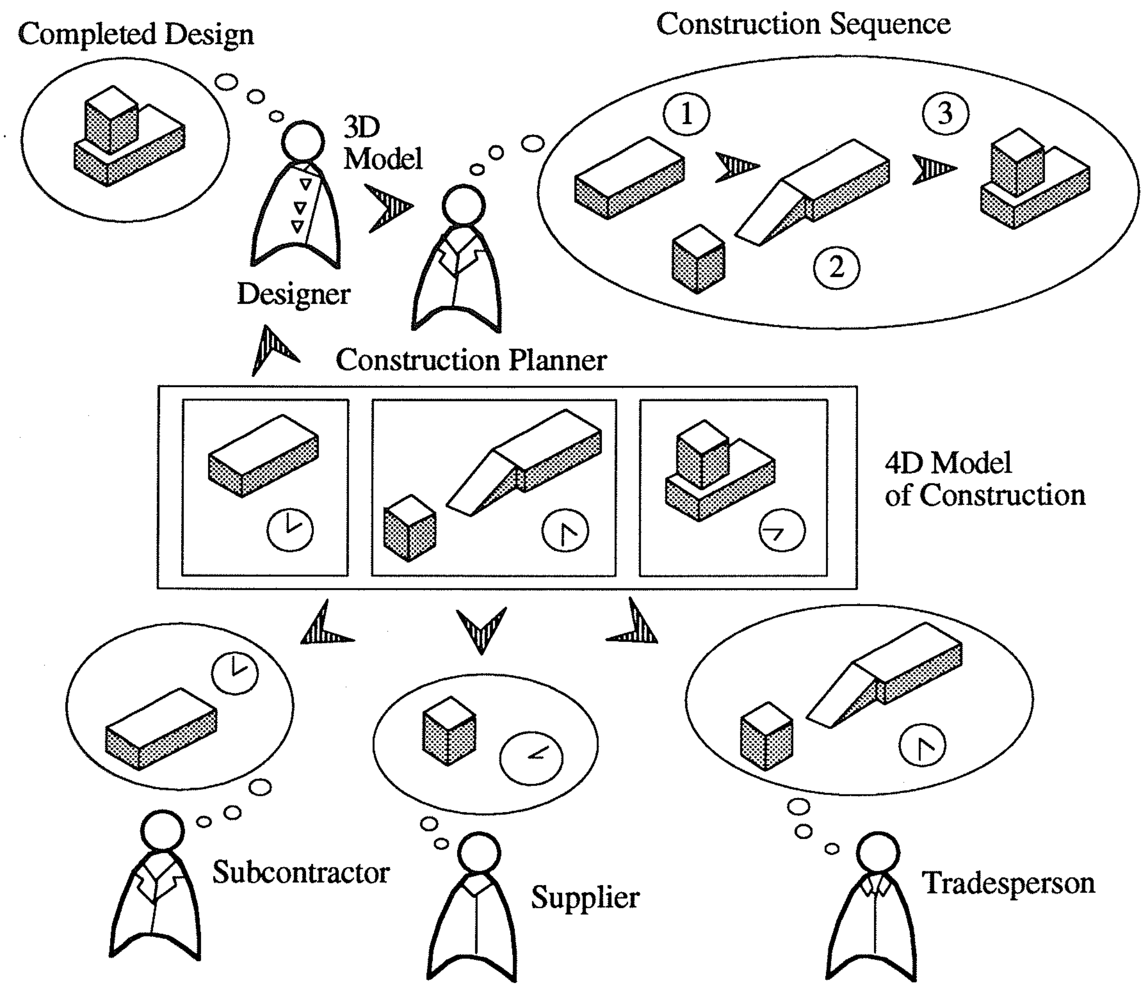


Figure 8 Construction Planning with 4D Computer Model

Multiple Models in One

Simulating construction with 4D CAD is similar to having a new 3D computer model for each day of construction. On any given day in the planned duration of construction, the model can show what parts of construction will be in place and what pieces will be under construction. This is the same as if someone were to build a physical model and take a picture of each day's construction. But with a 4D model, one can repeat the process again and again from different viewpoints, at different time increments, and in different scales.

Emphasis on the Process

Having a flexible, easily transportable 4D model, dramatically increases the number of people who are able to visualize the construction accurately. Everyone from clients to the suppliers of construction materials can view the planned sequence of work. By viewing the model, each can gain an understanding of the overall process and how each person's part fits in. This accessibility leads to participants who have better and more complete information who can work together more efficiently and create higher quality construction.

1.3.4 Continued Discussion

The remainder of this report will discuss the specific aspects of 3D and 4D CAD models for construction in more detail. Chapter 2 discusses an actual 4D model that I took part in developing. In this discussion, examples of the 3D model and the schedule are shown. Still images of the 4D CAD model animating the construction are also shown. The purpose of this case study is to demonstrate a practical example of a major project where 4D CAD was used in order to explain what we experienced in developing this model, and to set the groundwork for further discussions of 3D and 4D CAD models.

Because of the critical part 3D CAD models play in being able to build the 4D CAD model, a comparison of physical and 3D electronic CAD models is made in the beginning of Chapter 3. Different aspects are considered such as the fact that 3D CAD models can be used as a basis for numerous other programs that analyze, display, and utilize the 3D CAD data in various ways. I then discuss the value of 4D CAD; highlighting each of the different participants specific benefits from this one very powerful use of the 3D CAD model. Next I outline steps for implementing 4D in practice today in order to show that this technology can be implemented immediately and may soon be required by some clients. Recognizing that there are still obstacles to the use of 4D CAD, I use the next part of the section to discuss some of these challenges. This leads into Chapter 4 where I discuss how some of these challenges might be met.

Chapter 4 focuses on developing technologies that will make the use of 3D and 4D CAD more powerful as well as more practical. In discussing the future possibilities I recognize that many large firms are well advanced in the use of 3D and sometimes in 4D as well. I do not try and make a precise distinction between the benefits, current uses, and future uses of this technology. Some people may be using the technology and not realizing all the benefits of it while others who see the common use of 4D only far into the future may be persuaded of the value in trying it today. Chapter 5 includes a summary of this report and a section on conclusions that puts 4D modeling in the broader context of its implications for society.

2 CASE STUDY: SAN MATEO COUNTY HOSPITAL

This case study consisted of the modeling in 3D CAD over 30,000 three-dimensional elements of the buildings on the campus of the San Mateo County Health Center. It was a research project conducted by the Center for Integrated Facility Engineering at Stanford University, funded by Dillingham Construction Company of Pleasanton, California.

2.1 Purpose of Case Study

This case study was undertaken for the benefit of understanding 4D CAD. Although conceptually the value of 4D CAD can be explained and understood, the actual implementation of it, like any new technology, is more difficult. Understanding more closely the capabilities and limitations of new technology requires using it and testing it out. The project of modeling the San Mateo County Health Center buildings and linking them to the planned construction schedule resulted from the desire of two groups to understand and use 3D CAD and explore the added capability of animating the construction schedule with a 3D CAD model.

Members of the management team at Dillingham Construction had become familiar with 3D CAD through a small tunneling project that they had modeled and animated to help plan construction and explain it to the client. With the San Mateo job, they were interested in the possibility of modeling a large, multi-year job, and in being able to show the construction sequence as well. The Center for Integrated Facility Engineering has been in existence for seven years and has the purpose of assisting the advancement of the industry through better methods, including the use of computational tools. Although work developed at CIFE showed potential for the uses of 3D modeling, no extensive 3D modeling of an actual project had been done. One of the primary goals of this work was to be able to show people in the industry the potential for immediate implementation of this technology in the industry by using currently available low-cost software and by providing a visual example of a significant project modeled in 3D CAD and linked to a construction schedule, resulting in what we came to designate as 4D modeling.

2.2 Challenges of the Project

Description of Project

The San Mateo County Health Facility is a 70 year old facility that occupies most of a city block in San Mateo, California. In 1993, Dillingham Construction was selected as the Construction Manager for a remodeling and renovation project with a budget of $94.5 million and a completion date in the year 1999. This project involves over 280,000 square feet of new building floor area and the remodeling of over 40,000 square feet. The project was designed to replace all of the buildings on the east side of the health care campus. A total of five new buildings will be built, three buildings will be torn down, and the main hospital building will be renovated.

Uninterrupted Hospital Operations

The health facility is the only major hospital in San Mateo. It serves not only hospital patients, but other county programs including county psychiatric services and all county-sponsored food preparation activities from prisons to day-care facilities. Out of this developed the requirement that no hospital operation could be interrupted during construction. There needed to be continual access from patient rooms to all necessary areas of the hospital until the new rooms were ready. Departmental relocation had to be planned so that it caused the least disturbance to the department being moved, but also did not impede the operation of other departments.

Because of this, Dillingham had to plan the activities of the construction carefully. These plans included the location of temporary trailers on the site during some phases of construction and the building of a "link" between an old and a new building at another phase. Another major element of the plan was to build the new main entrance building in two halves to allow for the proper sequencing of construction. While all this was occurring, construction would also be taking place at other locations. Construction of the various buildings was planned to overlap in order to meet the necessary schedule for the use of each building.

Communication with various departments

Dillingham has full responsibility for coordinating all the construction activities with the hospital. This means that not only must the administrators of the hospital understand the construction schedule, but all the department heads as well. During construction, the path the ambulances take to arrive at the emergency room will have to change a number of times. Other departments will have similar changes occurring during construction. All of these changes could have a ripple effect and delay the project if all parties involved do not clearly understand when and where they have to move so that they can be prepared at the proper time.

Proposed methods for communication

The method that was used during the design phase of the project to communicate how the buildings would be built was to show a view from above of the entire site including all the old and new buildings. On each building was written the date that construction was to begin and the date that occupancy of the building was expected. For the buildings that were to be torn down, the dates indicated the expected demolition time period. To this was added a number of notes and arrows to clarify what would be happening over time. In another attempt at explanation, multiple small sketches were used to show the buildings that would be built or torn down at a certain date. Neither of these approaches gave a clear idea of the complexity of the schedule and the implications to the hospital. The first method of showing everything on one page was confusing and the second method oversimplified the process. It was felt that creating the schedule animation with a three-dimensional model would be a much more informative method of communicating complete information about the plans for the health center.

2.3 Accomplishments

With Martin Fischer as my advisor and principal investigator, I undertook the modeling and schedule animation of the San Mateo Facility. Modeling was done with AutoCad and animation was done on a Silicon Graphics Indigo Elan with Bechtel Walkthru software licensed to Jacobus Technology. Jacobus Technology also supplied the Construction Simulation Toolkit that made possible the linking of the schedule to the 3D models.

2.3.1 Building of models

The Ratcliff Group architects supplied their two-dimensional AutoCad Release 12 drawings of all the buildings on the campus. Using AutoCad, I took the information from the CAD drawings and the construction documents themselves (since some drawings were not drawn on the computer) and created three dimensional objects for the buildings.

Central Utilities Plant

I first modeled the Central Utilities Plant, the first building that is being built. I modeled all the concrete foundation work including step footings, retaining walls, and piles. I also modeled the structural steel beams and columns, the major equipment, some of the mechanical piping, the metal stud framing, and the exterior architectural features. While modeling the retaining walls, I discovered that there were two different representations for one section of one of the walls. The architect had shown concrete surface at the top of the wall that was wider than the columns for the length of that section. The structural engineer had shown a thinner wall with pilaster projections for the columns. The architect's elevation drawing showed a smooth surface instead of pilasters. As soon as it was brought to Dillingham's attention the lack of coordination was resolved (see Figures 9 and 10).

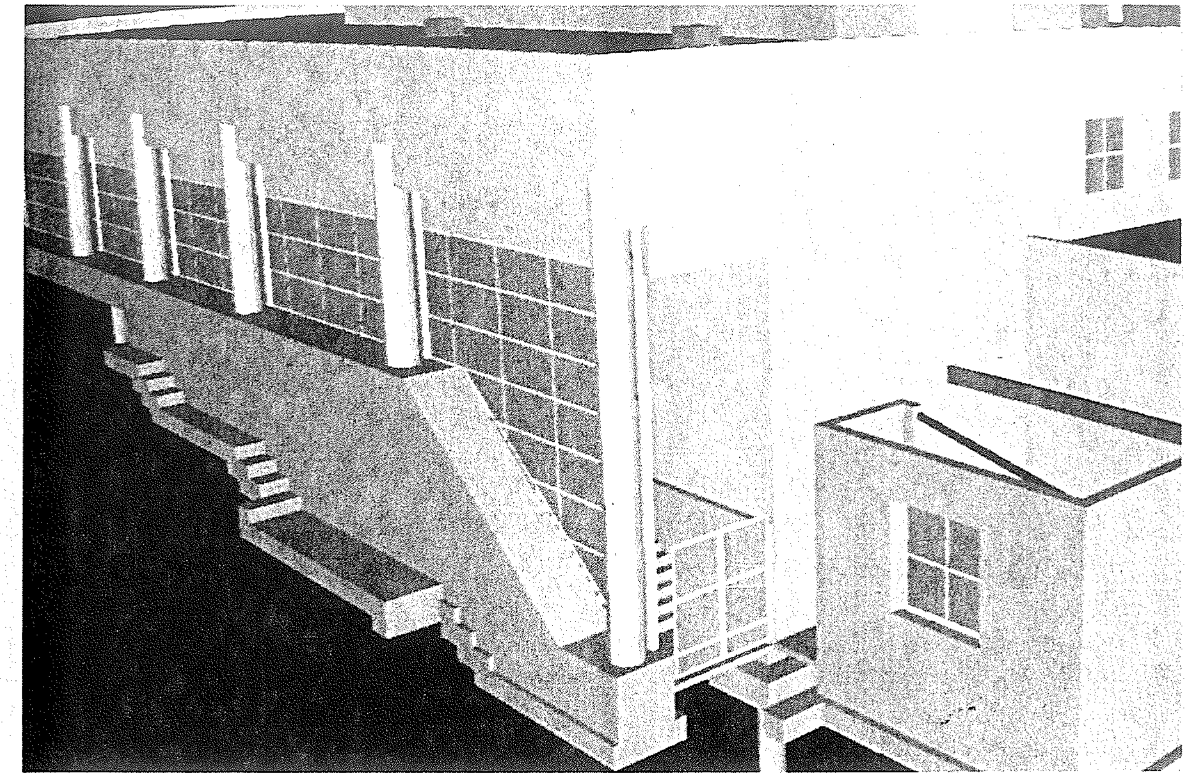


Figure 9 3D model of retaining wall, interpreted from architect's 2D drawings.

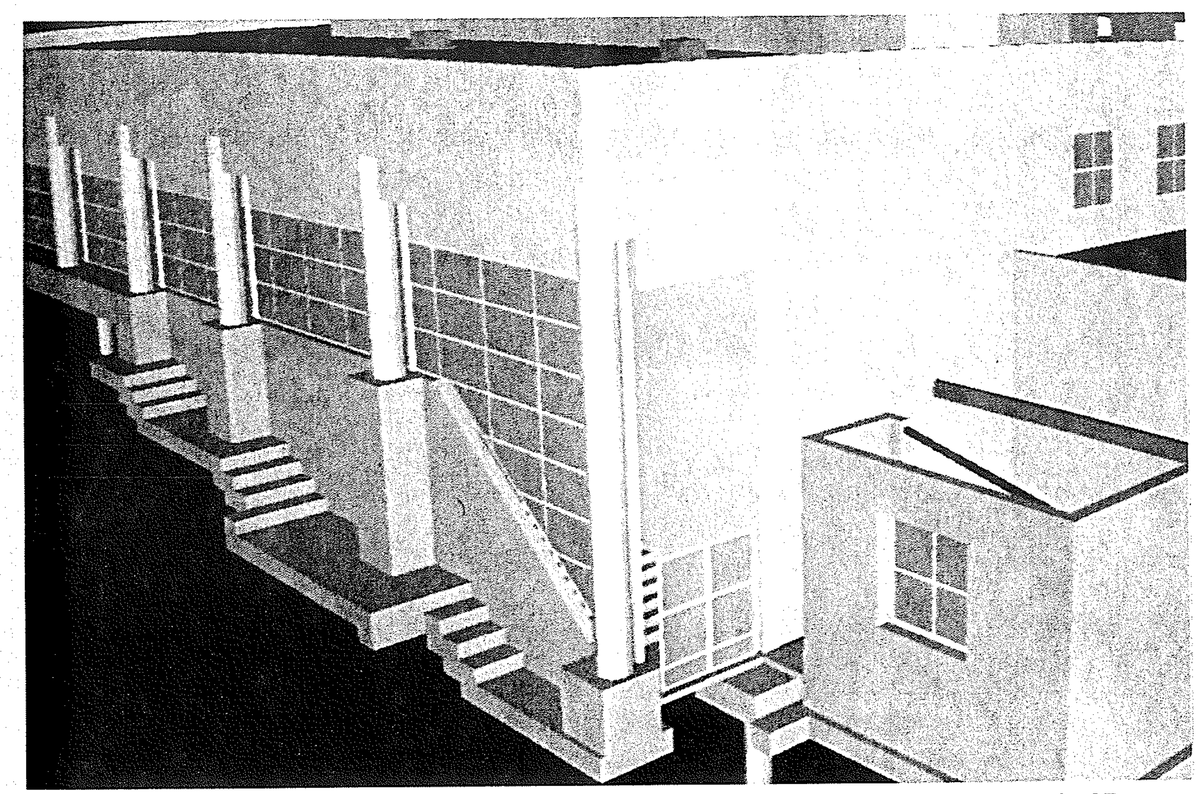


Figure 10 3D model of retaining wall, interpreted from structural engineer's 2D design drawings.

Although a number of people had examined these drawings, no one had discovered this discrepancy. The project had already been bid, and there probably would not have been a resolution of this item until construction had begun if the 3D model had not been built. The hospital was able to save concrete and what could have been costly change orders. In the 3D model the difference is obvious. This gave everyone working on the project a clear example of the clarity of this type of 3D model.

In another case, a subcontractor working on the concrete walls had been perplexed by the number of changes in elevation and the large number of step footings. He was able to come in and view the model of the concrete and immediately understood the design. He said that he could understand in 10 minutes what he had been spending hours to try and figure out.

Entire site

After the Central Plant the entire site was modeled. The exterior architectural features of each building were created, including individual glazing elements and window mullions, and the base structure of the buildings including structural columns and floor slabs. During the final stages of the process, Dillingham hired a person to assist with the modeling who completed the model of the existing hospital and the hospital site. Additional help was obtained from students who modeled all the interior walls and the stairways for all the new buildings.

Figures 11 and 12 show views of the AutoCad model. Figure 11 shows a close up of the central open-air atrium which will serve as the hub for the activities of the remodeled health center. Figure 12 shows a few of the entire site. These models are drawn with "wire frames." This method of modeling does not shade the surfaces in between the outlines of the objects. This is the way most 3D models are viewed as they are created. Even though they are difficult to decipher because of lines being drawn on top of other lines, they already provide more information than the 2D drawings, namely both the relative area of the atrium and the height of the atrium.

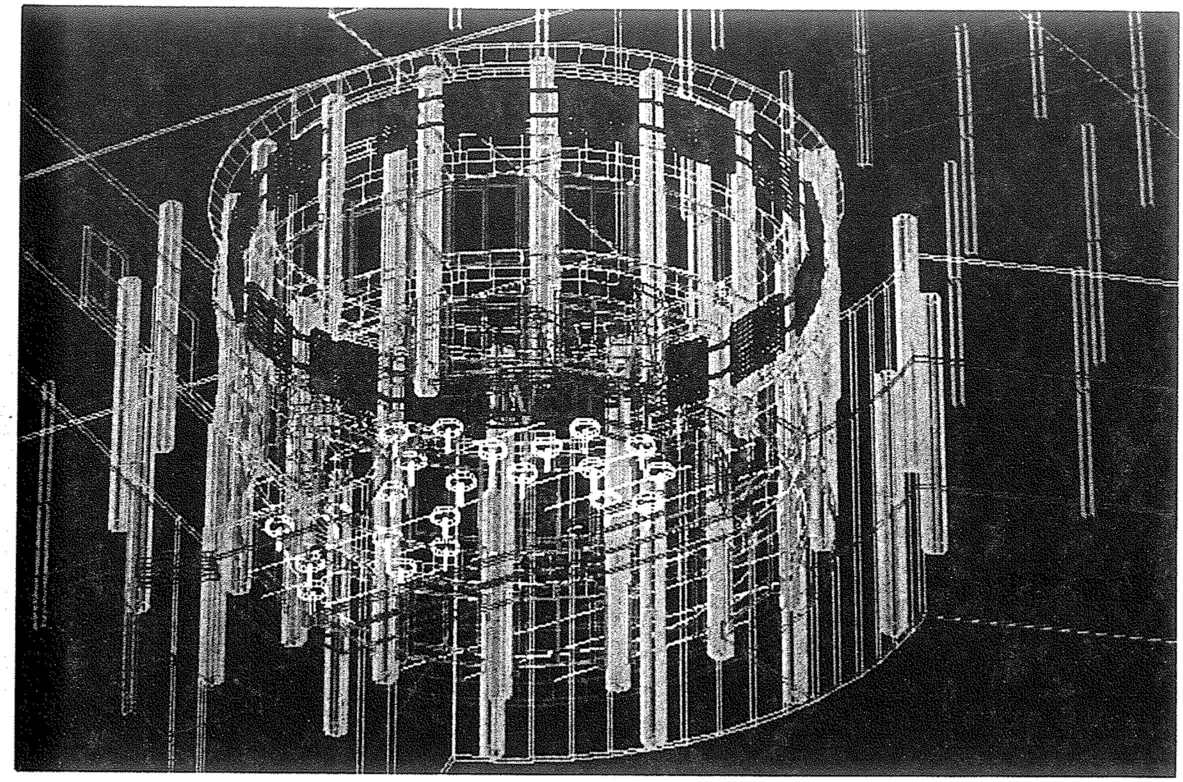


Figure 11 AutoCad model of atrium area, North Addition, San Mateo County Health Center.

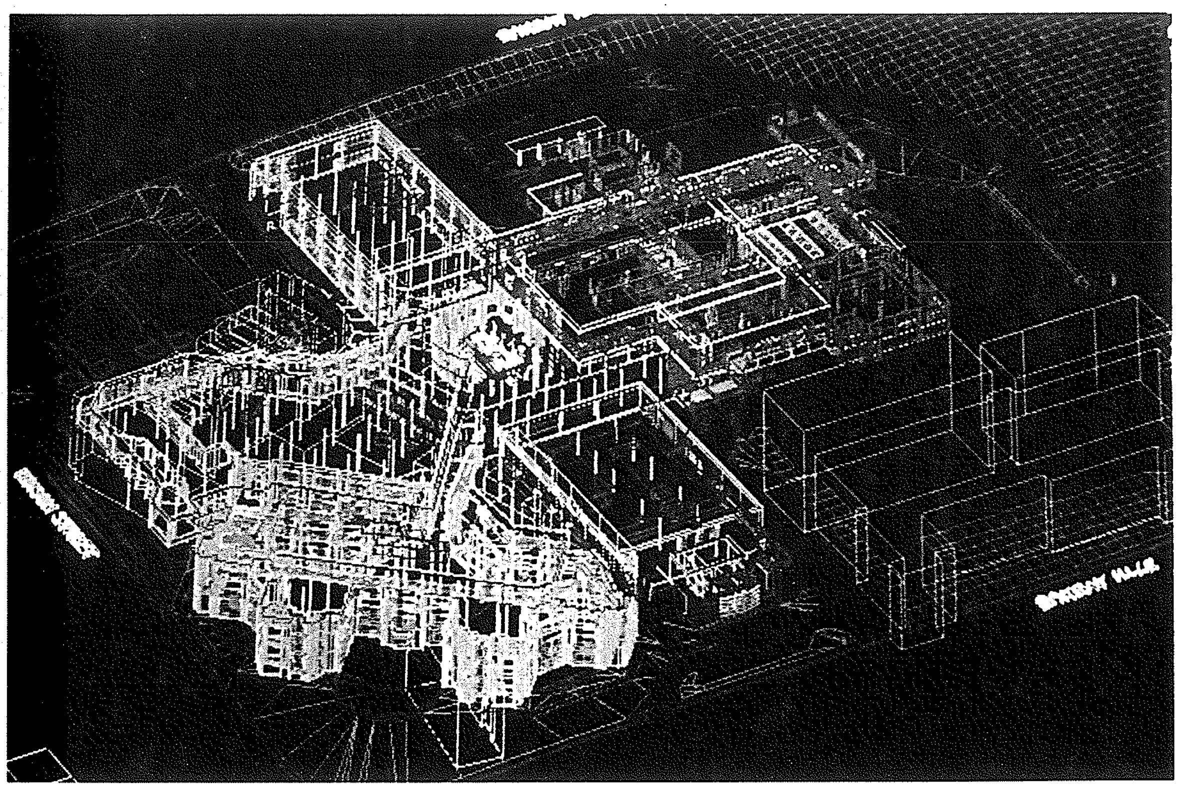


Figure 12 AutoCad model of entire site of the San Mateo County Health Center

During the same time that this computer model was being constructed, the hospital commissioned a physical model of the site. This model is approximately 18 inches by 30 inches. It is encased in glass and displayed in the lobby of one of the Health Center buildings. This model cost approximately $100,000 and was already out-of-date within a few months of its completion. The hospital had decided on a design change and it was estimated that it would have taken $20,000 to make the change. The entire electronic effort, including the Central Plant, the entire site, schedule animations and video creations could have been done for the original $100,000 if time had been billed at $80 an hour (and probably much less considering 20%-40% of the time could be considered accountable to the learning of new technology), and the change could have been done for a fraction of the estimated $20,000.

2.3.2 Linking the Schedule

The second phase of the project involved linking Dillingham's Primavera Schedules to the 3D CAD models. Figure 13 shows a bar-chart version of one version of the overall schedule created by Dillingham. Figure 14 shows a part of schedule print-out that shows the schedule dates. This is the type of format that schedules are currently presented in. One must carefully piece the different pieces of information together to understand the overall schedule.

The 4D model uses the information from these schedules to create the animation. These schedules give the start and finish dates for all the activities as well as calculating the activities that are on the critical path. Critical path activities are defined as those activities that will directly delay the entire job if they are delayed, while non-critical path activities can be delayed without affecting the entire job. By being linked to the corresponding 3D CAD objects, these schedules come alive even to the untrained eye. The animation of the schedule shows red (indicating critical path activities) and green (non-critical path activities) to highlight objects currently being constructed during the time frame indicated on the screen. The entire construction period is illustrated by weekly or monthly intervals (or any other interval the viewer selects). The linking takes place by extracting the layer names from the AutoCad model and linking them to the activity number from the Primavera schedules using Jacobus Technology's Construction Simulation Toolkit software (see Figure 15). The animation is then shown in Walkthru (Walkcst version.).

By animating the entire construction period one obtains not just a single 3D model of the completed project, but rather a new model for every day of the planned work. This technology thus represents a very practical and useful way of viewing information, not just in three dimensions, but with the fourth dimension of time as well.

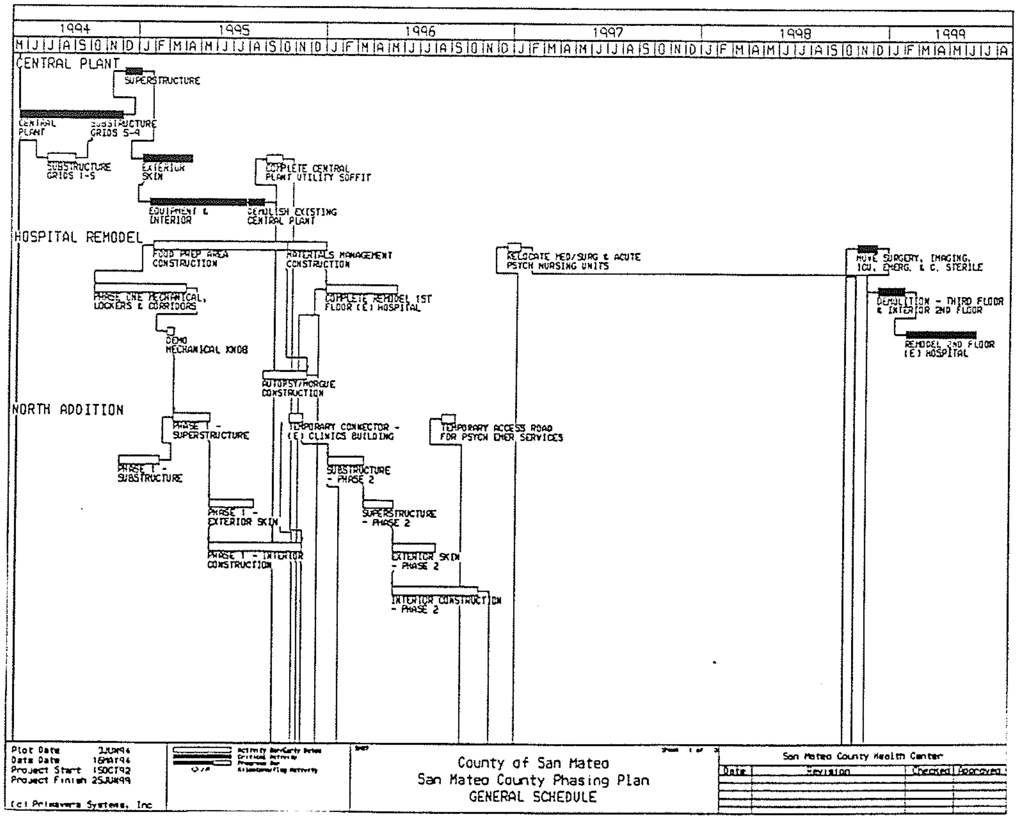


Figure 13 Bar-chart version of a portion of the San Mateo County Phasing Plan

ACT	TITLE	ES	EF
13	STARTUP/TESTING/CERTIFICATION	6FEB95	31MAR95
14	DEMOLISH EXISTING CENTRAL PLANT	3APR95	5MAY95
16	COMPLETE CENTRAL PLANT	8MAY95	9JUN95
274	DEMOLITION - THIRD FLOOR & INTERIOR 2ND FLOOR	23NOV98	15JAN99
276	REMODEL 2ND FLOOR (E) HOSPITAL	18JAN99	4JUN99
360	NORTH ADDITION - PHASE ONE CONSTRUCTION	5SEP94	7JUL95
378	TEMPORARY CONNECTOR - (E) CLINICS BUILDING	10JUL95	4AUG95
379	REMOVE TEMPORARY CONNECTOR	20MAY96	31MAY96
380	NORTH ADDITION - PHASE TWO CONSTRUCTION	21AUG95	19APR96
382	MAIN ENTRY CONSTRUCTION	24FEB97	11JUL97
440	NURSING WING & LINK CONSTRUCTION	8MAY95	20SEP96
480	MOVE PSYCH EMER SERVICES TO D & T BUILDING	21SEP98	9OCT98
652	MOVE BILLING OFFICE TO PORTABLE BUILDINGS	10JUL95	21JUL95
654	MOVE CLINICAL LAB & PHARMACY TO NORTH ADDITION	21AUG95	8SEP95
658	MOVE NURSING UNIT TO (E) CLINICS BUILDING	7NOV94	25NOV94
670	DEMOLISH EAST WING	11SEP95	6OCT95
680	CLINICS BUILDING CONSTRUCTION	9OCT95	12JUL96
708	INSTALL MODULAR UNITS @ S. SIDE OF (E) CLINICS	15SEP94	12OCT94
710	RELOCATE NURSING UNIT FROM (E) CLINICS BUILDING	18NOV96	13DEC96
720	DEMOLISH EXISTING CLINICS BUILDING	30DEC96	21FEB97

Figure 14 Partial San Mateo Health Center schedule in text form

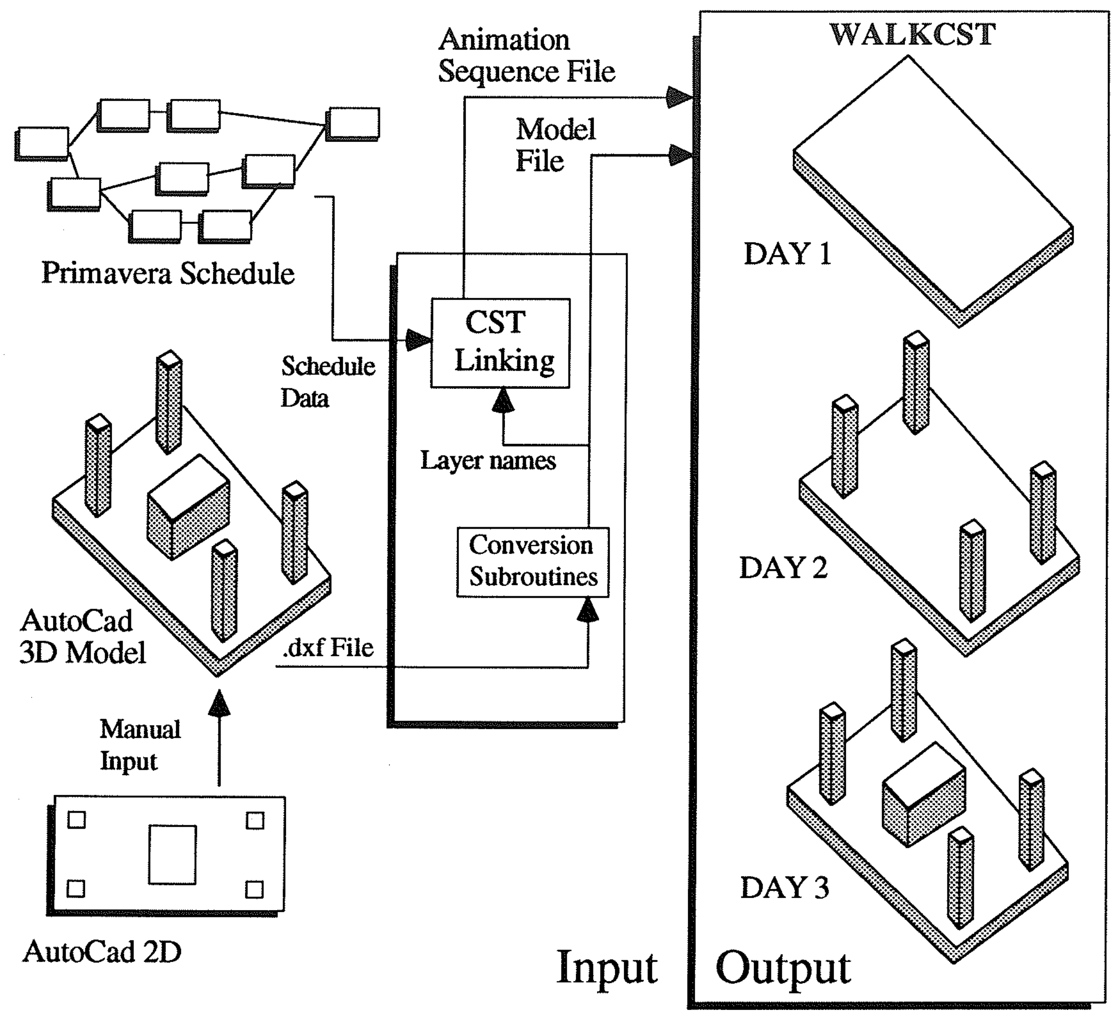


Figure 15 The Linking Process of the Schedule and 3D CAD Model

2.3.4 The Construction Schedule

The following pages show the Central Plant and the entire site as they will appear during construction. These are only a few days out of a few years. A new image could be shown for each week of construction. Additionally, the viewpoint is kept consistent for the ease of the reader in recognizing the progress of construction over time. The models can actually be moved around while the construction schedule is being simulated, or one can observe the schedule from any point inside the buildings as well. Four images of the Central Utilities Plant are shown for the construction schedule of approximately 11 months (Figures 16 through 19). Eight images of the construction of the entire site are represented, showing the construction from 1994 to the middle of 1999 (Figures 20 through 27).

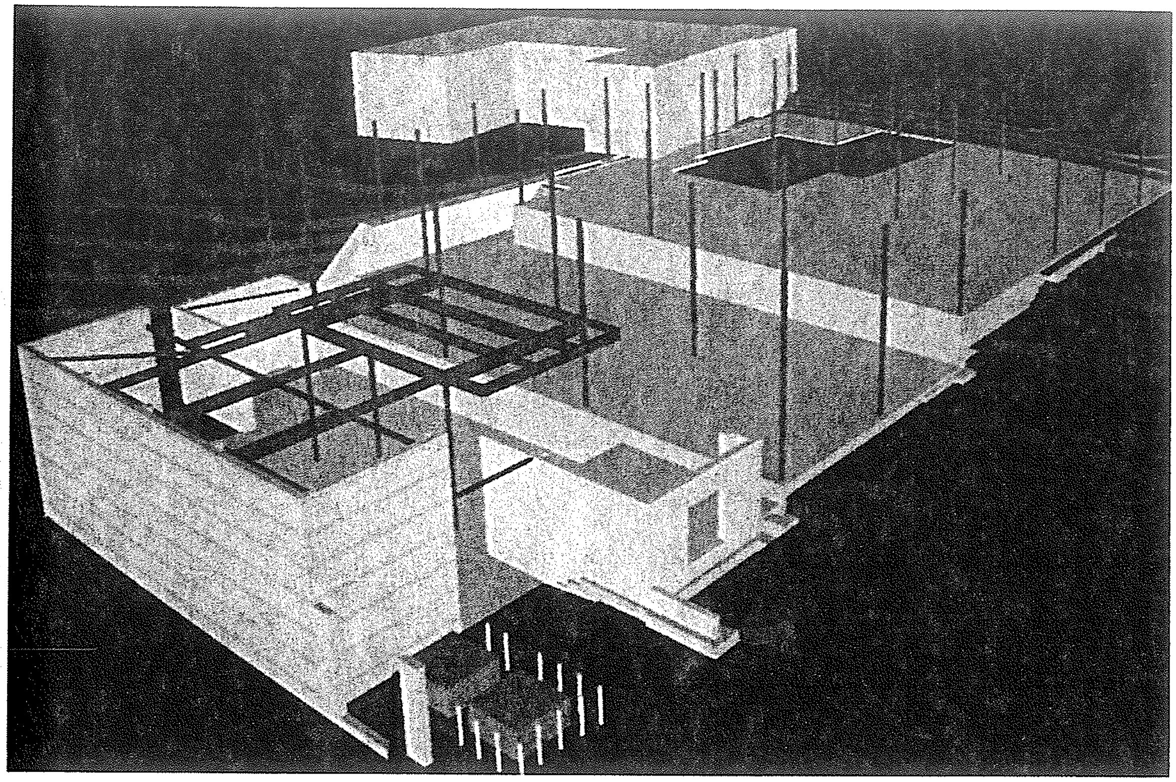


Figure 16 Nov 1994 Central Utilities Plant construction reaches installation of structural steel. All footings, concrete slabs, and masonry walls are in place.

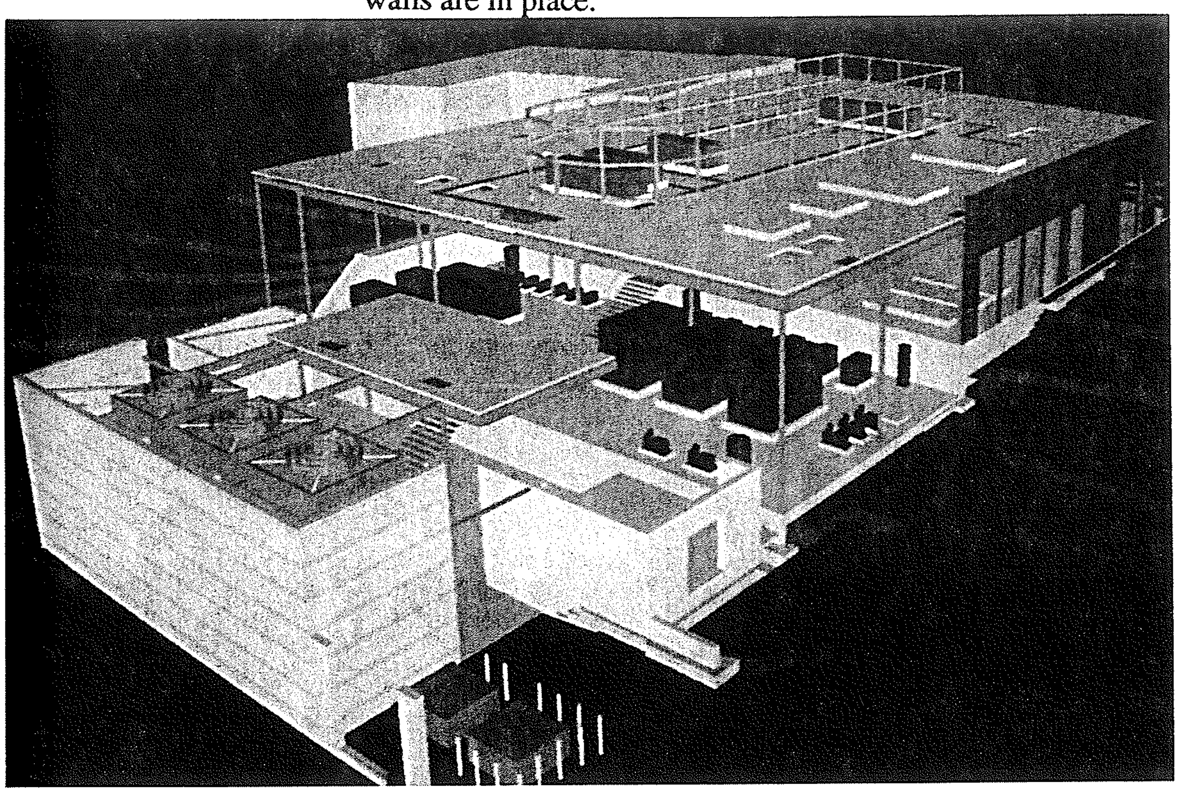


Figure 17 Feb 1995 All structural steel has been installed, concrete roof and all concrete equipment pads poured. Metal studs installed at the rear of the building to keep the front open to bring in equip.

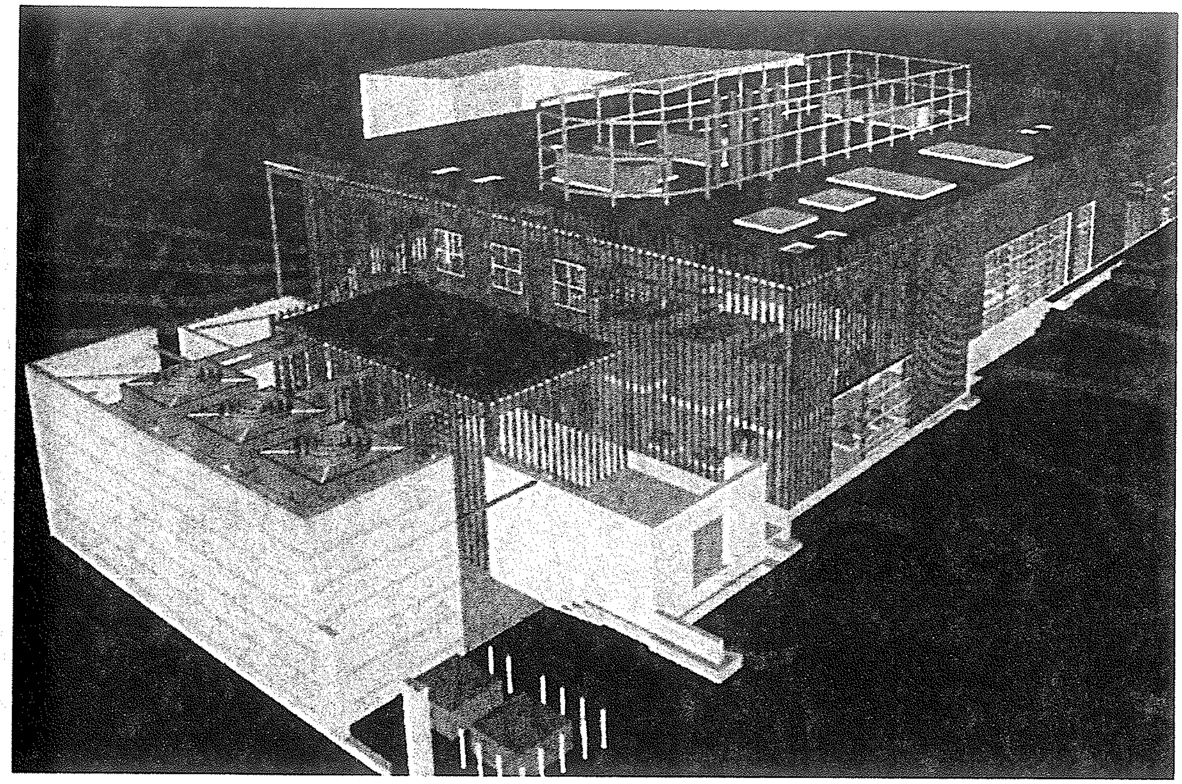


Figure 18 March 1995 Completion of exterior metal studs. Begin piping work on interior of the building.

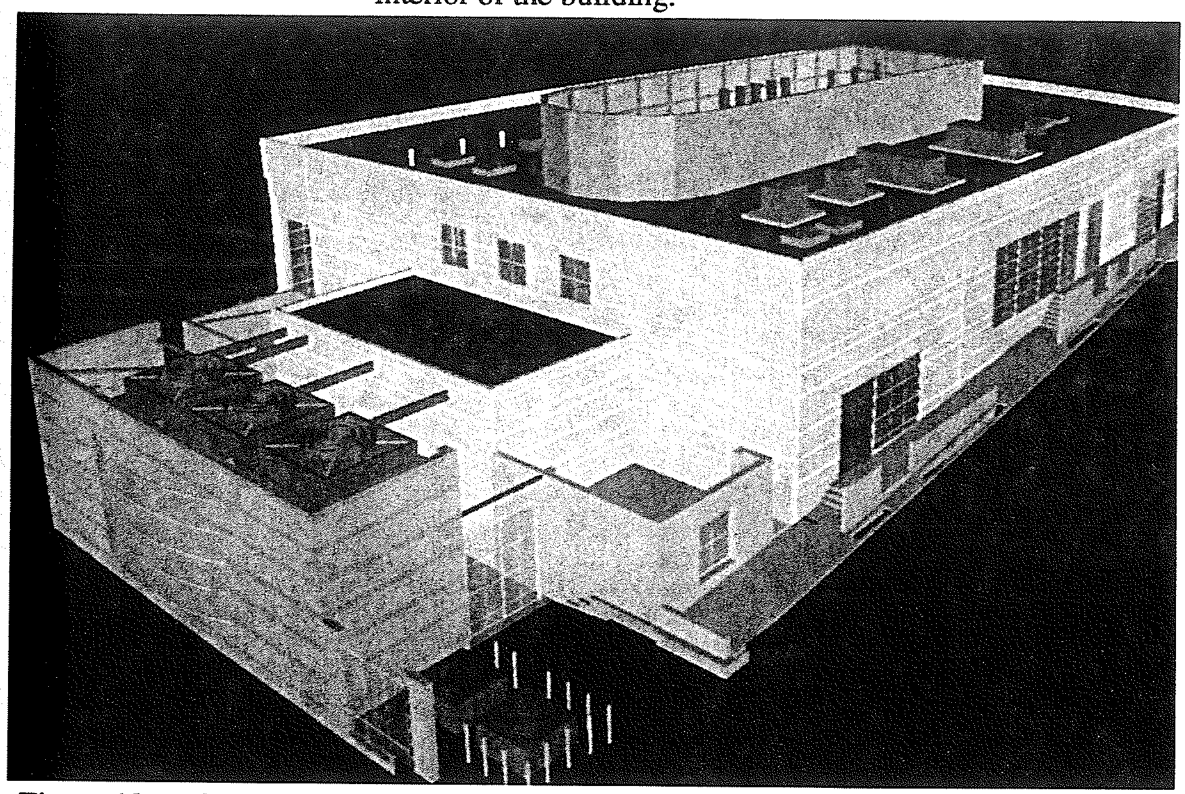


Figure 19 Oct 1995 Central Utilities Plant is completed and in operation. Old Utilities Plant has been demolished.

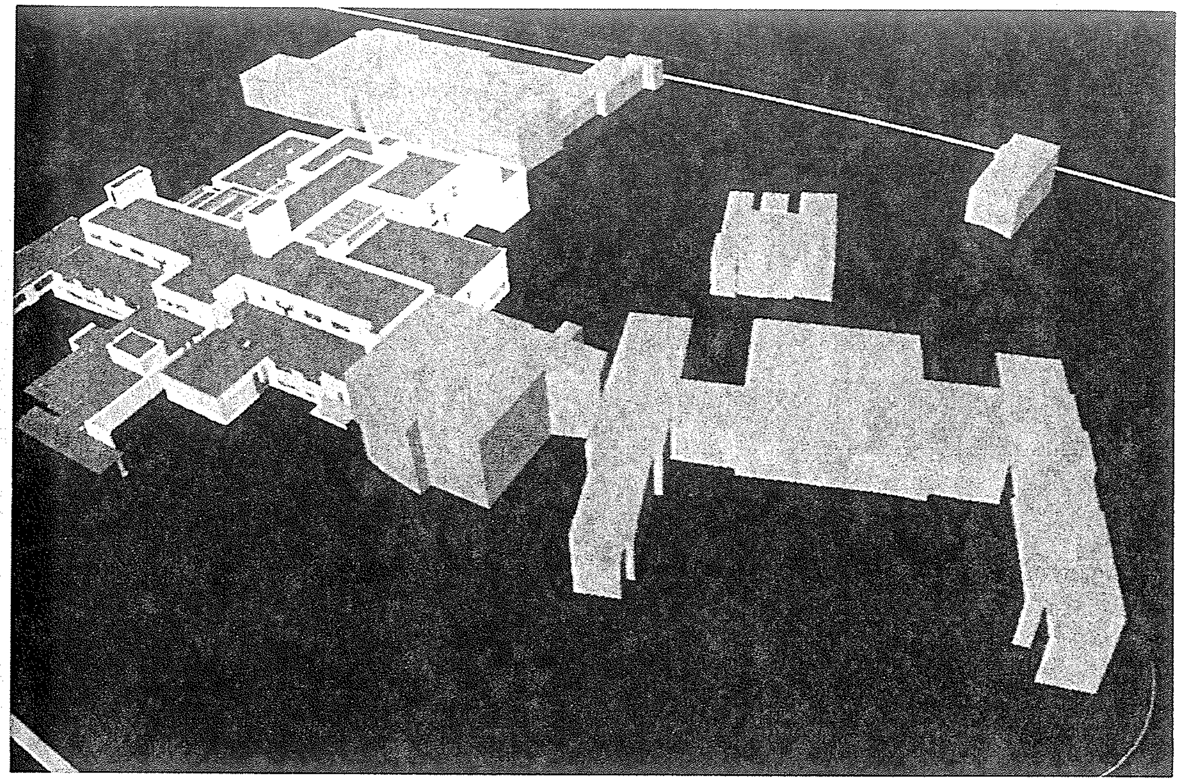


Figure 20 May 1994 Site with existing buildings: Main Hospital at left, Clinic Building at right foreground, East Wing in between, Existing Utilities plant in middle, Aids Clinic at top right.

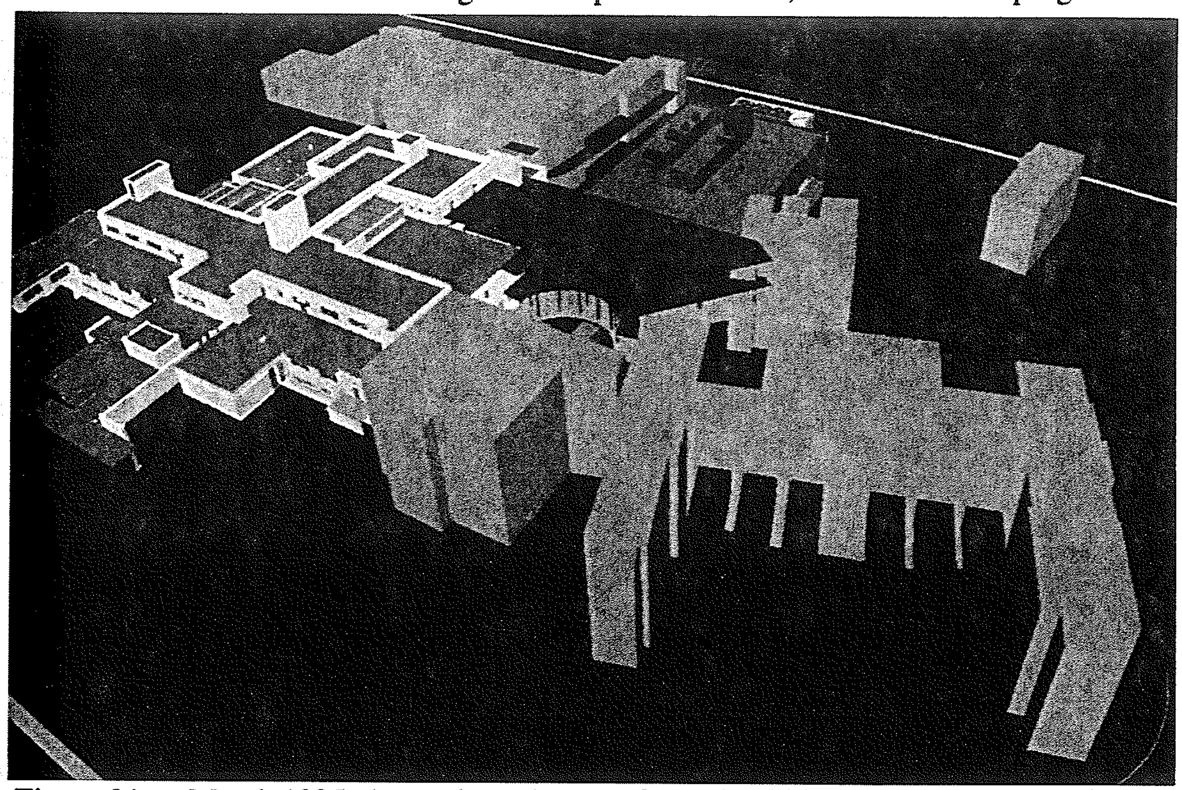


Figure 21 March 1995 As work on the new Central Utilities Plant proceeds as the critical activity, construction on the first half of the North Addition begins. Trailers are installed by Clinics building.

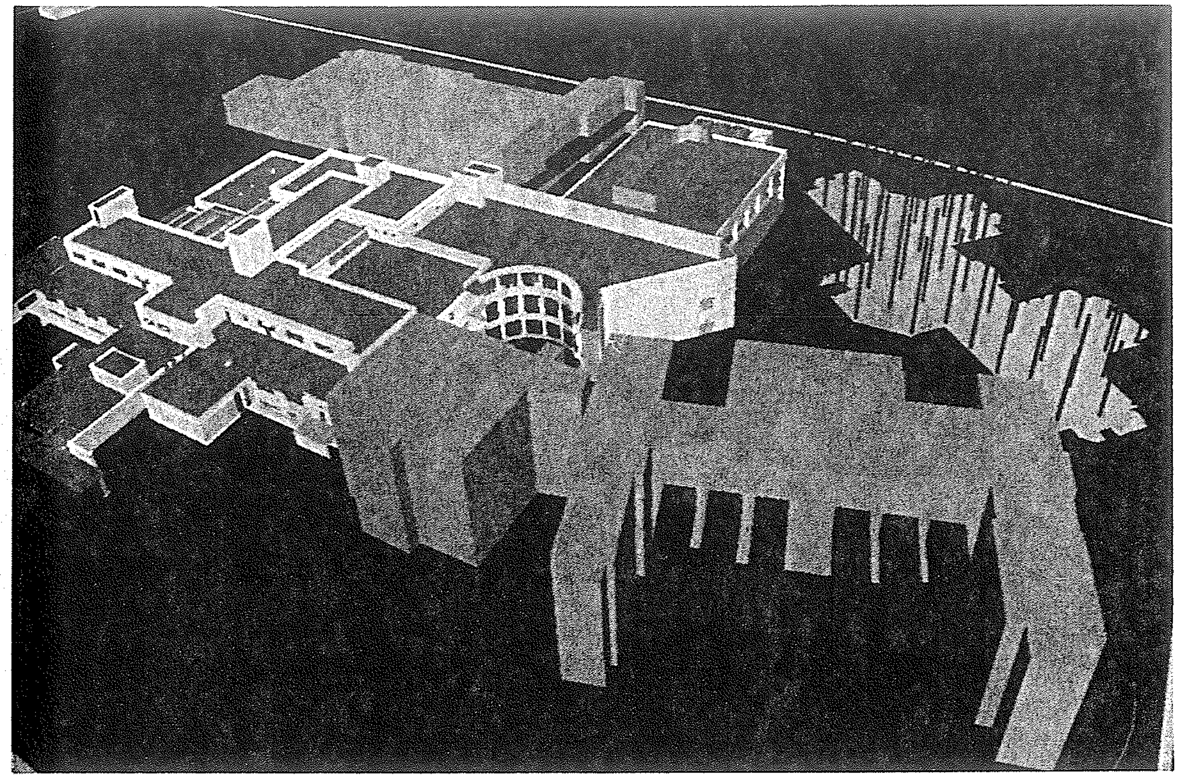


Figure 22 Oct 1995 Central Plant is completed, North Addition interior work being completed. Aids Clinic now in trailers. Aids Clinic is demolished and work has begun on new Nursing Wing.

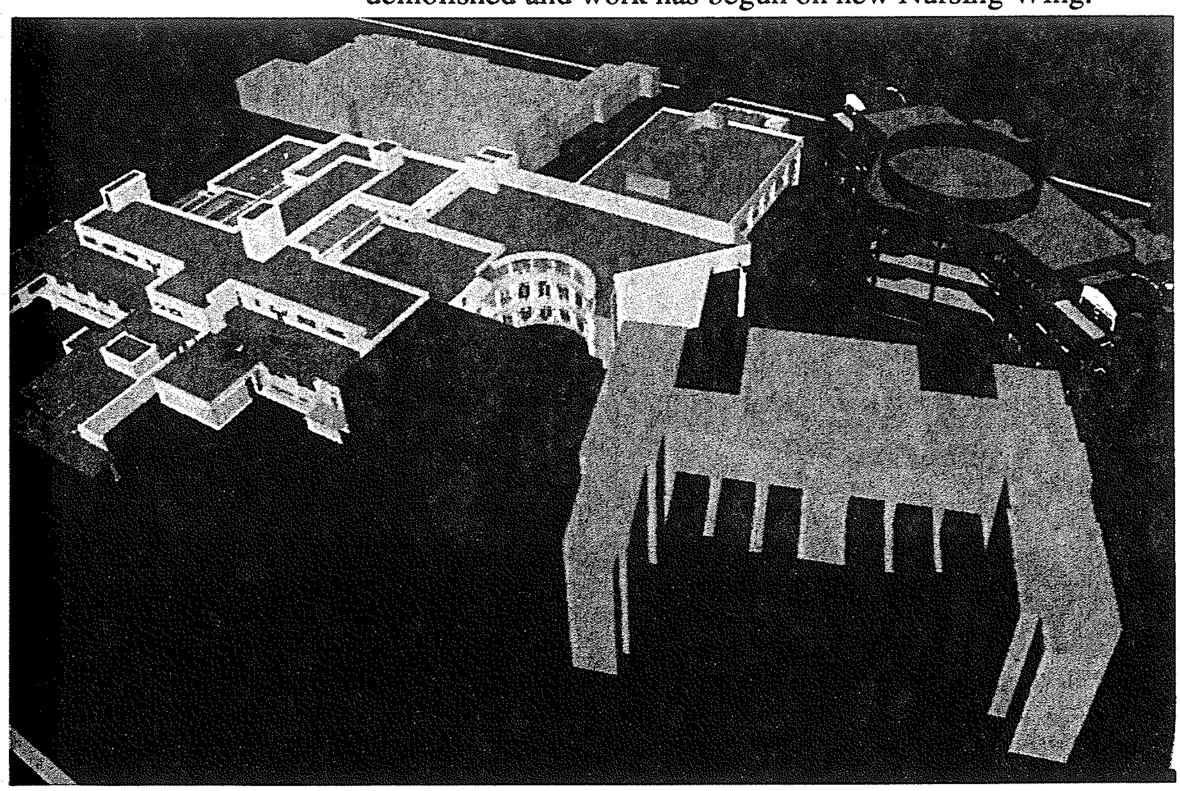


Figure 23 Jan 1996 Nursing Wing exterior shell begins construction as critical path activity. East Wing functions are moved to North Addition. Connector is created to link to Clinic Building.

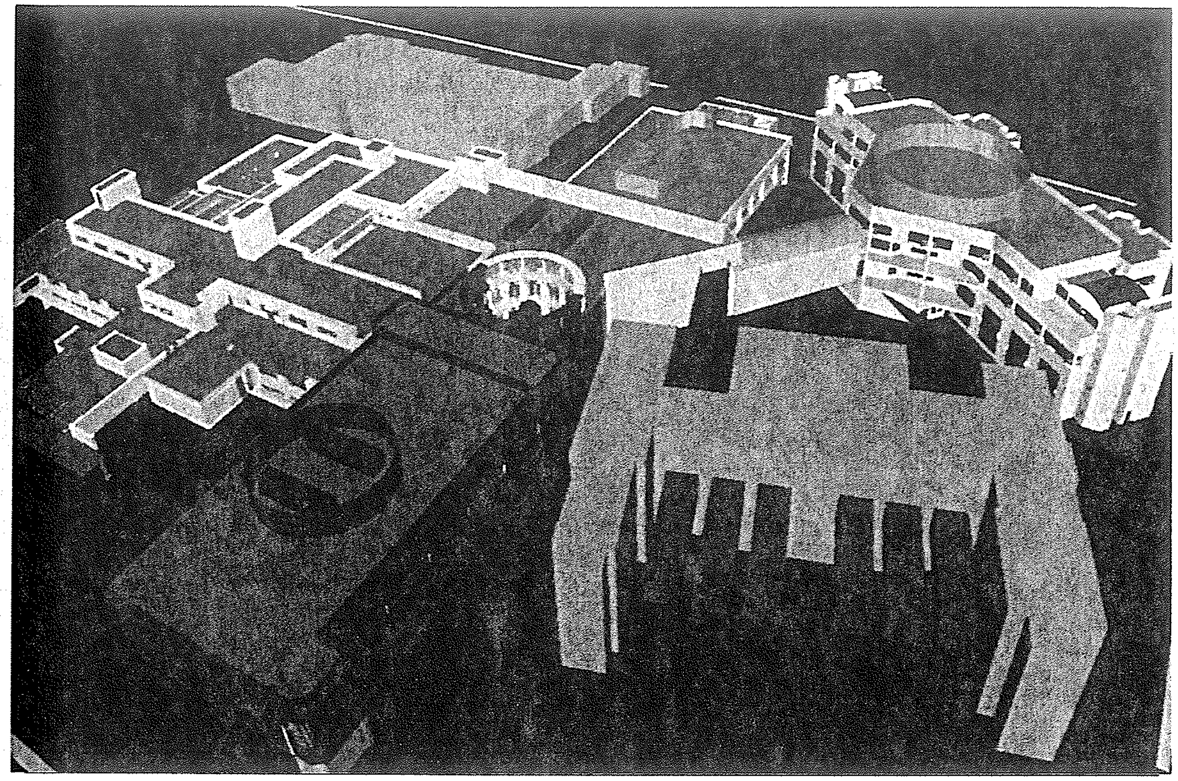


Figure 24 July 1996 East Wing has been demolished and new Clinics Building and second half of North Addition is under construction in its place. Nursing Wing work has moved to the interior.

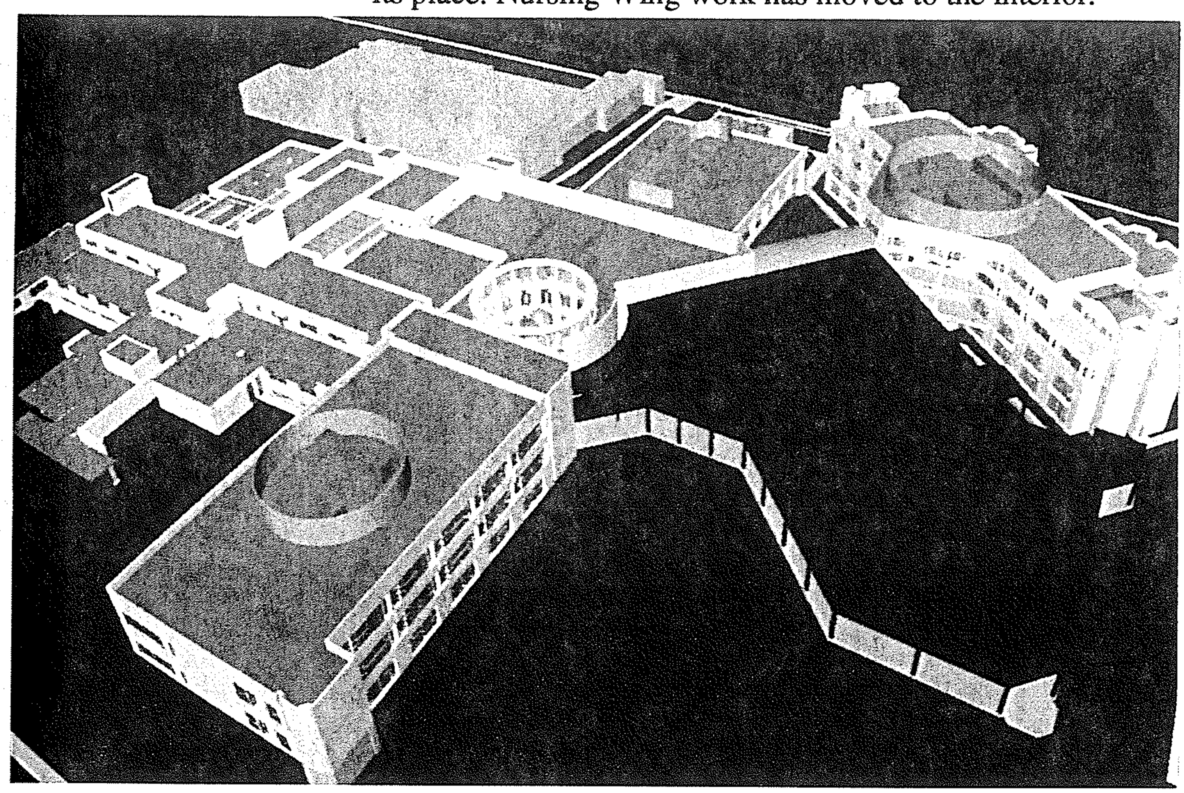


Figure 25 June 1997 Old Clinics Building has been demolished and construction of the new Diagnostics and Treatment Building (D&T) has begun.

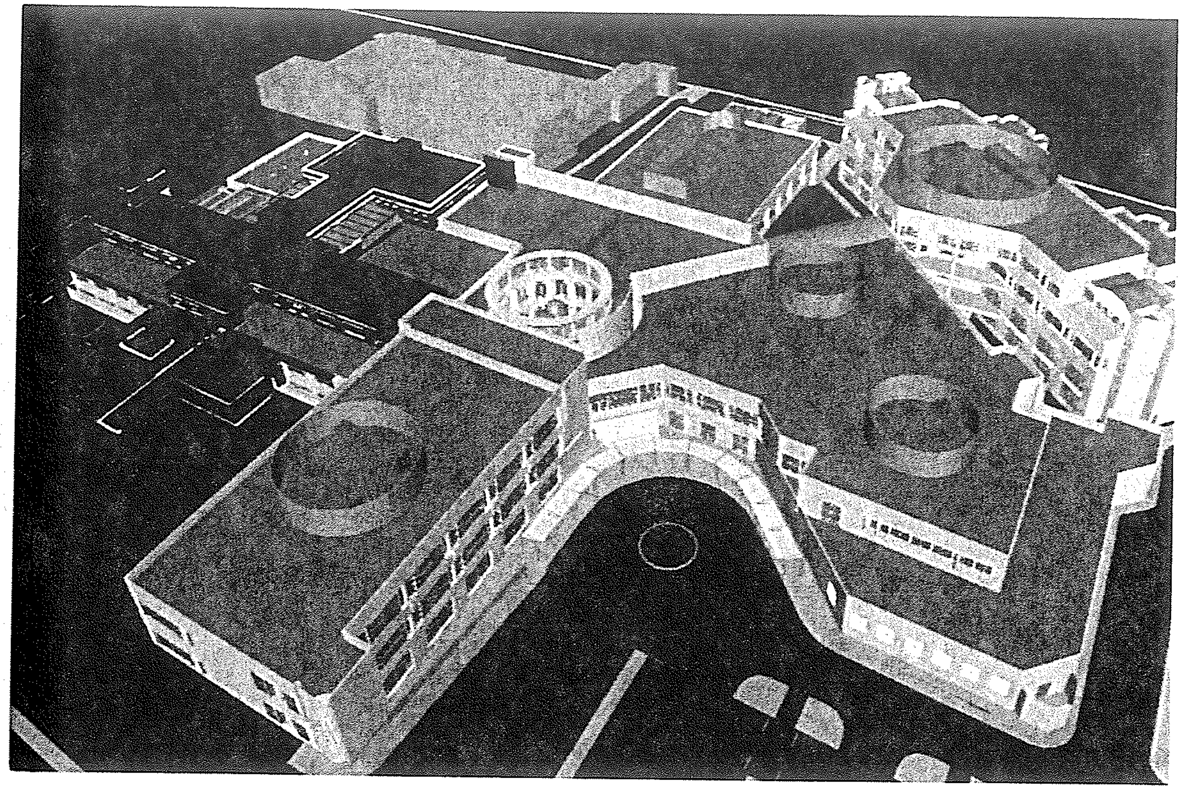


Figure 26 Dec 1998 Remodeling of existing hospital structure begins. Entire third floor is removed in addition to ancillary wings.

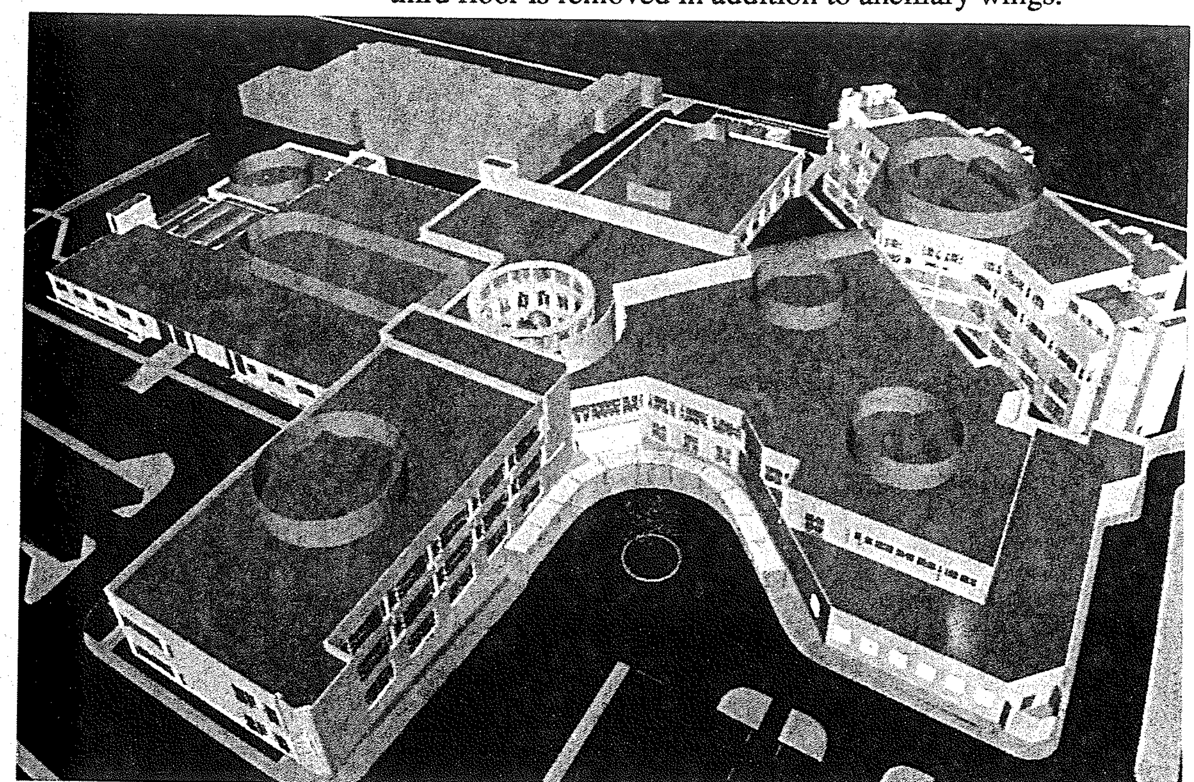


Figure 27 June 1999 The new San Mateo County Health Center complete and ready for the beginning of the twenty-first century

2.4 Results

As a result of this work Dillingham Construction was provided with a 4D CAD model that can be viewed by anyone in the hospital to understand the construction that will take place. This model is especially informative during times when work is going on in multiple buildings. By viewing this model, hospital administrators, department heads, ambulance drivers, and staff members can all be shown the planned construction sequencing. Additionally, all the contractors and subcontractors who work on the project in the future can see the construction plan.

Whenever there are changes to any part of the schedule a new schedule can be created and linked to the 3D model. These two different 4D models can be compared to each other to see the impact of the changes. We also found that by making videos of the 4D model, we were able to show people the model in many settings where it would be difficult to set up a computer display (CIFE and Dillingham 1994). This work also attracted great interest from the community and visitors to CIFE (Novitski 1994b, O'Toole 1994, Sterman 1994).

Future use of 3D Model

Dillingham and the San Mateo County Health Center now have an electronic database with geometric information describing all the old and new buildings as well as the entire site. This model can now be used to develop animations that are specific to activities that will take place in the near future. Models of ambulances can be added to show the different paths that must be taken at different stages of construction. Cranes, temporary fencing, and other equipment that will be used during construction can be shown. As it becomes necessary to show the relocation of departments, animations can be developed of the interior spaces that are affected. Additional objects, such as furniture or equipment, can be added to the model as desired to show specific areas in more detail. Instead of starting from a blank screen, any time such objects are added they can be placed directly into the electronic rooms of the existing model.

Unlike the physical model that will remain unchanged in the lobby of the building, it will be possible to view, modify, update, and animate the electronic 3D model throughout the entire construction project and into the operations of the facility. In the future when there are facilities management software applications that use 3D models, the staff of the hospital will have a model at their fingertips that they can use.

2.5 Usability of the Technology

The main conclusion drawn from this experience is that the actual building of each individual 3D object is the most time consuming element of creating the 4D model. Approximately two-thirds of the time spent on the project (a total of 1400 hours) was devoted to the building of the 3D geometry (see Section 3.4.3 for further data on hours spent, etc.). If the designers built the model as part of the design, they would benefit from having the model to design with, as well as providing a tool for the contractor and other subcontractors during the building of the structure. The amount of effort required to build the electronic 3D model is becoming less significant as 3D CAD tools become better. Furthermore, the designers would become thoroughly familiar with the 3D aspects of the design. Thus it is more efficient for them to build the model than to have it deciphered from 2D. This is an added service that design professionals can offer to clients. Once the model is created, numerous schedule alternatives can be shown, objects moved to check for interferences, and walk-throughs created in comparatively little time. This makes clear the opportunities that exist if the model is created in the design stage as part of the design process.

The linking of objects and activities to create the 4D model is a process that adds great value to the 3D model for a small amount of additional time invested. Although the software that links the schedule to the model requires a number of steps, the steps are straightforward. Changes can be made in the schedule or the model with varying degrees of difficulty, depending on the size of the model and the scope of the change, but these changes usually only involve a few hours. Steps could easily taken by frequent users of this technology to shorten this time.

More importantly, the value of the 4D model increases greatly as efforts are made to carefully match the schedule activities and the 3D objects. For example, if the schedule activity is, "erect structural steel," all of the structural steel will appear at once. If the schedule breaks this activity down into describing smaller areas of erection, such as "erect first floor structural columns, gridlines 1-3," a much more detailed 4D CAD model will result. Likewise, there may be construction activities that may not have specific objects to be linked to, such as painting or testing of mechanical equipment. This can be solved by either adding figures in the area where the activity is taking place or by creating and adding equipment, such as a paint compressor that disappears when the activity is completed. By adding such elements as people and equipment, the aspects of planning for proper workspace and material storage area can be addressed and shown in the model as well.

3 USING 3D & 4D TECHNOLOGY

The 4D modeling of the San Mateo County Hospital project shows a specific application of this communication technology to a single construction project. This section considers the broader application of this technology in the design and construction industries. Because 3D models are the basic elements of a 4D model, I first discuss the value of 3D CAD. This includes a comparison of physical and electronic models. I outline the benefit of 4D modeling to different participants. Next, I discuss why 3D and 4D is not currently being used widely in the design and construction industries. Finally I give considerations for the immediate implementation of 3D and 4D CAD modeling.

3.1 Benefits of 3D CAD

Although there are many benefits for 4D CAD, these will never be realized without having a 3D CAD model to which the timed construction sequence can be added . Even though the tools for using 3D & 4D CAD continue to improve, the basic fact remains that a 3D model must be built before any of these benefits can be realized. As the San Mateo modeling project demonstrated, the 3D model is the most cost intensive portion of creating 4D CAD. To get 3D models of construction projects built, the participants in the process must be convinced of the real long-term value of such models.

3.1.1 Physical Models and 3D CAD Models

Three-dimensional models are the most complete graphical representations of construction objects. Today on large projects with generous budgets designers build small-scale physical models first and then increasingly larger scale models (Gruber 1994). When an a specific area or aspect of a model is to be studied at a larger scale none of the elements from the smaller model can be re-used. Modeling has to begin from scratch. One can easily see the inefficiencies of such a method, but these models are highly valued for the amount of geometric information they easily convey.

Computer models are also able to represent design geometries, but there are many differences between 3D CAD models and physical models. Rather than focusing on the benefits of 3D CAD models to different groups and individuals, I have chosen to compare physical and electronic 3D models. Understanding the differences between the two demonstrates the great potential for 3D CAD's usefulness in the life-cycle of a construction project.

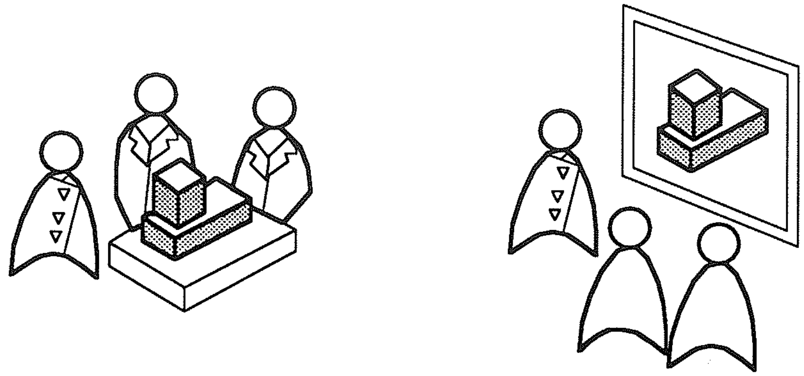
Historical Use

There is a long history of physical models being used to impress, persuade, and explain to clients an architect's proposed design. During the Renaissance architects created detailed models of churches complete with pieces that swung open on hinges to reveal the inside (Giovannini 1994). Since that time, designers, planners, and builders have used small scale models as an important way of visualizing proposed construction. Three-dimensional CAD models are a new creation of advanced electronics. They have only been around a few decades and many people have little understanding of the meaning of 3D CAD, even though they have seen electronic models in movies. With little historical precedent, the educating of those involved with the built environment will be required before the value of adopting this technology is fully realized.

Viewing the Model

A physical model is typically made to be viewed by a group of people standing around a table. People can move freely around the model and look at those parts of the model that interest them the most. People can point and discuss parts of the model in small groups while others wander around to look at other parts, just as might occur with a sculpture in an art museum. The designer can address a group of clients and point to the model while still being able to view the responses on the faces of the group (Gruber 1994). But if she points to a small detail on the model, some in the group may not be able to see the detail. Large groups may even have to take turns looking at the model.

With computer models, the 3D image is projected on a 2D screen (see Figure 28). The number of people viewing the model at the same time is only limited by the size of the screen and how many people can see the screen. By viewing it on a screen, one person controls what everyone sees. On the other hand, no matter how small a detail, everyone can view it simultaneously. In contrast to the physical model, the 3D model is turned while the people viewing it remain stationary. This makes possible rapid movement from one area of the model to the next.



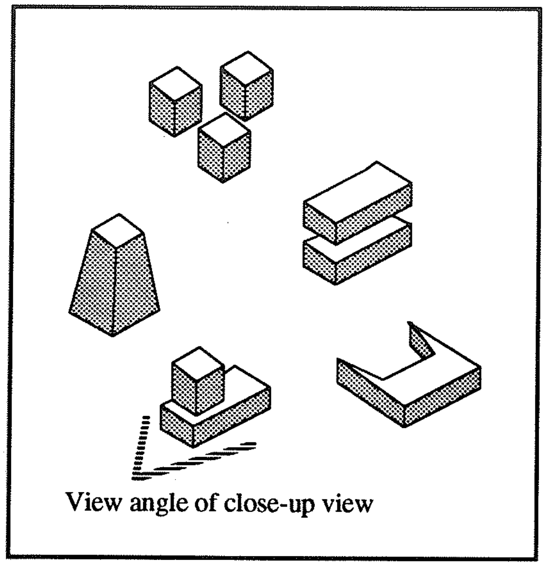
Viewing the Physical Model Viewing the 3D CAD Model

Figure 28 Differences in viewing the models

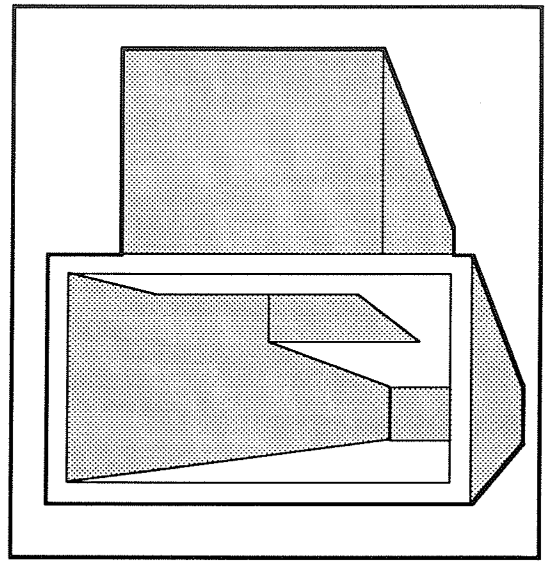
Changing Scale

Drawings and models that represent physical objects use the convention of scaling to represent an abstraction of them at the proper scale. In the United States we use the convention of a given number of feet in the real world being represented by an inch in the model or drawing. All physical models are built at a single scale. Most often an overall view of the project is created. The size of this model is limited by the size of the room it is to be shown in and the number of people who are going to look at it. Then, if the designer wants to show one area at a larger scale, a new, larger model of a smaller area must be created. On a large project where models of a number of scales are built, the same form will be built from scratch each time it is create at a different size (Gruber 1994).

A 3D CAD model is built in the computer using the exact dimensions that the final project will be built in. If the final building is to be 100 feet long, the model is drawn 100 feet long in the computer. Of course one never sees a line on the computer screen that appears to be 100 feet long. This is because the computer keeps track of drawing everything in the same proportion. Computer Aided Design software then lets people select how close or far away they want to view the objects they have drawn. Because of this, the 3D CAD model has, in one sense, infinite scale. Within a few seconds one can view the model from the eye of an eagle or that of a mouse. Thus only one model needs to be built in order to show the smallest details in addition to the overall view. The same 3D CAD model can be shown either at a small size within the context of other buildings or large enough to walk through (See Figure 29).



Small scale contextual view



Close-up view for walk through

Figure 29 Differing Scales of the 3D CAD model

Creating the Model

The creation of a physical model is usually done from 2D drawings. This is often accomplished by specialists who build the model in model shops that have the appropriate equipment. Models are usually made after the final look of the building is essentially "cast in stone." They are often created after design is complete instead of a tool during design. Even architects who build the model in their offices during design usually delegate the task to the least experienced because of the labor intensive work model building entails. Physical models also require materials of wood, paper, and/or plastic. The materials alone can be quite expensive. Large, complex models require skills in neither building design or construction but rather skills like those found in cabinet making, finish carpentry, or jewelry making.

Building a 3D computer model is also a building process. Objects must be created electronically with the proper dimensions and put in the proper location, but it is all contained within the computer. No material must be cut, no physical waste is directly generated from the process, and the pieces are assembled by electronically moving them next to each other rather than using adhesive or fasteners. The model can be created by the same people who are making design decisions, as it is easy to locate all the hardware and software necessary on their desk and relatively easy to train them to use it. Unlike the model building tools for physical models, advances in computer hardware and software continue to take place rapidly which will make 3D CAD models increasingly easier to build.

Changing the Model

One reason why accurate, expensive, detailed physical models are not created until the design is complete is because changes to the model are so difficult and expensive. Because material has been cut specifically for that design and most of the parts are glued, nailed, or screwed together, if changes are extensive it is often best to simply start over. Even for small changes the old materials must be removed and new materials installed.

With electronic models changes are much easier. Often the same model elements can be modified to meet the requirements of changes that are requested. A window in a physical model that is wrong must be cut out and replaced, but the same window in a 3D CAD drawing can be stretched, modified, and adapted to the new shape. What's more, the electronic model doesn't show any scars from the changes. The ability for swift modifications and additions is one of the strong points of 3D CAD. Besides being faster and easier to build than physical models, changes can be as much as ten times faster than changes in 2D drawings. Modifications are easier and different versions of the model, or "what if" scenarios, can be created and evaluated at stages in design where it would otherwise be too costly to change in 2D.

Model Mobility

Although it can be a satisfying and enlightening occasion for everyone to gather around a physical model and discuss it, many clients rarely see the model again until the project is built. It is usually necessary for individuals to go where the model is to view it rather than having the model come to them. The model typically won't fit in the back seat of a car and some models are large enough to require a truck when being transported. When a physical model is being moved, there is always the risk of dropping it, dropping something on it, or otherwise damaging it. Even if it does not get moved, it often gets dusty, looses its luster, and slowly deteriorates over a period of a few years.

Electronic models can not only be transported easily, but shared easily as well. Although it may make cognitive belief in a structure's existence more difficult, the possibility that a large model can be saved on a floppy disk or CD-ROM makes it very easy to transport. A CD-ROM can be put in an envelope and sent anywhere in the world for the same cost as a letter of a few pages. It now costs less than $5,000 to buy equipment that will record directly onto CD-ROMS. Experts estimate that data on these plastic disks will be good for at least ten years (Carroll 1994). Because of this one will be able to view an electronic model 10 years from now as well or better than one can now, with no changes to it. Equally important as CD-ROM technology is that of networks. Local and wide area networks, along with the information superhighway will make it possible to share 3D models simultaneously in different locations (see Figure 30). This will mean quicker transfer of geometric information than was ever possible with 2D CAD or physical models.

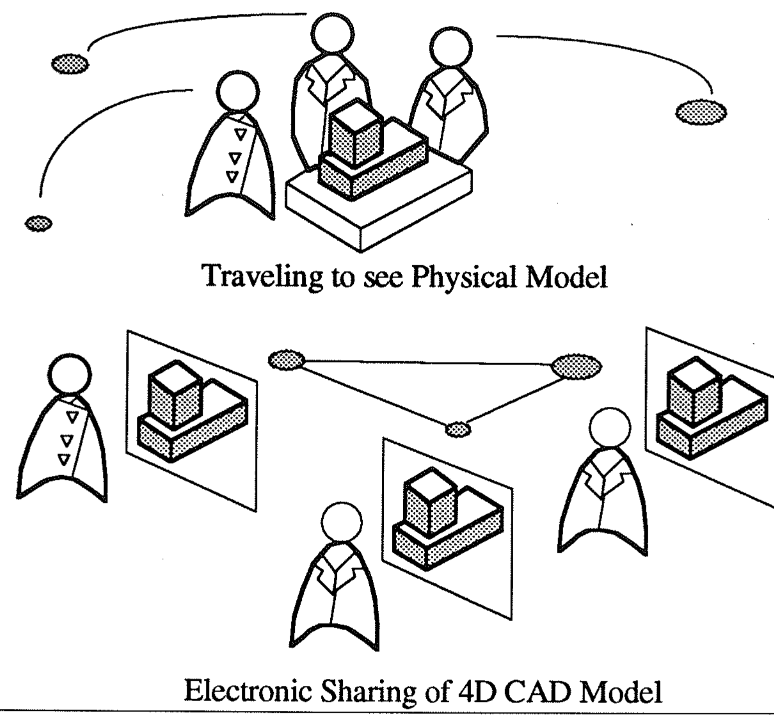


Figure 30 Mobility of the Models

Spatial Requirements

One reason that the client might not take a physical model home is the likelihood that there isn't enough space for it. Physical models require relatively large amounts of space to build and store. Because materials must be sawn, cut, clamped and glued, a shop building a large model requires warehouse-like space for equipment, tools, and material storage in addition to the actual space in which to build the model. Once the model is built, space is required in some or all of a room to display it in. This space is costly. In the best cases the model is put under glass and displayed in a lobby somewhere, but often it is stored in a back room or disposed of altogether.

Electronic models, as discussed previously, can be stored in very small amounts of space. Even the computers that display the models do not have to be dedicated for that purpose, but can be used for multiple other purposes as well.

Dimensional Accuracy

There is a common practice that I have experienced on construction sites throughout the United States to measure distances off the blueprints when dimensions are missing or in conflict with each other. On the other hand, an unwritten rule by which designers operate is "never measure off the blueprints in the field." If it is true one should never take measurements from drawings, it is even more risky to measure the physical model. It is so difficult to get physical models accurate that each successive model in increasing size that gets built most often becomes the model that controls the geometry for the portion it models since it can be evaluated more easily than smaller models.

There is much less risk in measuring from a 3D model since it is not difficult to construct accurately. Because the model is accurate and there is only one model for every construction object, measurements can be taken directly from the model. This can translate to fewer dimensional mistakes in the field, especially as further advances are made in linking electronic measuring devices to 3D CAD (Edmister 1994).

Sensing the Model

Just like sculpture, a physical model engages all the senses. Even if the lights are turned off, a person can reach out and touch the model. With the senses satisfied, even though the model is a miniature, abstract representation of the completed building, the proposed project seems real and possible to create. The physical model's tangibility gives credibilty beyond what can be imagined, drawn on paper, or even viewed on a computer screen.

People can enjoy seeing 3D objects being turned on the screen, but to believe that they exist in the computer is more difficult. If the power goes off while viewing a computer model, all visible traces of the model disappear. It is difficult to convince one's own mind that all the information about the model is in existence in a "black" box somewhere inside the computer or in a tiny disk that looks much too flat to contain the model of a building. All of the images remain 2D manifestations of 3D electronic data. Research in virtual reality is exploring the level at which the combination of perceptions, including orientation, hearing, touching, smelling, and responses to muscular movements, begins to convince the human body that the electronic world it is experiencing is a "real" world (Latta and Oberg 1994). This work will make 3D computer models more believable and versatile in the future. Even so, there will be specific instances where a physical model will be important and add value to the project.

Model as Prototype

Although there are significant differences in the two types of models, one does not have to choose whether or not to have just one or the other. Physical models can be scanned with lasers or digitized in 3D space to be entered into the computer (Lewis 1994)(Lewis 1994, Lewis 1994, Novitski 1992) Once they are in the computer they have become a 3D CAD model and have all the same characteristics as other 3D CAD models. On the other end of the scale, any model that is made in 3D CAD can be used to accurately generate a physical model at any scale, up to the capacity of the machine and the patience of the operator to assemble large pieces of a model. Small models can be made relatively easily. Numerically controlled milling allows for outside shapes of structures to be made, with cutting paths for machine tools derived from the 3D model. There are emerging technologies being used in manufacturing including stereolithography and other laser technologies that create a prototype out of thin cross sections from plastic, wax, or even metal (Economist 1994, Goldsmith 1994). This allows physical models with thin surfaces and very small details such as window mullions to be created directly from the 3D model.

Using Models for Construction

In cases where large, room-sized plastic models are built of industrial facilities, efforts are sometimes made to put pieces of the model together in the same sequence as construction and then to document that with photography. Unfortunately, the model then gets glued together and can only be taken apart again with difficulty and expense if the photographs do not show the information clearly enough. The use of electronic models is a flexible and inexpensive way to create models that can be taken apart and put together without any damage to the model as many times as one would like. This makes them very useful in construction where planning begins with bare ground and finishes with a complex structure.

Non-geometric Information

One of the reasons that physical models are not used more than they are is because they generally only show the geometric explanation of a project. There is always a large quantity of non-verbal information that tells more completely the performance requirements that should be met by the installation of each construction object. This information is never supplied by the physical model, but rather through notes on the 2D drawings and in books of specifications.

The linking of electronic information to 3D CAD models is becoming increasingly less difficult and more powerful. All forms of information can be directly accessed from the model. Not only can labels be attached to objects, but the simple selection of the object can trigger the established links to databases.

3D Model as the Core Framework

A physical model exists simply as a sculptural representation of a proposed structure. Its usefulness beyond conveying a sense of what the overall project will look like is limited. Beyond simulating the physical environment, such as moving a light around the model in the pattern of the sun to study shadow patterns, or moving small camera lenses into the model to create a simulated walk-through of the spaces, the usefulness of the model is limited.

The 3D computer model, by contrast, is an electronic geometric kernel that can be utilized for a great number of different applications in different specialty areas. Discussed earlier is 4D CAD, but there are many more. Each of these models becomes a new model with new capabilities; a new version of the old geometry with new skills (See Figure 31). In addition to simulating the sun and its shadows, lights can be simulated in each room to do lighting studies, and acoustic performance can be simulated as well, reducing the need for large, costly physical models built specifically for these purposes. A designer can also do elaborate texture mapping to simulate finish materials on architectural features and interior furnishings. Unlike a physical model, these can be interchanged quickly with other options to assist in the selection process. The model has the potential of being used by the structural engineer as input for analysis programs, providing data on not just the primary structure, but such items as partition walls that also influence the structural behavior of a building. For the construction planner, the ability to supply exact quantity of materials has the potential for reducing labor costs, not just to the firm who builds the building, but to the industry. The need for a number of contractors to estimate quantities even though they don't win the bid can be eliminated. Subconsultants, either design/build subcontractors or specialty engineers can take the base model and add specific details. The computer with rules of construction is able to automate this type of task, such as calculating and creating the model of all the elements of a 2x4 framed wall given only its shape and openings (see Section 4.1.2). Most importantly the applications that use the 3D model as a base or core framework are continually increasing in numbers and improving in capacity, capability, and reliability (Clayton and Kunz 1994).

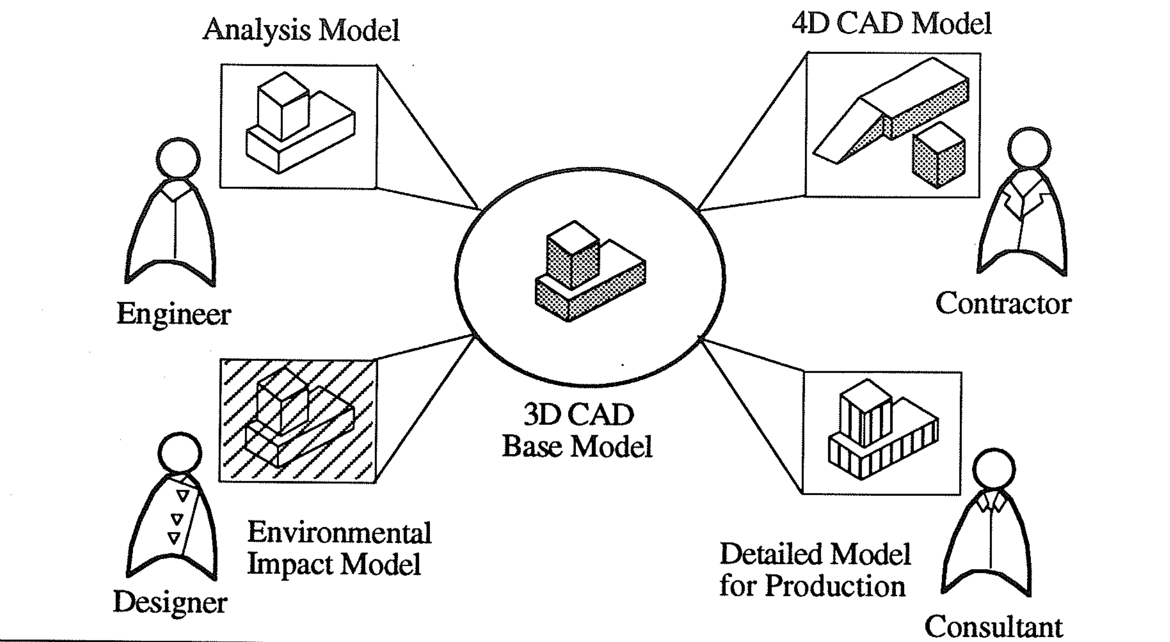


Figure 31 The Shared 3D Model

3.1.2 Benefits to Users

Having 3D computer models as a flexible, graphic representation of geometry benefits all members of the design and construction team. Clients will be presented with fewer "real-life" surprises in the differences between the product they imagine and the product that is delivered. Designers can solve and evaluate geometric issues more completely. Those building a structure will have a graphic tool to understand the geometry more fully. They will be able to make more accurate predictions of cost and schedule and be able to concentrate on the best methods to achieve the desired geometric relationships. Geometric duplication, which is created by multiple 2D drawings for different purposes and creates a high risk for inconsistencies, will be reduced.

The great potential for electronic computer models as electronic graphics, supported by basic electronic, mathematical, and computational skills is one of the realities of the twenty-first century, just as mechanical machinery was to the industrial revolution. It is not a question of whether 3D and 4D will be used in the construction industry in the future, but simply when and how fast.

3.2 Benefits of 4D CAD

Summary of 4D Benefits

The advantage of using 4D CAD for all individuals involved with the construction process is fundamentally the same: these models enable people to quickly perceive and understand complex information about physical geometry. But each person derives different benefits out of that advantage. In the following section I discuss separately the benefits to various participants in the construction process.

Traditionally in construction, each participant uses distinct media for communication. The client may only see the final model to approve the look of a building, the floor plans to approve the layout, and the unopened stack of blueprints before authorizing construction. The designer feels ownership of the original 2D documents and specifications, but has little to do with the construction schedule. The contractor takes the blueprints of the 2D documents and studies them in depth, customizing them with color-coded markers and notes, but also creates other new documents to plan construction. Once the designers finish the drawings most of the communication that goes on is non-graphic in the form of letters or conversations.

With 4D models, a new form of communication emerges that everyone in the construction process can share and use. For example, the owner can easily view the same 3D model and the animation of the schedule that the contractor uses to explain to suppliers what day materials need to arrive. Electronic communications are becoming more common for the flow of both textural and graphic information. Sharing information about the 4D electronic model will be part of such communications. The result of 4D models as readily accessible sources of common graphic information will benefit everyone involved in the construction process.

3.2.1 Benefits to Individuals at all Levels

Client

The client in construction can be an individual or group of individuals who has need for some kind of structure. They are the customer and provide both the funding and the final evaluation of the success of a project. The use of 4D computer models gives the clients the chance to understand the construction phase better and to be a part of construction planning.

A client typically does not have the time or the inclination to study the blueprints and the bar-chart construction schedule in order to understand how the contractor is going to build the building. The 4D model presents not only the overall view of how the construction will take place, but also detailed information that can provide more complete answers to clients' questions. For instance, if a client asks when the exterior of the building will be complete, the contractor might give one date when all the doors will be installed, all the walls painted and the landscaping completed. With the 4D model, the client will observe that first, the main walls are completed, then the windows are installed, then the doors hung, and that the landscaping is not completed until the final days of the project. Each client may interpret a different date as being the finish date. One's idea of when the exterior is finished might be when the exterior walls are completed, because they are concerned with the point in time that the building will begin to look like what it will look like when it is done. Others may have been wondering when the building would be secure with the doors and windows installed. By observing the construction schedule created in 4D, they can decide for themselves the answer to what only appears to be the same question.

Although clients engage the services of professionals to advise them on how construction should proceed, some clients unfamiliar with construction might still do such things as postpone the start date while expecting the completion date to remain the same. Other times they 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 makes them more aware that postponing the first activity delays the second, and so on. A delay of a critical activity can sometimes require a change of approaches for other work that multiplies the impact of the delay. The project manager can say "because item A didn't get installed on this day, we had to move operation X over to location Z, which meant that team Y had to be sent home until operation X could be relocated to location B," and the client might just nod and say, "if you say so." But with the 4D model, the contractor can point to the objects and show the movements and relocations.

Clients may desire to consider accelerated schedules. The inexperienced might feel that the choice to accelerate or not is one of only money versus time. Sufficient 4D modeling could be developed to show the extra density of activities, equipment, and people. This would enable the client to see that there are also other factors such as safety and quality control that would need to be considered as well. The contractor might have to use more lay-down area, or more points of access to the site that could quickly be shown to the client so that a more informed decision could be made.

In almost all public, industrial, and even commercial construction "the client" is not a single individual, but actually an organization, a board of directors, or an entire staff. By having a model that shows clearly the pattern of construction, all of the members of the client team can be informed to the same level. This will help them discuss among themselves the impact on operations from construction and how to minimize these impacts. By understanding the construction plan more fully, they will be able to make better plans for operations during construction. This will lead to a more informed dialogue with the contractor on ideas of the client for changes in construction that would lessen impacts and minimize conflicts with operations. For example, a contractor plans to block a certain road at a certain time. Two people from the client's side give approval for this operation. But a few weeks later, a third subgroup from the client's team is reviewing the 4D model of construction. That morning they have just arranged for an important piece of equipment to be delivered during the time in question. They bring up the matter and the contractor goes back and modifies the schedule. In a later meeting, the contractor returns with a modified model and shows how by not being able to use that road, the new construction sequence will take an extra four days. The purchasers of the equipment see this readily and agree that postponing the purchase will be the best solution.

The 4D model gives more explicit explanations of construction operations, enabling the client to play a more informed role in the construction process. The major benefit of this will be a more satisfied customer, who is surprised less during construction, feels more a part of the process, appreciates the complexity of the work, and feels that the contractor is taking an active role in helping them meet their goals.

Construction Planner

As 4D becomes more common, the construction planner will use visualization of the schedule as an integrated tool in the planning process. The planner will be able to test out alternative schedules visually by creating construction sequence animations for each different schedule that needs to be considered. Eventually the initial schedule will be built by combining the 3D model and databases of construction knowledge (see section 4.3.1). Even though the schedule and model are created separately and then combined, it was clear in our work that once the model has been built, there is relatively little additional work necessary to view any number of alternative schedules. With this tool, the model itself can be the answer to the "what would happen if we changed this" or "what would happen if we did this first" type of questions poised by the client, the designer, or the construction planner herself.

Viewing the sequential appearance of objects in their final location is what we were able to accomplish with the San Mateo project. Changing colors indicated that the objects were being installed during the days or weeks indicated. This gives a very clear and basic visualization of how the building goes together. There is additional information that 4D modeling can provide about construction, including spatial requirements for installation activities and the storage of materials. Every construction activity requires a place to have objects stored upon delivery, a pathway to the location of installation, and adequate room at that location to install the objects. Much of this planning can take place in 2D and work has been done to show the effectiveness of such planning (Riley 1994). The advantage of performing this type of planning with 3D objects is the same as the advantage of 3D CAD in general: the representations are more complete, including volumetric and not just area requirements, there is a greater ability to view objects as one will actually experience them, and there is the opportunity for representing the specific visual characteristics of the construction objects.

The ability to work in 4D makes some planning possible that would be very difficult otherwise. For example, Figure 32 shows the state of construction of the Central Utilities Plant when the cooling towers are to be installed. Since the structural steel around the cooling tower locations is not green or red, it is clear that it is already installed. From the 3D model it is readily apparent to the installer of the towers that a crane must be used to install them. In addition, the distance they must be lifted and moved is clear. Similarly, Figure 33 shows the Central Plant as the boilers and the chillers are being installed. It is clear from moving the equipment in the 4D model what else is occurring on site, what structural column must be worked around, as well other information viewed in the model.

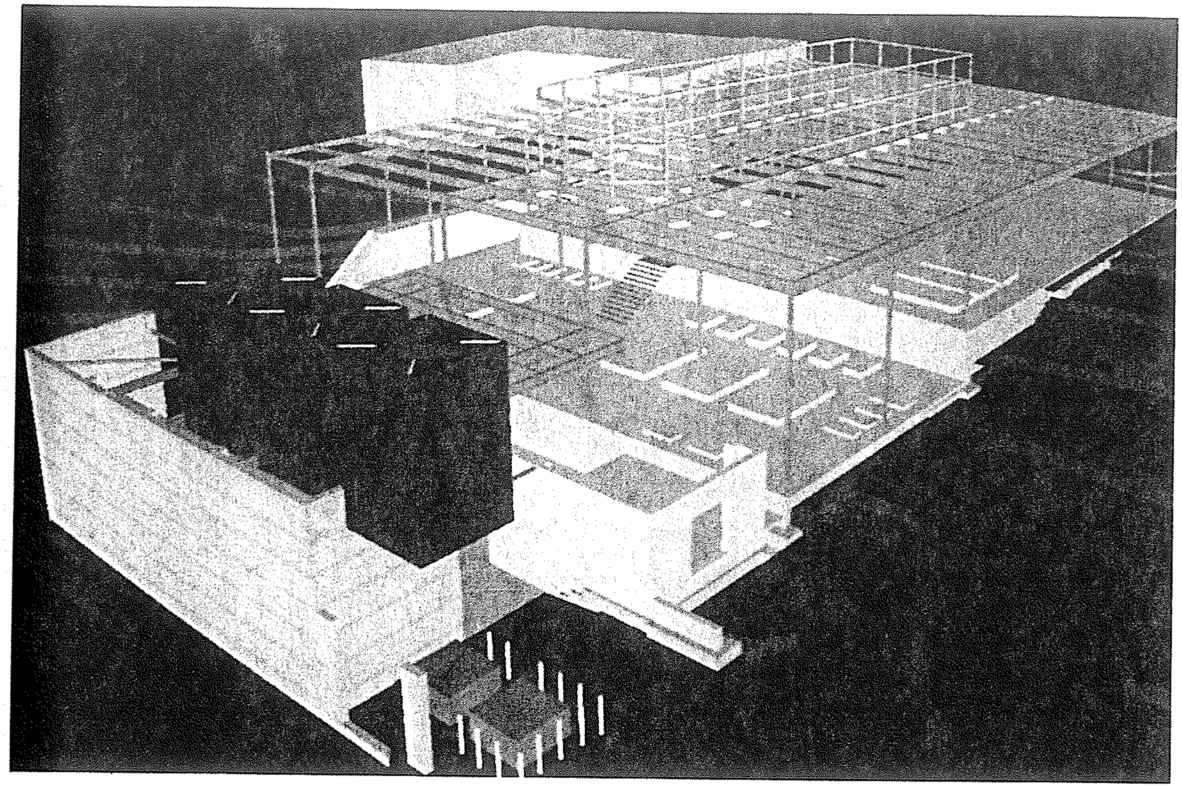


Figure 32 Planning for installation of equipment is clear in the 4D model. Here the cooling towers are moved to study their installation requirements.

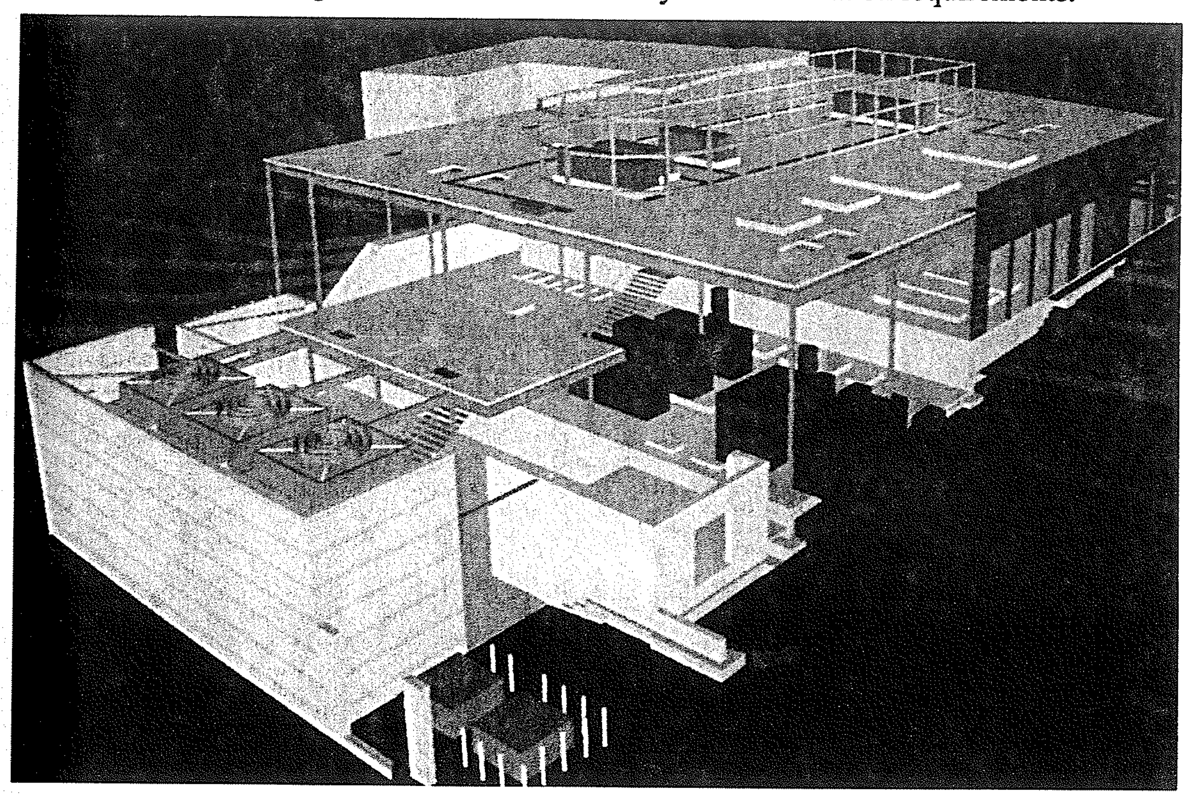


Figure 33 The boilers and chillers are moved into the building. Here the path of installation is shown so that all who see the 4D model will understand the importance of keeping the pathway clear.

One can imagine the added value for more complex operations. If a large machine is to be installed on the tenth floor of an office building, one could get the dimensions of the machine and compare them with dimensions of the elevator to see if it would fit. But if the machine had to be moved through a number of doors, down some steps and around a few corners, modeling the machine in 3D and moving it through the space in 4D would be a much quicker test, and more accurate than 2D calculations. This would be of particular value in cases where the collision with other objects would be costly or dangerous. In the same manner, 4D gives the opportunity to understand and plan for safety issues well before construction begins.

Planning the sequence of work by subcontractors will be enhanced by 4D. In addition to testing out different sequences, the sequence decided upon can be shown to the people actually doing the work. Subcontractors and their workers will be able to see what will be in-place when their part of the work is being installed, what other trades will be working at the same time, and so forth. They will be able to give feedback on the plan that is modeled that might enhance the project schedule. Subcontractors will also be able to clearly see the impact of their delays.

There will be a general tendency towards more accurate, honest, in the sense of explicit information. Even though it is possible to hide information in 4D by selecting what is shown, the amount of information that becomes explicit in 4D will force a more direct form of communication. Although a project manager may want to tell a supplier that the brick is needed a month before it is to be installed, if the supplier sees the 4D model, he or she will know the actual day it needs to arrive. On the other hand, the supplier will have less of an excuse if the brick is even a day late.

The construction planner will also be able to communicate constructability ideas back to the designer. In a situation of design/build or where the contractor's input is enlisted before the design is complete, the contractor will be able to not only tell the designer about ideas that will make construction easier or cheaper, he or she will be able to show the designer the ideas as well.

Timed construction animation with 3D CAD models, or 4D CAD, has many benefits that can improve the construction planning process. The main underlying benefit is that as the geometric aspects of a project are modeled more explicitly, less time will be spent on deciphering the visual aspects, and more on other areas of planning. The manifestation of cost may also be incorporated in 4D (possibly 5D with cost?). In this case, the value of the work in-place could be shown increasing with the passage of time and the appearance of objects in the 4D model. Other aspects of planning such as collecting accurate historical cost data or accurately predicting activity durations may not benefit directly from having 4D models, but they well might be given a higher priority as there needs to be less time spent on where things go and communicating when they will get there.

Designer

Designers often think of a project only in its final, completed state. Specifications for construction are often written as "performance" specifications, and state how a material or object must behave once it is installed, allowing for a choice of construction methods by the contractor. The disadvantage of this is that the designer seldom considers how to design a structure so that it can be built most efficiently. The use of 4D CAD would give designers a way of understanding installation problems that could be lessened by changes in the design. Simply by seeing 3D objects appear in a given order, a construction sequence can be visualized and evaluated. A contractor could be employed to give useful feedback during the design stage, without having to labor over the drawings for a few hours to understand the project.

Subcontractors and Trades people

Many subcontracting firms are becoming design/build operations. When the subcontractor begins to create 3D shop drawings of objects and then animate construction, they can realize the same advantages as the construction manager. In addition, the subcontractor can keep the contractor "honest" by visually checking the actual state of construction with the promised state of construction in 4D when they are to begin their work. Clarifying what trade is to install specialty items can also be assisted by 4D.

Trades people will benefit from 4D CAD by being able to see the overall project and their own specific tasks. Today, many workers come to the job and perform specific tasks without having any idea how their work fits into the larger picture. No one has the time to explain it and often enough the work gets done satisfactorily. But like the old story of two stone masons being asked what they were doing and one answering "chipping a stone" and the other answering "building a cathedral", workers who understand the entire process will be better able to realize how their work fits in to the overall effort. They will be able to feel more ownership and pride as they see their work being an important part of a larger project, and will be more inclined to work for the success of the project as a whole and not just their individual tasks. This could easily be conveyed to the workers when they view the 4D model. It's even conceivable that the first part of a crew's day would be to watch a detailed 4D explanation of the specific work to be done that day.

Suppliers

Suppliers of construction objects and materials are often left out of the loop of communications on a construction project. Materials and parts are ordered and the supplier is told to have them delivered by a certain day. In order to balance all the different orders, suppliers must make judgements as to which deadlines are most critical with very little knowledge except that which they have gained from experience. In addition, some materials are ordered and then used in a way that the manufacturer either did not intend, or could have accommodated had they known about the desired use. With 4D models, the supplier could be included among the people who viewed the construction schedule. They would know exactly the week and day that their materials would need to arrive, and could even ask for electronic photographs as updates to compare to the 4D model (or updates to the 4D model itself) to keep track of how the project schedule is proceeding. They could also see the way their product is to be used and give feedback to the designer early in the process.

Managers of Owners, Clients, Designers and Contractors

Managers have the challenge of making the most important decisions on a project while relying on information gleaned from reports by those who they manage and their own quick checks of the plans and specifications. Often they don't have the time to study the drawings and schedules in depth or to do the mental piecing together that is required to assist them in making the best decisions. By having 4D CAD, managers are benefited from quick access to the detailed geometry of a project. In this way, instead of having "my people talk to your people and work something out", upper-level managers would be able to discuss a 4D model and determine a solution to problems. This could greatly compress the decision chain. In the current situation it would not be uncommon for an owner that has a specific question about a specific product being installed to ask the client representative, who might then ask the project manager, and the chain would continue from the project engineer to the subcontractor to the supplier to engineer. Then the engineer might create a drawing that would clarify the situation, but it might be a few weeks before it returned back through the chain. With 4D CAD and the proper communication capabilities, the people at both ends of the chain could discuss the problem by viewing the model together.

Approval Agencies, Community Groups, Counsel, Insurance Agencies

Other groups that can benefit from the quick graphic explanation of the project are approval agencies and community organizations. Approval agencies often require lengthy periods of time before issuing approvals. Much of this time is spent in interpreting the graphic information from the 2D drawings. Planning departments and community groups are often concerned with how the building of a structure will impact the community and some are actively looking for how to incorporate 3D graphics technology into the review process (Brenner 1994). The use of 4D CAD is a way to allow the quick understanding of a project by a large number of people. The courtroom is another place where 4D models can be used to explain construction events and schedules. Today, physical models are already used because it helps people unfamiliar with construction, such as most juries, to understand the project quickly (ENR 1994). Since many claims involve schedule delays, 4D would give the added benefit of helping the jury to understand scheduling and the impact of delays. On the other hand, 4D CAD may help reduce the number of claims by having more understanding among the players on a project. Many claims go unresolved on a project as well, because it would take too long to figure out what happened. Using 4D CAD as both a plan for construction and a recording of construction could assist in resolving such claims.

Summary

Planning a project with 4D CAD gives the opportunity for everyone in the project to understand the project better. Once participants have seen the general plan, they will be able to plan their own work in a more timely manner and more accurately by creating their own 4D model that fits into the original 4D model of the contractor or construction manager.

3.3 Using 4D CAD Today

Even though there are many challenges in using 4D CAD today, there are also many opportunities. Early users of 2D CAD had to live with many of the limitations of early hardware and software, but soon realized that savings from increased drawing accuracy and increased ease of changes had offset the learning pains (Anadol and Akin 1994, Mahoney and Tatum 1990b). As 2D CAD continued to improve, they were able to keep up with advances easily.

In the same way, firms that begin to use 4D CAD will realize enough savings to offset their investments (see explanation of concrete savings on San Mateo project, Section

2.3.1), and will be in a strategic position to take advantage of the new developments in this area (Hendricks 1993, Edmister 1994). The adoption of 4D CAD will continue to grow and firms already using it will benefit from early efforts.

In this section I suggest three main areas in which firms can begin to implement 4D CAD. The first is the creation of the 3D model. One cannot move into 4D CAD without this. The next is the linking of the schedule to the model for 4D CAD. The last is a version of 4D CAD which is to animate the construction of 3D detail drawings.

3.3.1 Creating 3D CAD

The first step towards using a 4D model is to build the 3D model. The 3D model is the basis for any use of advanced electronics to display graphics for construction. It is important how this model is created. In order to maximize the value of this effort of model building there must be a demand for 3D. The client and the designers must be convinced of the critical importance of the model on a long term basis as has been discussed previously. Design must incorporate 3D into the process rather than having the model created after the design is completed. This means that designers must learn to use 3D as a daily tool. Eventually construction personnel must also learn to use 3D, as well as subcontractors, and eventually those performing the work. Fortunately it has been found that people are often enthusiastic about learning 3D CAD who have no interest in 2D CAD (Coles and Reinschmidt 1994).

Initially this may require shifting resources from the construction phase to the design stage. This is not because 3D takes more time and money to create than typical 2D drawings, but rather many issues that can be left unresolved in 2D to be figured out in the field must be resolved in 3D in order to create the model. The model must be created with the intent that it will be useful and valuable to participants downstream from the designer; most particularly the construction planner for development of the 4D animated construction sequence.

Most importantly, some kind of 3D model needs to be built. As more 3D models are built, the tools to build them will get better, the ease of their linkage with other applications will increase, familiarity with their use will increase, and they will begin to become a standard requirement for design and construction planning.

3.3.2 Creating 4D CAD

A catalyst to the creation of 3D models could be the increased demand by clients, approval agencies, community groups, and insurance companies for 4D CAD presentations of a proposed structure before any construction can begin. The City of Cupertino in the heart of Silicon Valley was recently persuaded by the local chapter of the American Institute of Architects to postpone their intentions to require presentations to the planning department to show a 3D model of the building in its proposed context (Brenner 1994). As soon as such groups begin to realize the technology is already in existence there will be an immediate increase in requirements for its use. Community groups may demand 4D visualization to show such things as the intended sequence of construction, the average amount of construction traffic anticipated, the type of trees to be planted and what they will look like in 10 or 20 years, and so on.

The insurance companies of design and construction firms and client organizations may also encourage change. As they become more informed about the accuracy of planning using 4D CAD, they may begin to offer lower insurance rates to companies that use it. They would do this as the use of 4D CAD is shown to reduce the risk of failure, interferences, and delays. In addition, lawsuits about claims for damages due to delays often involve extensive graphics and sometimes modeling to explain the reasons to a jury (ENR 1994). With the 4D model already created and used in construction, it would be readily available at no extra cost for evaluation of any problems that arise.

3.3.2 Creating 4D Details

In the explanations in this report of 4D up to this point it has been described it in general terms as the ability to visualize the entire construction schedule of an entire building. But another area of usefulness for 4D is in showing details of construction. Many in design and construction talk about the devil being in the details. Detailed drawings describe specific aspects of critical importance in construction. The difference in whether or not a roof leaks can often be traced back to the exact way materials were put into place. This is described in the detail drawings of a set of construction documents.

The reason why details are used is that they show many more of the specifics about construction materials that are necessary for their proper placement. They can show such things such as nuts and bolts at a very large scale to help convey the design intentions of a designer. The disadvantage is that there can be numerous details on the smallest project. These details must all be coordinated with other details, the floor plans, the sections, and the other elevations to achieve a full understanding of their application and purpose. They also only describe the final outcome and give no indication of the order in which pieces should be put together. They are often quite complex. Since they lack the third dimension they must use drawing conventions and notes to describe the third dimensional characteristics, or yet another detail.

4D details can be created by isolating small portions of the model. These electronic sub-sets of the larger 4D model would be able to be taken apart and put back together and rotated to be understood fully. Because they are derived directly from the model, there is no problem with coordination of different scale details or differences in representation from plans, section cuts, and elevations. Each 4D detail part of the larger 4D model. It is a geometric representation that can be viewed either closer or farther away, just like the overall model. Each trade can understand what part it plays in creating the assembly that is shown. By seeing each piece of the assembly it will be easier to understand what is important about its portion. This can also be used by the superintendent on the job to plan and control the sequence of the work.

3.3.4 Using the Advantage of 4D

In many large engineering and construction firms 4D CAD is a reality. Many significant projects have been built with extensive use of 4D, and many millions of dollars have been saved (Coles and Reinschmidt 1994). Although significant changes have not been made over the last decade in how many of these 4D systems work, the capacity to handle large models and large amounts of other data has increased, making it an even more powerful tool (Coles and Reinschmidt 1994). The San Mateo Case Study demonstrates that use of 4D does not require a full-scale programming effort, but can be used today with existing tools for a reasonable cost. The future is 4D and it is just a matter of how fast everyone will get there.

3.4 Why isn't 4D used more today?

There are many conceptual reasons for the use of 3D and 4D CAD. The reality is that there is continued limited use in the construction industry of these tools. No matter how good the arguments for use are, if the industry is to ever reap the rewards from the use of electronic models, we must first understand the roadblocks.

3.4.1 3D Design: A New Approach to Design

The ability for computers to display images rather than just "crunch" numbers was an important turning point in the development of twentieth-century technology. The ability to draw and edit electronic 2D images made an irreversible impact on the design industry. When computerized drafting was first introduced, even the people adopting it most readily thought that its greatest strengths lay in making current practices faster and easier. Today, many in design and construction are realizing that 3D modeling is heralding not just the automation of existing methods, but the "reinvention" of the way design is produced and delivered (Novitski 1994a). In other fields, such as mechanical engineering, this is already the case.

3.4.2 Driving force: Concurrent Engineering

The first business area that started wide-spread use of 3D CAD was mechanical engineering. Aeronautic and automobile manufacturers began using 3D modeling as a way of streamlining the production cycle of developing new products and getting them to market (Hodgetts 1994). It was seen that the wall between design and manufacturing had to come down so that products could be developed more quickly and with higher quality so that they worked right the first time. Electronic models and electronic communications about those models began to be used as a method of communication that had much greater power in streamlining production than any other method that had been developed for decades (Wallace 1994). Although not without difficulty and problems, the computers have caused a revolution in manufacturing such that it is impossible for almost any manufacturing facility to compete in today's marketplace without computers (Economist 1994). This revolution was prompted by international competition where quicker time to market of new quality products from anywhere in the world could put out of business someone else almost anywhere in the world.

One example of a new way of looking at design and construction is the recent design of the Boeing 777. This airplane was entirely designed in the computer with no full-scale mock-up typical of airplane design. The review of parts which once took place on paper in 2D, took place in the computer. The entire process shifted more development resources to the design phase and the results showed the wisdom of this shift. This example is significant in demonstrating the potential for 3D CAD and computerized manufacturing (Economist 1994).

The design and construction industry is very different from manufacturing. The international competition and mass production that typify manufacturing do not exist in most firms in construction. Most structures are unique, are built outdoors in the elements, employ local knowledge to deal with problems unique to the construction location, and are performed typically by local or regional firms or divisions of larger firms. But, just like the changes that transformed manufacturing, technology is available today for construction related firms to streamline the process of designing and constructing in the built environment. Those firms who are able to use the technology of 3D and 4D CAD will be the firms that spark the same revolution in construction as occurred in manufacturing.

3.4.3 Management Challenges for 4D

Because few 3D and 4D computer models are being built, there is little information on how much time and computer resources they require. Some large companies that do very similar operations, such as design piping, have developed systems to count the number of pipes modeled per unit area. They even have the computer run nightly productivity checks on the work performed that day (Celis 1994). For those modeling buildings where there are fewer standard shapes, it is more difficult to estimate time. Figure 34 shows the results we obtained from working on the San Mateo County Hospital. These are not conclusive and there still must be more careful study done on this topic, but I present them here as a starting point for comparison.

3D & 4D Model Building
San Mateo County Health Center

Buildings	Aprx. Sq. Ft.	3D Modeling Time
Central Utilities Plant	20,000	320
North Addition	47,000	100
Clinics Building	45,000	110
Nursing Wing	110,000	200
Diagnostic and Treatment	65,000	120
Existing Hospital	40,000	170
Site		180
Total	327,000 sq.ft.	1200 hours
Average per building	3 hours per 1,000 sq. ft.	

Figure 34 San Mateo 4D Model hours

By contrast, we had the experience of modeling a residence in which we placed cars, furniture, and other furnishings. We applied texture mapping to the brick walls and wood floors and created a walkthrough of the entire house. This took approximately ten times longer per 1,000 sq.ft. than the hospital project. All of these numbers are greatly affected by the learning curve. For example, it took me 40 hours for initial training with the various software packages that were used in the schedule animation. At one point I had 6 students work 40 hours each on the model. I was able to give specific instructions and convey some of the lessons I had learned. With this training and having a specific task, they were able to each produce 1000-2000 objects for the model in 40 hours. Productivity levels varied with some students much more comfortable working in 3D than others. Similar time savings were seen when I had another student replicate the modeling of the Clinics building. By seeing the computer model first, she immediately understood the geometry of the structure. She was able to work from the 2D drawings but already had an image in her mind of what it looked like in 3D. This, along with focused training in 3D modeling enabled her to complete the same model in significantly less time than time required to model the building the first time.

In another situation, we estimated modeling time for a few of the buildings using more abstraction and less detail. When Dillingham determined they wanted to show all the architectural features, the actual modeling time was 4 to 10 times greater than estimated. But it must be kept in mind that even in this preliminary state, these numbers indicate that 3D CAD modeling is less expensive than physical modeling for a certain level of detail, recognizing of course the limitations of this kind of comparison as explained in Section 3.1.

3.4.4 Challenges of 3D and 4D CAD

Much of the resistance to the use of 3D and 4D CAD is that there is not an intense economic reason to change current practices. Because of this, people can use traditional methods and still be able to compete in the marketplace. There are many reasons for the slow adoption of CAD such as resistance to change, risk of financing, cost of training, legal barriers, and shift from centralized control to decentralized control (Mahoney and Tatum 1990a). These can also be stated as behavioral, institutional, legal, and organizational barriers (Mahoney and Tatum 1990b).

There are some technological challenges that make the adoption of 3D and 4D CAD challenging as well. These include the way in which the model is viewed, the way that information from a 3D model is manipulated, what level of detail that is put into a model, who sees the model and when, and how additional information needed with the model is accessed. These issues are addressed in Chapter 4 with suggestions for addressing some of them.

Despite these challenges and the relatively slow application of 3D CAD in construction, it should be noted that many firms have been doing some form of 3D computer modeling for over ten years. Firms in the process and power industry, where components are easily broken down into relatively large objects, have used 3D CAD extensively during the last five years. Many process and power engineering firms do the entire design of some projects in 3D and then generate 2D drawings at the end of the process. They have found that by building the model this way they can create a 3D model and 2D documents more productively than by simply doing the project in 2D. Although the capital costs increase for equipment, fewer people are needed than on 2D projects. These large firms see no turning back from using 3D CAD (Delashaw 1994, Celis 1994, Orenstein 1993).

Many architectural firms do extensive 3D modeling to walk clients through new buildings (Mahoney 1994, Kempfer 1994) . Some use computers not only to present the models but change them while meeting with the clients (Crosbie 1994). Other uses include extracting views of the 3D model in the 2D drawings, using 2D sections of 3D models as a template for 2D details, and even the manufacturing of complex building surfaces directly from the 3D model (Novitski 1994a, Novitski 1994b). But most of these efforts today do not progress beyond the design phase. Two dimensional drawings and line diagram schedules are used for construction.

The use of 3D CAD is not a brand-new idea. The problem is that its use has been limited to a single application such as a walk-through of a building. Designers, contractors, and owners must realize the potential of 4D CAD and other applications. Although many are suspect of the new technology today, there are greater degrees of satisfaction in store for designers and users in using 4D CAD. One of the findings of a firm that uses 3D extensively in design is that once the designers become proficient in 3D, it becomes their preferred method for design (Orenstein 1993).

4 4D CAD- FUTURE USES

4.1 Better 4D CAD

The use of four-dimensional models in construction is developing rapidly. There are strong conceptual reasons for using 4D, there are successful full-scale implementations of this technology in large firms, and there is increasingly better computer hardware that is making the manipulation of large models faster. Software is the enabling element in the use of 3D and 4D models. Good, resilient, error-free software is critical to the continued use of electronic modeling, as it is to all other areas of computer use (Denning and Dargan 1994, Gibbs 1994). More importantly, software development holds the key for many of the enhancements in 3D and 4D that will lead to greater use of these tools. Better software tools and the development of new hardware tools will lead to better 4D CAD. The purpose of this section is to describe the developments that will make this happen.

4.1.1 Viewing the Model

There are continued advances being made in how 3D models can be viewed. These are being studied and developed as the limitations of viewing 3D and 4D models on a flat, two-dimensional computer screen become increasingly evident. These advances are also being driven by the desire to view 3D models with more of a feeling of reality and the willingness to pay for these enhanced viewing capabilities. Some of the developments in this field have application to the improved use of electronic 4D CAD models in construction.

Electronic Desktops

The desktop or the table has been the location for most architectural and engineering designs throughout history. Both 2D drawings and physical models are viewed easily when displayed on such flat surfaces. People can gather around, point at things, look back and forth at each other, move around to see something more closely and then step back to view the entire piece, and carry on interactive discussions with managers, clients, or others on a team. The development of electronic desktops (Krueger and Froehlich 1994) is making these same qualities applicable to electronic models The first kind of electronic desktop is one where the computer image is simply transmitted to a desktop. This desktop has been adapted to be a large horizontal computer screen. This puts design activities back into a wider frame of view for creation, but adds the new capabilities of 3D modeling as well (See Figure 35). Once the computer image resides on the desktop, the next logical step is to make use of two hands instead of one, just as in manual drafting where one hand holds the tool and the other draws the line. This will increase productivity beyond the current single-handed use of a computer mouse.

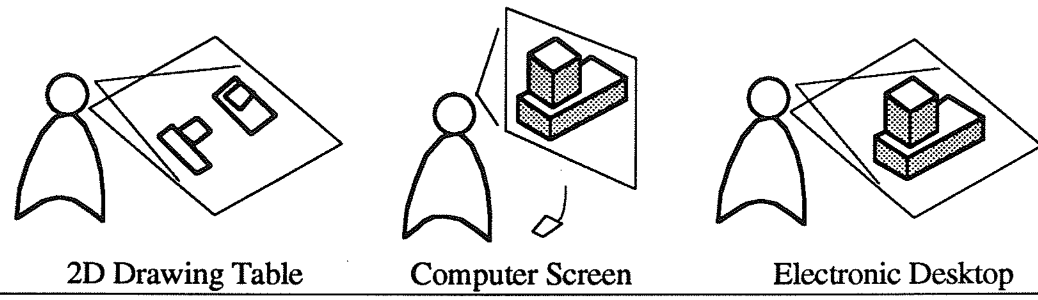


Figure 35 Surfaces for creating images

Another form of electronic desktop uses stereo shutter glasses and gloves that have electronic data receiving and transmitting capabilities to make the image from the desktop appear to be floating in the air above the desktop. This environment lets people select and move around objects, modify the geometry and interact in other "life-like" ways with the electronic model (see Figure 36). Sound, such as a level of static noise, can be implemented to make "contact" with the virtual objects seem real. Viewing the 4D model with this electronic tabletop combines the flexibility of electronic viewing and manipulation with many of the characteristics relating to the viewing of physical models.

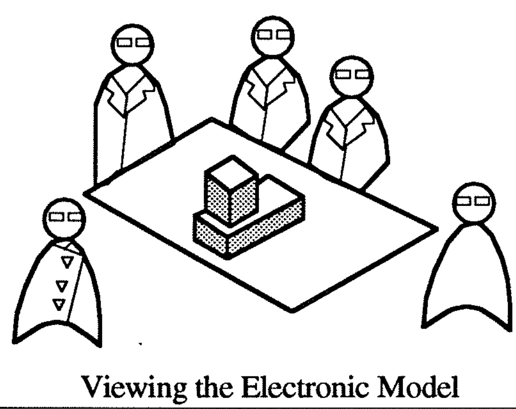


Figure 36 Using the Electronic Table

Electronic enhancements will create a more informative viewing of the model. In addition to seeing the construction sequence people can hear the sound of construction. For example, recognizing at the planning stage that jackhammering is a very noisy activity will save both inconvenience and time in coming up with remediation efforts. Simulated redirection of traffic, or simulation of people moving through the hallways will bring the capabilities of more informed planning together in the 4D model.

Virtual Reality

Virtual reality seeks to provide an immersive environment in which electronic models can be viewed (Latta and Oberg 1994). Just as with flight simulators, the goal of virtual reality is to make you feel like it is real and not just a model. As early as the 1960's head-mounted stereo displays were developed to create "cyberspace" an electronic "virtual" world (Machover and Tice 1994). Today virtual reality rooms have been developed where three walls are used as projection screens. This comes quite close to convincing the visual senses of a real experience. From client walk-throughs to training for construction equipment operators, this technology has great potential as yet another way the electronic model can be understood and used as a planning tool (Ribarsky and A. op den Bosch 1994).

Work is also being done to make possible the creation of models using virtual reality rooms. Using a pointer and an electronic paint pallet, shapes can be created in front of the creator just as a model builder builds a physical model (Deering 1994). Such sculptural tools will enable designers to design in new ways. The designer will be able to assemble three-dimensional spaces to create spaces, move inside of them to test them out visually, and step back to adjust and continue the design process.

Along the same lines, developments are being made so that the 3D model can be displayed on clear lenses in front of one's eyes while seeing the real world as well. This could mean that workers building a structure could use a combination of references from the real world and images from the electronic model to determine where construction objects need to be located. Work at Boeing is being conducted with location devices mounted on head gear that keeps track of where the worker's head is so that a computer image with diagrams of the work to be done can be displayed on a work piece (Sims 1994). Eventually a worker will be able to work within the real structure and within a virtual 4D model at the same time.

4.1.2 Viewing the Objects

There are conventions for working with objects in 2D design that were adopted by 2D CAD, but no longer are valid in 3D. Two of these are (1) how objects are grouped and (2) how much detail is shown about an object. Two-dimensional CAD uses layers to group objects, named to mimic the use of overlay sheets in 2D drawing. Each different layer of paper or mylar contains different information from the architectural, structural, and mechanical disciplines and they can be combined or separated at printing time to give the desired level of information. Turning images on and off in 2D CAD is similar to taking layers of drawings on and off a drafting table.

Abstraction has always been a strong point of 2D drawing. Walls can be shown as two lines and not as a series of vertical studs with gypsum board on either side. Where higher levels of detail are need, small detailed drawings of increasing size and specificity are used. Neither of these approaches is efficient in 3D CAD.

Object Control

Three-dimensional modeling consists of objects that are parts of larger groups or types of objects. If you have a simple two-story frame drawn in 3D it is difficult to divide the columns up in a logical fashion. One could put all the first floor columns on one "layer" or "level" and all the second floor columns on another. But if you wanted to be able to view, modify, and move only the columns in each corner of the building, the "layers" or classifications would need to be named corner 1 columns, corner 2 columns, and so forth.

The alternative to this arrangement that would allow the flexibility necessary to use the full benefit of 3D is to divide objects into groups or classes. In this way, each column can be a part of either the columns of that floor or the columns of each corner. Additionally, the columns can all belong to the group "columns" without having to have any further subdivisions (see Figure 37).

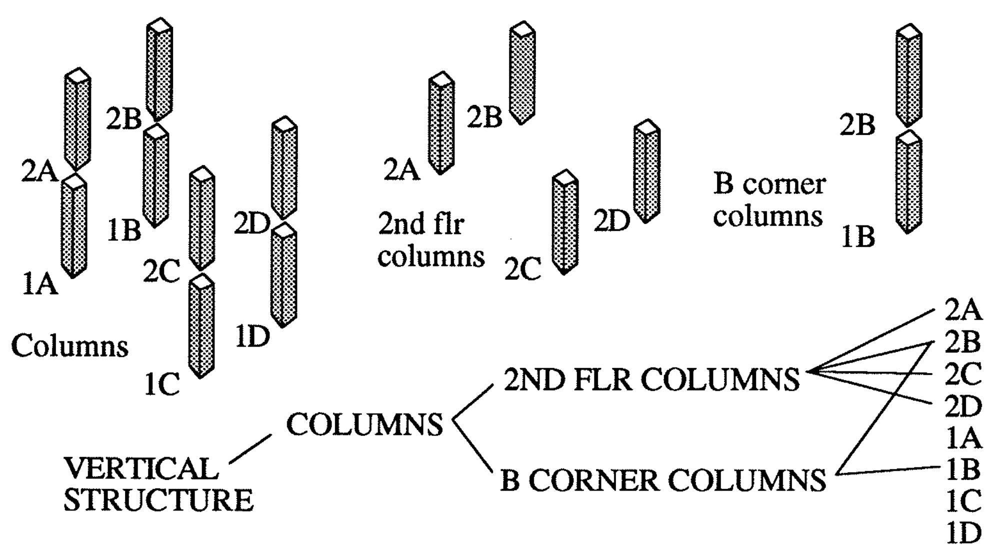


Figure 37 Classification of Objects

The power of this is that an object with 50 components can be selected, moved, or deleted by selecting just one single object type rather than all 50 components. For example, if the north wall of a building has to be moved out one foot all of the subcomponents including doors, door jambs, windows, window jambs, and so forth would follow with the move, without having to be selected independently. This form of object control is critical for further developments in expert systems (see Section 4.1.5).

Levels of Detail

Even 2D drawings must include a determination of what level of abstraction will be indicated in the drawings. Standards and conventions have developed such that 2 lines drawn close together with a perpendicular line at each end represent a window in a floor plan (see Figure 38). By contrast, a window may be shown in 3D as a rectangular box, but this also may be the representation of a door. The amount of lines and surfaces needed to change this box into a recognizable window can be ten times greater than the simple six faces of the 2D box.

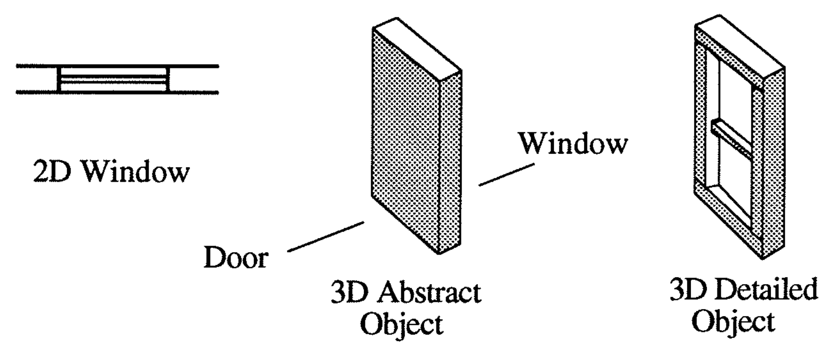


Figure 38 Levels of Detail

There is a dilemma that is presented by the question of how much detail to show in 3D between how specific and complete information is in 3D and the ease at which the model can be manipulated and viewed. First, detail is demanded in 3D because abstraction is more difficult, as in the case of the window and the door both being represented by a box. Important details and connections that can be avoided in 2D must be resolved at some level of specificity in 3D (Coles and Reinschmidt 1994). But each element of detail drawn takes valuable time to enter it into the computer. Also, each additional object added for clarity increases the storage file size of the drawing. This means that moving the objects around on the screen will be slower since computer speed is tied directly to the amount of information that needs to be processed. Larger file sizes mean more information which means it takes more processing power to display the updated image on the screen as the object is moved around.

For example, a building might have 2,000 doorknobs to be installed. In a typical set of 2D construction documents, the door would be shown by an arc in plan and a symbol would direct you to a table that contained the specific doorknob that was to be installed on that door. No 2D drawing would be made of the door. But if one is to build a 3D model, do the doorknobs need to be shown? If so, how many? If all 2,000 are put into the model, the model would be difficult to navigate because rendering time would increase, and no one is likely to be concerned about doorknobs anyway.

Finding solutions to the issue of detail in the 4D model can be broken into two parts: how to generate the detail efficiently and how to view the detail efficiently. A major part of the solution to help with the generation of detail is to have more than one source for detail. Each designer should be able to add the geometric objects to the model that are important to her work. Subcontractors could add detailed 3D elements to the more abstract model original design model, just as shop drawings today show greater specificity than design documents, but are based on them. Material suppliers may also start supplying free detailed 3D representations of their products that can be inserted easily into 3D models. Perhaps most importantly, software tools are being developed that can use rules and guidelines to generate detailed 3D objects (Hodgetts 1994). Some examples of automated applications include one that will take a first pass at framing a wall, including studs at 16" on center and headers over the doorways and window openings. Another performs automated pipe routing given an entrance point, exit point, the geometries of objects in the space, and the desired size of pipe. These applications will increase in numbers as 3D modeling is used more extensively.

In order for the 4D model to contain large amounts of data, it must be possible to view different levels of detail at different times. This can already be accomplished by manually turning on and off objects, but there may be significant advances in speed if this can be done in an automated fashion. One way to do this would be for the software to include some rules about what objects to render and at what level of complexity. For example if the computer viewpoint is only a few feet away from a bolt, it could be displayed as a detailed geometric object, perhaps complete with threads. Then if the viewpoint moved back 30 feet, a simpler geometry could be substituted for it. Finally, if it was behind a wall or if the viewpoint was 300 feet away, it would not be shown at all. In the same manner, a window could be displayed as a flat 2D plane from a long distance away and as a completely detailed window from a few feet away, with a few levels of detail in between (see Figure 39). This information could be accessed from databases of geometric information. Current graphic software already computes most of these calculations and is able to not render any faces of objects that are out of sight of the viewer. But the actual formalization of rules about viewing large amounts of detail, and keeping track of it in "subfiles" will be helpful in the long term use of 4D CAD models.

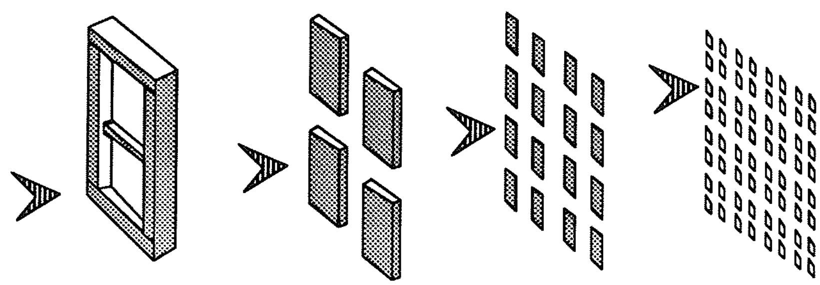


Figure 39 Differing Levels of Detail for the same Window

4.1.3 Working in a 3D Grid

Because of the flexible characteristics of CAD, especially the ability to view an object at any scale, there must always be a method of getting closer to an object or farther away. Some CAD programs use the terminology "zoom" from the "zoom lens" familiar in photography. This lets the viewer get farther away from or closer to an object. This method works well for 2D drawings because it essentially mimics what you would see if you put your face closer to a drawing and then stepped back from it.

The capacity to view pieces of the model is important to being able to use a computer model. In three dimensions, zooming works fairly well for viewing the outside of completed objects and exterior details. Other conventions from photography have been developed, so that you can pick a "camera" location to look from, chose a camera lens with particular perspective angles, and so forth, to view the model from any angle as a camera would. This is especially helpful in walking through an electronic model. You can also use view planes to see the model in new ways. Only the elements of the model between the front and the back view plane are visible. By adjusting the distance from the user's view point to the two planes, sections of the model can be viewed. This allows for defining views of horizontal sections (floor plans), vertical sections, and elevations which are important to view in understanding the overall function of the building.

Since much of the work in 3D modeling has been of objects that are small in comparison to buildings, these viewing tools continue to be sufficient in most applications.

Buildings and other structures have large, open spaces surrounded by areas that are tightly packed with necessary support structure and equipment. There needs to be a way to view smaller volumetric areas in 3D models other than showing the entire building or turning on and off layers. Gridlines are often used in two dimensions, passing through column centers at right angles to each other. Models in three dimensions need the additional subdivisions in the vertical direction. By having a 3D grid, small volumetric areas can be viewed individually. Instead of turning any objects on and off, everything outside the specified volume is just made invisible so that the volume selected can be turned around and examined more closely in 3D space (See Figure 40).

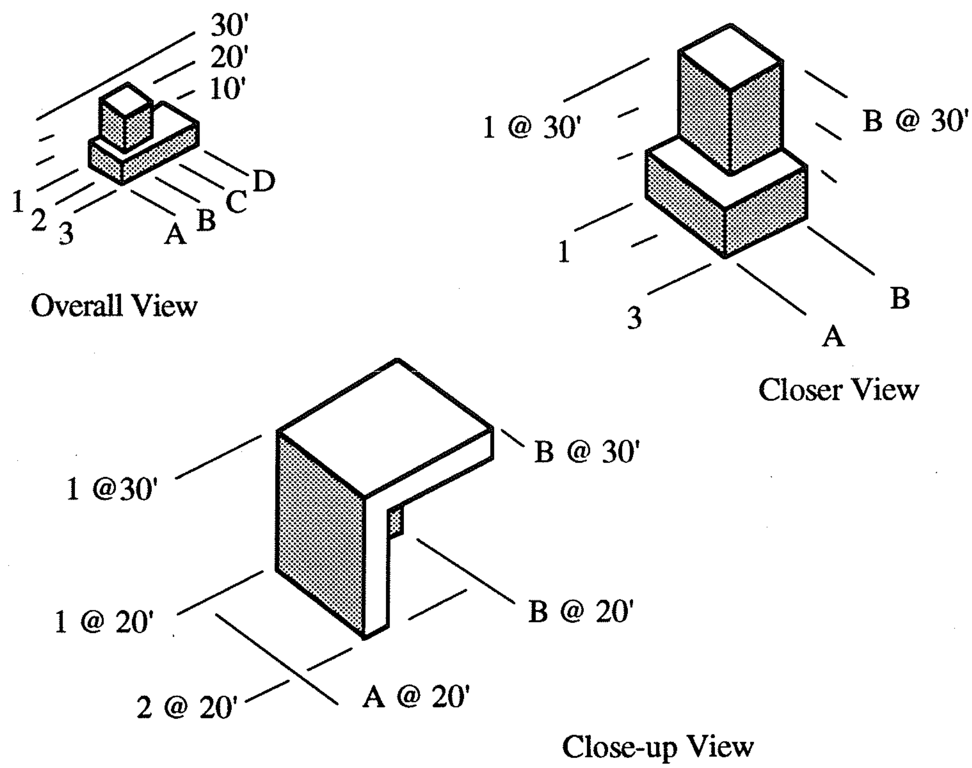


Figure 40 Zooming in with a 3D Grid

Once a 3D grid has been established, a new type of viewing takes place. Volumes are viewed either in the smallest unit available or as a set of volumes. One can imagine this as a three-dimensional spreadsheet. With this you could tab between volumes, select volumes, and even perform operations such as cut and paste with the volumes (see Figure 41). Objects such as piping that passed through a volume that was to be "cut" or deleted, would be cut accordingly at the points of entry and exit with the volume. Otherwise, the piping object would remain one piece, even though one viewed pieces of it separately in different volumes.

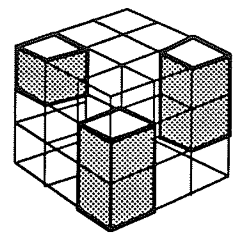


Figure 41 Volumes selected in a 3D Grid

The Boeing Company used a similar approach on the building of the 777 airplane. The plane was built in sections, so each section had to be displayed separately, but with all of the appropriate sections of piping, wiring, and other necessary elements. The model could be viewed in individual slices or all together (Economist 1994). This approach to viewing the 3D and 4D models in volumetric components of a 3D grid allows for simpler consideration of details of the model as described earlier in Section 3.4.2 on 4D details. Essentially, each volumetric area becomes its own 4D detail. In this way a room of a building can be viewed without having to figure out and turn off all the objects that are not part of that room. It also suggests a way in which volumes can act as objects, so that volumetric areas can be selected and manipulated.

4.1.4 Sharing the 4D Model

Another area of importance in using electronic models more effectively is the resolution of issues surrounding the sharing of the model and the storing of the model along with all the data attached to it. As described in Section 3.2.1 the Information Superhighway and other networking capabilities will make it increasingly easier to share the model with various people working on a construction project. But if the actual files of the model are transferred for viewing they could be easily changed or modified. Because of this, liability becomes a concern. The ability to record such models on CD-ROM may be a key technology to solving this problem (Carroll 1994). The CD-ROM records the model at a fixed point in time. The images of the model could be shared and updates sent back to a central location. Then weekly updated CD's could be simply mailed out to the parties involved. Other advances in locking files and adding electronic signatures will make it increasingly possible to transfer files electronically between all concerned parties.

In the future, review agencies may ask for the complete design of a facility to be presented on a CD-ROM as a 3D computer model. This will not only be environmentally effective in reducing the usage of paper, but it should make the approval process less laborious and lengthy since the graphic interpretation of designs will be simplified. Obviously, the amount of storage space required for documents will also be greatly reduced. An entire roomful of drawings could be reduced to a filing cabinet of CD-ROM's or other some other electronic storage medium of the future.

As an important part of sharing the 4D model, advances in viewing hardware will also need to be improved. Currently UNIX-based workstations are the lowest-end platform on which interactive animations of large 4D models can be viewed. As this technology becomes possible on the PC in the next few years and then moves to the laptop, the images of the model will be accessible at any job-site location in the world. Other viewing technology as described in Section 4.1.1 will need to incorporate teleconferencing and images of people in various locations in addition to the model itself.

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The issue of sharing the model goes well beyond the design and construction stage into the sharing of the model throughout the life-cycle of the building. As the facility is being built, the model can be changed to reflect the exact position of all elements in the model. This provides an as-built record that can be used by facility managers in managing and operating a facility. One can imagine that all the equipment in the building could be bar-coded so that not only is it recorded in a database, but shown in the model as well. The model would be accessible for remodeling, with all locations of critical elements, such as structural components, easily shown. The model could even be shared with local fire fighters for simulation of emergencies and training on how to deal with emergencies in that specific facility. They might develop evacuation plans that could then be taken back to the facility to assist in training the people there as well.

4.1.5 Models and Databases

As the electronic model becomes the central tool in the planning and design of facilities, all the non-graphic information important to a project will need to be added to the model. Obvious information, such as the dimensions of objects, will be necessary to be accessed easily. Other information may be contained in databases and queried to be displayed on the screen. Jacobus Technology in Gaithersburg, Maryland, is one of the companies developing this type of approach with their J Space product. This added dimension of object description will provide information for everyone in the building process.

At a minimum this information includes installation specifications and notes conveying design intent. But there is no limit to the type of information that can be attached. In addition to notes, video clips could be attached to an object. These might include an installation video from the manufacturer as well as one from the designer adding special instructions, or from the construction planner explaining problems that have been encountered in other installations of this type of object. Other information could include delivery information, cost information, and schedule information (see Figure 42).

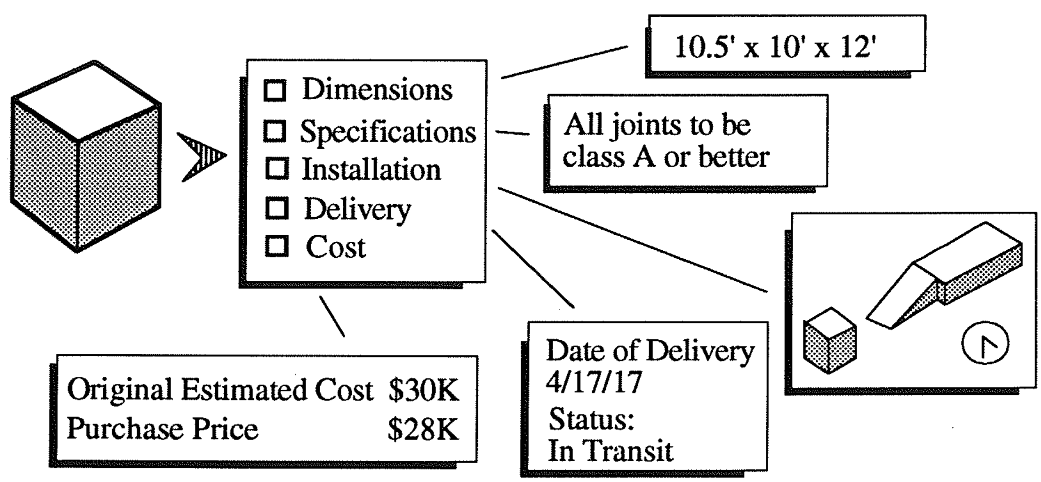

Figure 42 Information attached to the 3D object

Further flexibility will be provided by the ability to work back and forth between graphics and database information. In addition to being a description of the model, information such as dimensions could be changed in the database of the object that would change the graphic representation of the object. In the same way, the schedule dates could be changed to reflect, for example a delayed delivery, which would then modify the object's appearance in the 4D construction animation. This type of linking information to a 4D model gives a clear indication of the power of the electronic model being the single source of design information.

4.1.6 Additional Value of Electronic Model

Symbolic Models

Of great importance to the continued value of 3D modeling is the step of higher representation where an object is described using semantic definitions. Semantic models, or product models, include the geometric model as only one part of the definition. Other parts of the model definition include function, material, composition, and behavior in addition to the form or shape itself. Thus there can be a description of an object that remains intact even though the geometry or other characteristics change during the design and construction process (Luiten 1994, Fischer 1991, Clayton 1994, Morad 1994). The power of this idea is that reasoning capabilities such as artificial intelligence can be applied to analyze objects with the goal of automating engineering tasks. In this way the computer is able to store and apply large amounts of reasoning and experiential knowledge (including those that have been formalized into regulations) gained from many years of building in the world. The ultimate application of the computer is to automate tasks. The automation of initial cost and schedule estimates and the control of construction robots are some areas where automation tools are currently being developed.

This type of tool holds great promise for the improvement of productivity in construction. The 3D geometric model is a basic requirement for these tools to operate. The 3D CAD electronic model is the graphic manifestation of all the data. Ultimately, as described in the Introduction, the geometry of an object must be understood before anyone can build it properly. Semantic definitions and product models will lead to more powerful electronic models as the increased use of better 3D modeling makes possible the wide-spread implementation of such technologies.

4.2 Vision for the Future

The use of computers in all phases of design and construction with a shared 3D electronic model is the future of the design and construction industry. The exact way in which 3D and 4D CAD models are used will vary greatly depending on the size of firm and the type of work done by the firm, but the fundamental benefits will be sought by many firms.

Advancements in the capabilities of 3D and 4D CAD modeling capabilities such as the ones described in this chapter will create greater demand from clients for the use of models to explain proposed design and construction. Design and construction professionals will also use models to implement methods of both the planning and executing of construction that have increased clarity and accuracy over current methods.

Building and viewing of 3D and 4D models will be easier than ever. Access to the model will be a standard element of participation on a construction project. Automation will assist in performing repetitive tasks. Communications, even over great distances, will include graphic explanations.

The improvement of current software and hardware will continue to bring rapid change to the industry. A new generation of computer-literate participants in the construction industry will overcome many of the current obstacles to 3D and 4D CAD, implement these technologies, and use them to create higher levels of productivity in construction.

5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report is an examination of 3D computer modeling and its relevance to the design and construction industry. Current methods of presenting graphic information of three-dimensional objects in two dimensions requires one to continually piece together images as in a puzzle. This leads to errors in both the creation of accurate two-dimensional images and in the interpretation of them especially with large, complex systems such as buildings. In construction, significant time is spent on explaining geometries and resolving errors that result from such misunderstandings.

Three-dimensional computer models can create a complete and very accurate representation of objects. By using 3D models in communicating design intent, a common geometric understanding is possible between the various participants in a construction project. Electronic CAD models are similar to physical models of objects in the complete description of an object's geometry. They are very different in other ways. The flexible qualities of electronic models is what makes them valuable for construction. These include the capacity to view the model at any scale, to transmit it electronically, and to attach non-graphic information to it.

The use of 4D models gives a graphic description of construction intent. Four-dimensional models are created from three-dimensional models animated by displaying objects as they are to be installed in order to reflect the planned construction schedule. Once the construction sequence is animated, everyone involved in the realization of a physical structure can benefit from understanding what is planned to occur at a point in time in the future. Changes of all kinds--in methods, geometries, and the behavior of individuals--are easier to make in the planning stage, rather than once the project begins construction.

The ability to use digital descriptions of objects through the use of 4D CAD will enable the construction industry to improve productivity by reducing the high percentage of construction costs that are caused by miscommunication, changes of scope during construction, long lead times on equipment delivery, and poor planning.

5.2 Conclusions

The technology of three-dimensional electronic modeling will make a significant impact on how structures are designed and built. The impact of this technology is just beginning to be felt. Just like change that has come from other developments in history, believing that it will not have an impact will not stop its growth. Steam engines began as a curiosity. Even after they were used to make locomotives that could pull carloads of people, few who saw and heard about this new type of contraption ever felt they would be affected by it. But once railroad tracks were laid out across continents, even the poorest person was affected by the economic changes this brought. Whether or not a person ever rode a train, that individual had to compete in the marketplace with people and goods that were transported by rail. Some people resisted this change and fought to continue in their old ways. A very few were able, because of strong incentives such as religious beliefs, to continue to prosper (in their own eyes) using horses and buggies and are still using them today. But most people eventually adopted new lifestyles, moved to new locations, and became trained in jobs in the new economic structures resulting from this new form of transportation. The ones who where the earliest to make these changes realized the greatest economic benefits.

Technology such as the information superhighway may result in the computer having a similar impact as the transcontinental railway on the next century. Even casual participants in urban areas are affected by computers in almost every aspect of their existence, from the way they get their money, to the way they spend their money, to how the products are made that they use. Adapting to new technologies is not uncommon in the construction industry, but 3D modeling, and its empowerment with such applications as 4D, has the potential of making an impact that is an order of magnitude greater than the impact of other technologies thus far implemented in design and construction. This will be the same level of change that the creation of a network of railroad lines brought to the transportation of goods and people in this country. In a few short years, transversing distances was reduced from weeks to days, days to hours, hours to minutes. Today computers are used in construction to automate existing systems. Three-dimensional modeling is the key to the introduction of a new methodology. Just as the horse moved from a necessity to a luxury because of the train, the car, and other mechanical vehicles, two dimensional drawing, especially hand drawing, will become secondary to three-dimensional modeling in design and construction.

This is not to say that these changes will bring only good or welcome results. The concept of improvement and advancement is a vague one in all areas of existence. In looking at the history of the world, there have been many changes, but it is often debated whether those changes have been improvements. The automobile was introduced as a curiosity at first. Today it is an economic necessity for a large number of people in the world. Automobiles have provided a level of comfort and a range of accessibility unheard of even just a hundred years ago. Their wide-spread use has also brought pollution, environmental ground contamination from fuel, traffic congestion, and other negative results.

The same dichotomy exists in the development of 3D and 4D computer modeling and its use in construction. There is a danger that electronic worlds will be used by some people as a substitute for quality human interactions with the environment and other people. Three-dimensional models and electronic communications will let people pretend to visit almost anyone and anything. The appreciation of the "real" environment with real people, real materials, and real problems may decrease. Automation might be used by some to build the same box over and over again for any use-- just faster and cheaper. Professional designers and planners might become less valued or operate only in virtual design worlds.

However, there are many promising opportunities that may be made manifest with increased 4D CAD modeling and animation. More original designs, with new materials and more geometrically free shapes may well become increasingly economical to build. One may have more liberty to choose between a square box or a free-flowing space because the cost may be similar due to the ease of designing and building electronically. Waste will be reduced through better planning, and working conditions will be improved. Buildings and facilities will be less expensive to build and more responsive to the needs of those who use them. Professionals will become increasingly valued as coordinators of the integrated design and building process who assist in making structures responsive both physically and emotionally. By having many of the rudimentary tasks done automatically, more time and effort can be spent on quality and on using the power of the mind to develop better and more creative solutions.

BIBLIOGRAPHY

(Anadol and Akin 1994)
Anadol, Z. and Akin, O., "Determining the Impact of CADrafting Tools on the Building Delivery Process," pp. 1-8, vol. 2, The International Journal of Construction Information Technology, 1, 1994.

(Brenner 1994)
Brenner, J., "Computer Simulation Task Force," *Tracings- San Jose Chapter American Institute of Architects Newsletter*, September 1994, 5.

(Carroll 1994)
Carroll, C.R., "Trends," *A/E/C Systems*, issue 6, December 1994, 8-9.

(Celis 1994)
Celis, A., "Measuring Progress in 3D Projects," Audiocassette, Convention Cassettes Unlimited, Palm Desert, CA, 1994.

(CIFE and Dillingham 1994)
CIFE and Dillingham, "San Mateo County Health Center A 3D CAD Model," Video tape, Stanford, CA, 1994.

(Clayton and Kunz 1994)
Clayton, M.J. and Kunz, J.C., "First Drawings, Then Semantics," pp. 13-25, The Association for Computer Aided Design in Architecture, Reconnecting: ACADIA '94, 1994.

(Coles and Reinschmidt 1994)
Coles, B.C. and Reinschmidt, K.F., "Computer-Integrated Construction," pp. 50-53, Civil Engineering, June 1994.

(Crosbie 1994)
Crosbie, M.J., "The Virtual Practice," *Progressive Architecture*, September 1994, 86-87.

(Deering 1994)
Deering, M., "Lecture in Human Computer Interaction Series," Computer Science Department, Stanford University, October 21, 1994.

(Delashaw 1994)
Delashaw, D., "Management Issues for 3D Plant Design," *A/E/C SYSTEMS Computer Solutions*, issue 6, November-December 1994, 5-7.

(Denning and Dargan 1994)
Denning, P.J. and Dargan, P.A., "A Discipline of Software Architecture," pp. 55-65, Interactions, January 1994.

(Economist 1994)
Economist, "Manufacturing Technology, On the Cutting Edge," *The Economist*, March 5, 1994, 3-18.

(Edmister 1994)
Edmister, R.R., "A Very Good Day in the Third Millennium," *Construction Business Review*, issue 4, July-August 1994, 60-63.

(ENR 1994)
ENR, "Graphics focus the issues," *Engineering News Record*, November 14, 1994, 23.

(Fischer 1991)
Fischer, M.A., "Using Construction Knowledge during Preliminary Design of Reinforced Concrete Structures," Ph.D. thesis, Stanford University, Ca, USA, 1991.

(Gibbs 1994)
Gibbs, W.W., "Software's Chronic Crisis," *Scientific American*, September 1994, 86-95.

(Giovannini 1994)
Giovannini, J., "Renaissance Models at the National Gallery," *Architecture, Incorporating Architectural Technology*, issue 11, November 1994, 28-29.

(Goldsmith 1994)
Goldsmith, S., "The Shape of Things to Come," *San Jose Mercury News*, Sunday, October 23, 1994, 1D-2D.

(Gruber 1994)
Gruber, M., "A Look at Making in the Meier-Getty Model Shop," *Architecture California*, vol. 16 (issue 1, 1994), pp. 32-41.

(Hendricks 1993)
Hendricks, R.H., "Designing in Three Dimensions for Manufacturing Facilities," *Computing in Civil Engineering*, (issue June, 1993), pp. 61-69.

(Hodgetts 1994)
Hodgetts, C., "Rubbing Out The Craft: Architecture and Fabrication in the Age of Information," *Architecture California*, issue 1, May 1994, 7-11.

(Krueger and Froehlich 1994)
Krueger, W. and Froehlich, B., "The Responsive Workbench," (1994), pp. 12-15.

(Latta and Oberg 1994)
Latta, J.N. and Oberg, D.J., "A Conceptual Virtual Reality Model," in *IEEE Computer Graphics and Applications*, pp. 23-29, vol. 14, 1, January 1994.

(Lewis 1994)
Lewis, T., "The Replicator," *Computer*, July 1994, .

(Luiten 1994)
Luiten, G.T., "Computer Aided Design for Construction in the Building and Construction Industry," Ph.D. thesis, Delft University of Technology, the Netherlands, 1994.

(Machover and Tice 1994)
Machover, C. and Tice, S.E., "Virtual Reality," (1994), pp. 15-16.

(Mahoney 1994)
Mahoney, D.P., "Walking Through Architectural Designs," *Computer Graphics World*, June 1994, 22-30.

(Mahoney and Tatum 1990a)
Mahoney, J.J. and Tatum, C.B., "Barriers to CADD in the AEC Industry," Technical Report, Center for Integrated Facility Engineering, Stanford University, 23, 1990a.

(Mahoney and Tatum 1990b)
Mahoney, J.J. and Tatum, C.B., "Construction Site Applications of CAD," Technical Report, Stanford University, October 1990b.

(Morad and Beliveau 1994)
Morad, A.A. and Beliveau, Y.J., "Geometric-Based Reasoning System for Project Planning," vol. 8 (issue 1, 1994), pp. 52-71.

(Novitski 1994a)
Novitski, B.J., "Extracting 2D from 3D," *ARCHITECTURE Incorporating Architectural Technology*, issue 1, January 1994a, 115-117.

(Novitski 1994b)
Novitski, B.J., "Linking Up the Building Team," *ARCHITECTURE Incorporating Architectural Technology*, issue 9, September 1994b, 131.

(O'Toole 1994)
O'Toole, K., "Computer animation can save money, time, conflict on construction projects," *Campus Report*, October 12 1994, 9-10.

(Orenstein 1993)
Orenstein, G.S., "The 3D Approach to Design," *Computing in Civil Engineering*, (issue June, 1993), pp. 51-60.

(Ribarsky and A. op den Bosch 1994)
Ribarsky, W. and A. op den Bosch, "Visualization and Analysis Using Virtual Reality," pp. 10-12, IEEE Computer Graphics and Applications, January 1994.

(Riley 1994)
Riley, D.R., "Modeling the Space Behavior of Construction Activities," Ph.D. thesis, Pennsylvania State University, PA, USA, 1994.

(Sims 1994)
Sims, D., "New Realities in Aircraft Design and Manufacturing," *IEEE Computer Graphics and Applications*, March 1994, 91.

(Sterman 1994)
Sterman, P., "Builder has high-tech plan on site," *The Times, San Mateo County's Daily Newspaper*, September 22, 1994, A1-A2.

(Wallace 1994)
Wallace, S., "Accelerating Engineering," *BYTE*, July 1994, 62-74.