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Analysis of 4D Modeling for Use by the Naval Facilities Engineering Command

By

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Analysis of 4D Modeling for Use by the Naval Facilities Engineering Command

An Independent Research Study

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Patrick C. Jors

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Analysis of 4-D Modeling of Construction for Use by the Naval Facilities Engineering Command

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Abstract

The purpose of this paper is to explain recent research on the costs and benefits of 4D CAD technology to determine if it can benefit the U. S. Navy in management of its construction projects. The report will begin with a brief history of project management and the development of 4D computer based models. Sections 3 and 4 will discuss advantages and disadvantages of using 4D programs. An overview of the Navy's organization, mission, and construction management team will be presented for understanding the 4D CAD implementation plan discussed in section 6. The report will conclude with a financial analysis to determine what size and type of Navy project 4D CAD would be most economically useful for.

Reader's Guide

Chapter 1.0 explains the problem statement and purpose of the research and is recommended to all readers. Chapter 2.0 explains some basic project management concepts, the background and development of 4D CAD technology, and how it is used today. Chapters 3.0 and 4.0 explain benefits and drawbacks of 4D CAD, respectively, and are intended to provide insight in to why it may or may not be useful in construction. Chapter 5.0 is a basic explanation of the U.S. Navy's construction contract administration. Chapter 6.0 discusses methods for implementing 4D CAD in the Navy's construction contract administration organization (NAVFAC). Chapter 7.0 provides a method of analysis for determining the minimum dollar value project on which the Navy could profit from using 4D CAD.

The author suggests that any readers new to the idea of 4D CAD, with little background in construction management, and no knowledge of the NAVFAC organization read the report in its entirety. Readers with an understanding of the advantages and disadvantages of 4D CAD and a background in construction management may skim for review sections 2.0, 3.0, and 4.0. Readers who understand the basic organization of NAVFAC may choose to skim section 5.0.

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1.0 Introduction

1.1 Problem Statement

Construction planning is a crucial and challenging management task. A good plan is critical for project success. Plans are the basis for the project budget, the production schedule, and communication with project participants. Although project planning is an extremely important and complex undertaking, it relies largely on mental conceptualization and is typically performed in an intuitive fashion with considerable reliance on engineering judgment. If planned budgets and schedules are based on miscalculated judgments, considerable cost and time growth can result, leading to change orders, claims, and law suits.

Despite an increase in the use, size, speed, and capabilities of computers over the past ten to fifteen years, few new and beneficial computer based tools have developed widespread applications in the construction industry. Certainly, there are numerous computer based scheduling tools in use throughout the industry. However, scheduling is no new concept, only a well established instrument made more accessible by computers, and the increased use may not necessarily be good. According to a recent *Engineering News Record* article: Four scheduling experts "say they see widespread abuses of powerful software to produce badly flawed or deliberately deceptive schedules that look good but lack mathematical coherence or common sense about the way the industry works. The result is confusion, delayed projects, and law suits." (Korman, and Daniels 2003)

Besides the widespread abuse, experts have also noticed limitations of construction scheduling software on the market today. Professors at the Hong Kong Polytechnic University and the Tsinghua University in Bejing have stated:

> These types of tools are not capable to display the spatial construction features as well as the pertinent resource and workspace requirements, which are envisioned only in the mind of the planners. They do not furnish data integration or visual representation of the project versus time, such as project progress and status of site space usage. As such, planners can only glean information from design documents to adopt the appropriate construction scheme and site facility layout, on the basis of their intuition, experience, judgment, and heuristic. It can be said that the potential assistance they can receive from the computer has not been fully exploited. (Chau, et.al. 2003)

Koo and Fischer (2000), from the Construction Engineering and Management Department at Stanford University mention two more limitations in their research:

> First, interpreting the schedule can sometimes be cumbersome as typical schedules have hundreds or thousands of activities, and the assumptions for the precedence relationships are not represented in the . . . schedule. This can make identifying mistakes (e.g. checking the schedule for its completeness and correctness of logic) in the . . . schedule difficult. Second, different project members may develop inconsistent interpretations of the schedule when viewing the . . . schedule. This in turn makes effective communication among project participants difficult.

As the United States Navy performs billions of dollars of construction each year it is an active user of the types of scheduling software described. Typical Navy Construction Contracts specify the contractor develop a schedule, using the types of scheduling programs described, and submit it for acceptance to the local construction contracting officer. Upon receipt of the schedule the contracting officer must review the schedule for completeness, correctness, constructability, and logic. Published Navy guidelines, such as the *Atlantic Division Construction Contracting Handbook*, outline typical scheduling "games" contractors play and advise contracting officers not to accept schedules with those flaws. However, since the schedule reviewers must mentally conceptualize the relationship between the usual hundreds of construction activities in the schedule and the many components in the 2D drawings, a thorough schedule review can rarely catch all the errors. In some cases, certainly, the contractor is not purposefully manipulating their schedule, but they too face the same conceptualization problem. As a result, schedules are accepted and used containing uncaught errors leading to delays, disputes, and cost overruns.

To overcome such deleterious errors, many researchers and industry experts have developed a partiality for an emerging technology called four-dimensional computer aided drafting (4D CAD), or 4D modeling, or 4D simulation. 4D CAD combines 3D CAD models with construction activities, from a schedule, to display the progression of construction over time. Researchers and industry experts claim it can mitigate the limitations of and the tendencies to misuse traditional scheduling programs. Two of the pioneers in 4D CAD, Kathleen McKinney and Martin Fischer (1998), say it overcomes the mental conceptualization problem "by representing the associations between schedule information and CAD information through a *4D movie* that visually communicates the sequence of building construction. In this manner, CAD is used to generate a visual representation of the construction schedule and enhances existing scheduling techniques." Bonsang Koo and Martin Fischer (2000) state that "4D models increase the comprehensibility of the project schedule, thereby allowing users to detect mistakes or potential problems prior to construction." They further extrapolate from their experiences that benefits of 4D models are also as a visualization tool, analysis tool, and integration or collaboration medium. (Koo and Fischer 2000)

Besides scheduling errors leading to setbacks, the constructability of a design may lead to complexities causing delays or cost overruns. Many times the designers will not consider construction methods when designing, and the contractor is left to choose how to construct a facility based on the 2D drawings and specifications. Recent research suggests constructability concerns can also be conquered through the use of 4D CAD. According to Koo and Fischer "if the 4D model is built in the early planning stages of the project, the construction planner can review alternative scenarios to decide upon the best construction method that is most cost effective and time saving. On the other hand, the construction planner can provide feedback to the designer by performing feasibility studies and determine which design is most appropriate for the selected construction method." Barrett (2000) views the technological development as capable of potentially providing an improved relationship between constructors and designers. In the case of contracts with the US Navy, relationships with the contracting office can also potentially be strengthened by limiting design changes and cost overruns.

Other research and observation notes that 4D models can be used to speed up and improve decision making and to involve more project stakeholders than traditionally possible. One researcher explained:

> Since a CAD model provides the basis for a common language between all parties, adding time to a 3D model creates a visual simulation of the construction process--4D CAD. With 4D CAD, design and construction planning activities can be assessed realistically within the context of space and time. Simultaneous modeling of temporal and spatial aspects of scenarios can optimize and justify the conscious decisions that jeopardize or hinder the completion of many construction projects. . . . This tool also encourages the communication, approval and improvement of construction schedules by various parties, such as construction managers,

> clients, designers, subcontractors and community members. (http://gaudi.stanford.edu/4D-CAD/INTRO-4DCAD.HTML)

Such a tool would benefit Navy construction offices when explaining the progress or delay of a facilities' construction to non-technical naval personnel. Since 4D CAD models are electronically based they could be sent via email to headquarters to utilize additional resources or they could be sent to remote locations via wireless connections for wartime purposes.

Although 4D CAD provides benefits with potential to improve naval construction contract administration, there are major upfront costs involved in implementing its use. Therefore, the costs and benefits need to be weighed to develop guidance on when use of 4D CAD would profit the Navy. Certainly, one would not realize much gain from its use on the construction of a $10,000 garage, but 4D CAD could potentially benefit the renovation of a naval hospital.

1.2 Purpose of Research

The purpose of this paper is to explain recent research on the costs and benefits of 4D CAD technology to determine if it can benefit the U. S. Navy in management of construction projects. The report will begin with a brief history of project management and the development of 4D computer based models. Sections 3 and 4 will discuss advantages and disadvantages of using 4D programs. An overview of the Navy's organization, mission, and construction management team will be presented for understanding the 4D CAD implementation plan discussed in section 6. The report will conclude with a financial analysis to determine what size and type of Navy project 4D CAD would be most economically useful for.

2.0 Background of 4D CAD

2.1 Scheduling History

Project management has been around as far back as human history has been recorded. Long before King Cheops planned the construction of his pyramid, the Mesopotamians re-synchronized their calendar, based on the phases of the moon, with the seasons by adding an extra month to ensure planting would begin at the right time of year (project start). From the ancient Mesopotamians to today, project management has been the foundation of the success of human endeavors. Without the tools and techniques of project management, society would not be able to function at the speed, affordability, and complexity it does today. (http://www.pqa.net/ccpm/W05002001.html)

A project, as defined by the Project Management Institute, is "a series of tasks, arranged in defined sequences or relationships that produce a pre-defined output or effect. A project always has a start, middle, and an end." (http://www.pqa.net/ccpm/W05002001.html) Some projects are commonplace and repetitive, such as placing a concrete sidewalk, while other projects are unique, one-time events, like building the Hoover Dam. But in construction, no matter how commonplace and repetitive a project may be, reconstruction of a similar project will rarely be repeated in an identical manner. Why not? How can the construction of a sidewalk in Florida be any different from one in Michigan? The possible variations in sidewalk placement between one job site and the next will be caused by differing resources (concrete suppliers and laborers), environmental conditions (weather, local labor practices, and job-site constraints), and management styles (work hours and preferred construction methods), among others. Due to the changing conditions from job to job, to plan for efficient project accomplishment, a project manager must apply judgment to the particular conditions of the project at hand, and schedule based on past experience of similar projects. Then, as work progresses, the project manager will re-plan and reschedule when delays or unforeseen conditions occur.

Although project management has been around since the dawn of human history, no one had really looked at the accomplishment of projects scientifically until the industrial revolution. Frederick Taylor (1856-1915) realized work is not a monolithic "thing" but a series of linked, smaller tasks. He reasoned, to improve productivity, the individual tasks need to be performed more efficiently. Up to that point, productivity was mostly improved by demanding workers put in more hours of labor.

Henry Gantt (1861-1919), an associate of Frederick Taylor, focused his work on the construction of U.S. Navy ships during World War I. He broke down all the tasks in the construction process and diagrammed them using the now familiar grid, bars, and milestones. The charting method, which bears his name, has developed into a powerful planning and evaluation tool for project managers. In fact, the appearance has changed very little over the last 100 years. Not until the 1990s were link lines added to the task bars to show various kinds of dependencies and the critical path. (http://204.144.189.70/index.htm)

The development of critical path methods (CPMs) in 1958-1959 by James Kelley and Morgan Walker for the duPont Corporation provided the basis for a more formal and general approach for project management. CPMs include a graphical portrayal, or network, of the interrelationships of the elements of a project, and a mathematical procedure identifying the relative importance of each element with respect to the completion of the project. Since their development, CPMs have been applied with some success to construction work and other activity oriented projects. Today, almost every construction project requires the submittal of a schedule showing the critical path, which is the set of activities that cannot be delayed without delaying the project. The CPM schedule, usually presented in the form of a Gantt chart, developed by computer programs, is used by both owners and contractors to monitor progress, determine delay impacts, and act as a basis for progress payments. (Moder and Phillips, 1984 and http://enr.construction.com/opinions/lettersupdates/archives/030623.asp)

Also in the late 1950's, Admiral Raborn, of the U.S. Navy, was in a hurry to develop the Polaris missile program due to the perceived threat of a "missile gap" between the U.S. and Russia. Traditional project management was not enough to ensure the safety of the nation so the problem was solved with the help of Willard Frazar's PERT (Program Evaluation and Review Technique). PERT became the mandatory requirement of all U.S. Navy projects. One of the principal features of PERT is a statistical treatment of the uncertainty in activity performance time; it includes an estimate of the probability of meeting scheduled completion dates at various project stages based on “most likely,” “optimistic,” and “pessimistic” production times for various activities. (http://www.pqa.net/ccpm/W05002001.html and Moder and Phillips, 1984)

2.2 4D CAD Development

While thorough planning and scheduling are significant in the management of construction they cannot be accomplished without interpretation of the design. In construction, besides being concerned with the project schedule and timeliness, project managers are also occupied with how the design will be assembled. Today, most construction projects are conveyed to the successful contractor through paper based working drawings. The project manager is required to interpret the drawings to prepare the schedule. In their preparation, the project managers must consider human, material, economic, and equipment resource requirements, workspace logistics, construction methods, and construction sequence within spatial and time domains. While the computer based Gantt charts, CPM schedules, and PERTs will provide tools for project managers to monitor construction sequencing and time relative requirements, they are not capable of displaying spatial construction features or related resource and workspace requirements such as site space usage over time for storage of plant, materials, and equipment.

Planners typically use CPM-based networks and Gantt charts to describe the proposed schedule of their projects. The CPM schedule helps coordinate the activities of all project team members. The activities are associated with one or more components encompassing a project and the associations are explicit in the CPM schedule by pairing an action with a component (e.g. install formwork). To identify spatial aspects users must look at the 2D drawings and relate components with activities, but not all project players develop the same mental images when referencing the schedule with the 2D drawings.

Limitations of the CPM schedule include: cumbersome interpretation due to the usually large number of activities; assumptions for the precedence relationships are not represented; identifying mistakes in the CPM schedule is difficult; different project members can and will develop inconsistent interpretations of the CPM schedule – thus communication among project participants is difficult; and information concerning spatial context and complexities of components is not provided. (Koo and Fischer 2000)

The shortcomings of the computer based CPM schedules thus led to the development of tools to combine CPM schedules (time) and 3D CAD models (space) to convey the sequence of construction visually in four dimensions – the fourth dimension being time. The linking of the 3D graphic images to the fourth dimension of time results in the 4D CAD model. In some cases, a model can also be linked to the estimate or schedule of prices to show cost progression resulting in 5D, 6D, or more. Primarily though, the 4D model connects the space and time aspects of a construction project, as they are during the actual construction process.

The model allows planners to analyze, visualize, and collaborate on the construction process. (Koo and Fischer 2000) According to Fischer, "4D models enable a diverse team of project participants to understand and comment on the project scope in a proactive and timely manner. They enable the exploration and improvement of the project executing strategy, improvements in constructability with corresponding gains in on-site productivity, and the rapid identification and resolution of time-space conflicts." (http://www.stanford.edu/~fischer)

Systems linking 3D CAD models with schedule and other project information started to be developed in the mid-eighties. In 1984 visual construction simulation software became commercially available with the introduction of Construction Systems Associates' *PM-Vision*. In 1986 Bechtel Corporation developed a 3D animated design review tool called *Walkthrough* for Silicon Graphics workstations. In 1991, Jacobus Technology was established by former Bechtel employees where they developed an interface between *Walkthrough* and a CAD system. Later Jacobus integrated *Walkthrough* with Primavera's *P3* scheduling program. Jacobus called the program *Construction Simulation Toolkit*, and additional work led to a real-time 3D visualization system called *Navigator*. During the development of *Navigator*, the first project to apply 4D CAD was sponsored by Dillingham Construction and performed by Eric Collier and Martin Fischer at the Center for Integrated Facility Engineering (CIFE) at Stanford University. The project involved the development of a 4D model to communicate the four-year construction project of the San Mateo County Health Facility beginning in 1993. In the work performed at CIFE in 1993, 4D modeling alerted project managers to a major space-time conflict restricting access to portions of the hospital during a six month construction period, which they were able to correct before construction began. Due to the success of the project, Martin Fischer continued to pursue research related to 4D models, focusing on improving 4D tools and the value of 4D models in design and construction. (http://www.stanford.edu/group/4D/projects/projects.shtml, McKinney and Fischer 1998, and Sheppard 2004)

Following the success at CIFE, the idea of 4D modeling moved on to the Fortune 500. Benedict Schwegler championed the use of 4D tools inside the Walt Disney Corporation's Imagineering Division. Schwegler's objective, back in 1998, was to develop the leading 4D software when he set out to use the technology to plan construction of a $50 million roller coaster at Disney's California Adventure theme park in Anaheim, California. The technology worked so well it was used to plan the construction for the park's entire Paradise Pier section, featuring rides, restaurants, shops and a boardwalk. Paradise Pier had between 10% and 20% fewer design changes as a result. (Muller 2003)

2.3 4D Technology in Use Today

Today, 4D modeling is being used to build Space Mountain at the new Hong Kong Disneyland theme park. Additionally, the technology is being used for the reconstruction of the 26-year-old Space Mountain at the Disneyland in Anaheim. Muller explains:

> Among the hassles: Contractors must remove a giant crane from the temporarily closed ride by 2 p.m. every day to make way for the Mickey Mouse parade. And materials must be lifted through a hole in the mountain that is 30 feet above ground. . . . When contractors previewed the project in 4-D, they spotted a flaw: Had they started to build the steel structure where they had originally intended, they would have had to halt construction for two months while they reinforced the site. Instead, they began laying the steel at another site inside the mountain while they prepared the first site. By doing this, they kept the renovation on track for a 2005 reopening. (2003)

A number of big contractors are also using 4D models to map construction or renovation projects. California's DPR Construction has used it for a San Francisco-area shopping mall. A 4D model helped plan complicated logistics like moving concrete up five floors in tight quarters. The contractor stated that the technology helped shave three weeks off the mall's one-year construction schedule, and allowed stores to open in time for Christmas. Genentech used a 4D simulation for portions of its Founders

Research Center, one of the world's largest biotech labs. Planners have also used 4D to sketch out a 600-mile Shell pipeline off the coast of Russia. (Muller 2003)

However imaginative the technology is, Muller's summarization of the 4D pioneer's statement best explains its development: "No one can lay claim to the idea of 4-D visualization, says Stanford's Fischer. After all, it's what most of us do in our heads every day. 'The nice thing,' he says, 'is that it makes sure that what's inside your head looks the same as what's inside my head.' Without that kind of collaboration, a construction project can get really scary." (2003)

2.4 Interacting with 4D content

The 4D modeling software in use today is fairly flexible, interactive, and easy to learn and use. Figure 1 shows the interface developed for Walt Disney's Imagineering, and is typical of 4D software running on Windows.

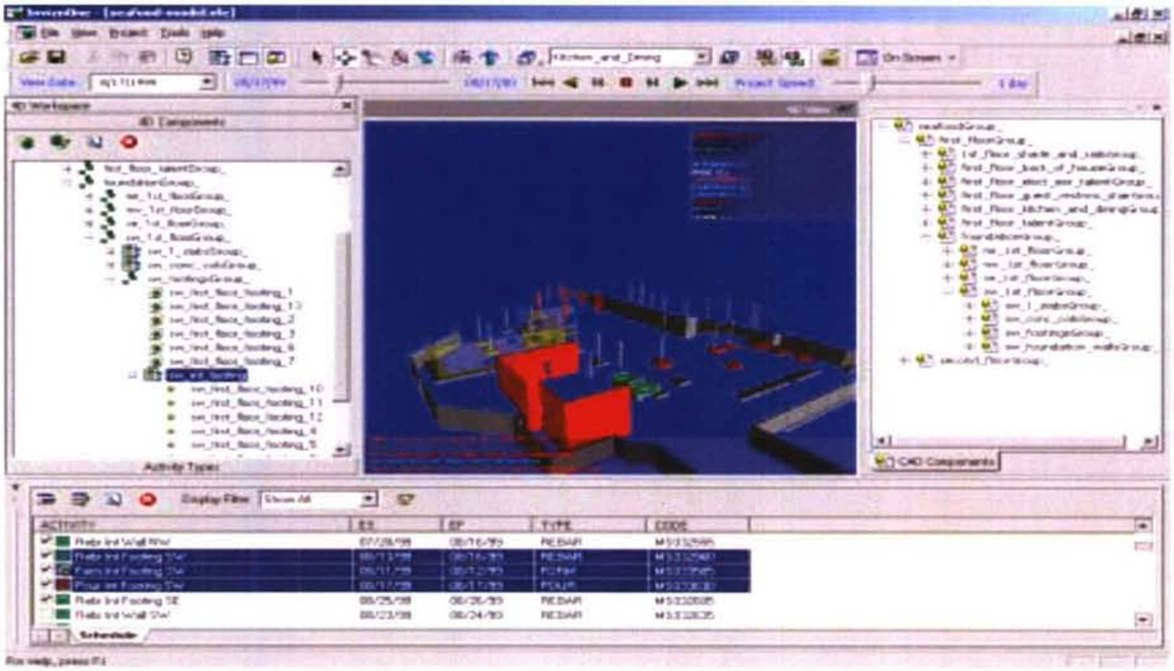


Figure 1. 4D Model Interface

The area below the tool bar contains the time and space controls for orientation and positioning of the 3D model in the center window and to move through time. One can designate a timeframe to view by selecting a date, moving the time slider, or using the video-like controls (play, pause, rewind, and fast-forward). Users can select a speed, or interval length between frames, for viewing the model. The speed can be set to one day, one week, one month, and so on. If the speed is set to one day the 4D window will show activities taking place on the various 3D components day by day. A CAD components window shows the hierarchical organization of the 3D components comprising the facility. The 3D model organization is typically imported from a .vrml computer program file produced by any 3D modeling software. A schedule window shows the activities that are needed to build the project, and colored boxes next to the activity names indicates what color a particular type of activity will display in the 4D window. The schedule activities are typically imported from scheduling software like *Microsoft Project* or Primavera's *Project Planner*. The 4D window shows the 4D components organized hierarchically, where a 4D component is one or several CAD components linked to one or several activities from the schedule. Users can select components or groups of components in the CAD components or 4D windows to show only part of a facility. For example, a user could highlight a 4D component for the foundation footings. The collection of individual footings would show up on the CAD components and 4D windows and the schedule window would show the activities needed to build the highlighted footings: rebar placement, formwork construction, and placing of concrete. (http://www.stanford.edu/~fischer)

4D software can be programmed to associate the CAD components to the schedule activities in three ways: a batch process, a linking process, and an interactive process. Batch process is when the 4D tool associates an imported construction activity with an imported CAD layer or CAD entity. The batch process programming method does not allow users to edit any of the 4D content; if changes are needed they must be performed on the separate 3D CAD and scheduling programs and re-imported. This type of software would be useful for showing project information to parties who are not in control of construction methods or activity sequencing such as owners.

The linking process requires the planner to import both the CAD and schedule information into the 4D environment, but the user can then directly select CAD entities and associate those entities with a construction activity. This is a slower and more tedious method than the batch process because of the manual assignments between construction activities and CAD entities, but the users can edit some, but not all of the 4D content. This type of software would be useful for the schedulers who need to be able to develop assignments between components and activities, but they do not require access to make design changes.

The interactive process allows planners to generate CAD, schedule, and 4D content in one environment. The user can open the 3D CAD model and edit it, generate or edit the schedule information, and associate CAD entities with construction activities. The planners can edit all of the 4D content for redesign, re-sequence, or re-association of CAD components with construction activities to quickly develop alternative solutions to problems. This style of program would be advantageous for design-build firms or projects with players who can both design the components and schedule the activities. (McKinney and Fischer 1998)

Appendix A lists various 4D CAD programs currently available and gives information concerning: cost, number of projects used on, types of projects used on, hardware requirements, software requirements, ease of updating, model size, types of CAD software compatibilities, types of schedule software compatibilities, output file format, analysis, 4D playback options, color coding options, automation, various options availability, types of graphics, and other unique features.

3.0 Benefits of 4D Models

3.1 Introduction

4D planning provides an opportunity for the advancement of construction scheduling past the Gantt chart, and allows analysis of construction operations prior to the construction phase. For example, at a Phoenix hospital where a contractor was building a new wing, a 4D model alerted contractors to a problem with their crane. The mast of the crane would interfere with the flight path of the hospital's medical evacuation helicopter. Since the problem was spotted before work began, the hospital was able to file a revised flight plan with the Federal Aviation Administration. They were able to solve the problem before it became a problem. (Muller 2003)

When performing a constructability review, a project manager must consider time-space conflicts, safety issues, and workspace management. A 4D model allows a project manager to consider all the factors at once in a single medium. The ability to use a single medium, however, still requires project managers to plan and schedule prior to using a 4D tool since they must coordinate before hand a 3D CAD model and a construction schedule. Therefore, the use of a 4D model forces the planners to thoroughly consider, and analyze, the marriage between the schedule and the design. Although the work may be tedious in some cases, the benefits yielded by the development of the model can be great, as explained by Xu et. al. (2003): "The construction process, once modeled, can be experimented with to study alternative construction methods, allocate resources, plan construction . . . and evaluate constructability issues."

This section explains how 4D models can be used to benefit construction operations by anticipating safety hazard situations, allocating resources and equipment relative to site workspace, running constructability reviews, developing and reviewing the schedule, visualizing the construction sequence, aiding collaboration among project stakeholders, and assisting in training construction management personnel.

3.2 Anticipating Safety Hazard Situations

The construction industry, by its nature, is dangerous and burdened with hazards and risks. During the period from 1980 through 1995, at least 17,000 construction workers died from injuries suffered on the job. Construction lost more workers to traumatic injury death than any other major industrial sector during the same time period. Construction has the third highest rate of death by injury: 15.2 deaths per 100,000 workers. Only mining and agriculture experience higher rates. The annual toll of accidents in the construction industry is high in terms of both cost and human suffering. OSHA provides for mandatory civil penalties against employers of up to $1000 for each serious violation and for optional penalties of up to $1000 for each non-serious violation. Therefore, in addition to the humanitarian aspect, there is a compelling economic motivation in accident prevention. (http://www.cdc.gov/niosh/injury/traumastruct.html)

There are many benefits for contractors who conduct their operations safely and whose accident record is low. The immediate and obvious benefit is the savings realized because of accidents that do not happen. Workers appreciate and value job safety and tend to be more loyal and cooperative with employers who are genuinely concerned about their protection. Additionally, fewer accidents correspond to a reduced cost of insurance. Maintaining a low accident record can also aid a contractor in securing future work. The Federal Government, and the Navy in particular, is awarding more contracts to constructors with lower accident records, despite higher bid prices, based on past performance evaluations and source selection procurement.

Due to the importance of and the emphasis placed on job-site safety by the Federal Government these days both contractors and government agencies would gain from any tools available to foresee potential safety problems before they become hazardous. Since contractors are usually given a bulky set of 2D design drawings by contracting offices, they must develop a mental picture for construction purposes. The contractor then must prepare additional plans such as a quality control plan and safety plan.

If creating a mental picture from 2D is difficult, then integrating the information with other plans such as safety regulations can be even more burdensome. Koo and Fischer (2000) believe that by viewing a 4D model, project mangers can detect areas where accidents may occur and execute prevention measures. Furthermore, project managers can see how separate crews will impact one another and create hazardous situations. Once hazards are foreseen by project managers they can anticipate them by adding installation of safety equipment or prevention measures.

Rowlinson and Hadikusumo (2003) believe 4D simulation products and processes can be used to develop a "design-for-safety-process" (DFSP) methodology to view the design and point out potential safety hazards, and the necessary actions to avoid them. A 4D simulation shows construction progress over time and would allow users to note, before hand, what safety hazards will be encountered. Thus enabling management to prepare protections in advance or to change the design and prevent hazards that are costly to keep.

3.3 Allocation of Resources and Equipment Relative to Site Workspace

Site space is a resource as important as time, material, labor, equipment and money, and like any other resource, the amount of space demanded by various activities changes as construction progresses. Using limited workspace economically and effectively can create a significant difference in project time and cost. Therefore, during a project the site layout may need to be re-organized to meet upcoming requirements and maintain safety and productivity. Thus, efficient planning is needed to facilitate site re-organization as work progresses. Yet the planning of space usage on a construction site is a known arduous task.

Since the early seventies researchers have applied optimization methods to solve site layout planning problems in construction. (Warszawski and Peer 1973, Popescu 1981, Rodriguez-Ramos 1982, Rad and James 1983, and Tommelein 1989) Now, some researchers believe the development of 4D CAD models can allow constructors to allocate and use site space resources more efficiently. (Vaughn 1996, Fischer et al. 2003) Liu states: "Since most construction resources are expensive, it is not cost effective to experiment with real resources. Using computer simulation, construction engineers can model construction operations on the computers before construction actually starts. Decisions and alternatives can be tested by experimenting with what-if scenarios on the computer model to find the best operation plan." (1996) 4D simulation provides the opportunity to investigate how different types of spatial situations constrain or control the sequence and duration of construction.

Many if not most Navy construction contracts these days are awarded to general contractors who subcontract a majority of their work. On large projects, there will be numerous subcontractors on site and each with their own work crews, equipment, materials, and space requirements. When space is tight, time-space conflicts are bound to happen. Time-space conflicts will lead to decreased productivity, subcontractor disputes, and eventually increased costs.

In most cases the owner (U. S. Navy) would not be impacted by such time-space conflicts since the responsibility for coordination of subcontractors is the general contractor's responsibility. However, due to the dynamics of naval bases, where space is sometimes scarce, mission requirements can demand additional space. When mission requirements do require additional space the Navy may need to infringe on a contractor's workspace. If a contractor is infringed upon he may demand additional time, money, or both due to owner caused delays. 4D models could be used in the situation to determine an alternative solution for the contractor's time-space dilemma, to justify the delays and allow for a change order, or prove a non-impact to the contractor.

For example, suppose a contractor is building an aircraft maintenance hangar at a Navy airfield. In most cases the Navy will provide a reasonable amount of space for the contractor to work in, store materials, and set up temporary facilities. But in this case assume mission requirements demand the airfield to receive three squadrons of large aircraft. Imagine the airfield parking aprons are full of aircraft and the only space available is some of the contractor's by the maintenance hangar. The Navy is forced to park planes in the contractor's space. As a result, the contractor says the infringement will delay his work and he requests a time extension and extended overhead due to the owner caused delay.

Upon visiting the jobsite, the Navy representative views the situation and believes the contractor may have a possible claim for delay damages. However, because of the contractor's arrangement of the temporary facilities and material and equipment storage the Navy representative thinks a site-reorganization could free up additional space. The representative is reluctant to recommend a site re-organization because she does not want the government to incur the costs, and is not really certain the change would be beneficial. She could, if a 4D model is available, experiment with configurations on the computer to free space. The model could then be used to communicate a solution to the contractor and settle on an agreement for site reorganization. On the other hand, if reorganization would not free up space, the model could be used to determine the impact of the infringement on the contractor. The impact analysis could then be used to justify the time extension and corresponding extended overhead to personnel in charge of approving modifications to the contract.

3.4 Running Constructability Reviews

A general problem in the construction industry is constructability, or the ability to convert a design document into a real project. A great design document, to a construction project manager, is one reflecting an inherent knowledge of how the design will be built. The details support the construction process. The design avoids ambiguity, and as a result, reduces claims and disputes.

Research has shown (Fischer et. al. 2003) that designs developed with a 3D model will most likely have fewer errors and coordination issues because the construction of the model by multiple designers (structural, mechanical, electrical, etc.) forces and allows them to correct inconsistencies. Evaluation of a design in 3D is also faster because reviewers can more quickly understand the scope and status of the design. Fischer et. al. (2003) further states: "Designers involved in projects that used 3D models from design through construction reported that they saw an increased coordination effort during the design phase of the project followed by fewer requests for information (RFI) during construction." (2003) In the end fewer RFIs mean fewer delays and ultimately lower costs.

For example, a 4D model was used for the 1997-1999 construction of the Sequus Pharmaceuticals pilot plant in Menlo Park, California. The model helped coordinate the mechanical, electrical, and piping contractors' day by day work. As a result there were no field interferences, no re-work, higher productivity, only one contractor initiated change order, no cost growth during construction, and 60% fewer requests for information than expected for this type of project (Staub et. al. 1999).

Since most Navy contracts are not awarded until after the design is accepted, and in some cases many years after, a 3D design would be useful for naval personnel performing pre-award constructability reviews. Many times, because of budgetary constraints, Navy contracts are not awardable in a given fiscal year, so they are put on the shelf until funds are available. In some cases, funds eventually become available and the contract is approved for bid solicitation. However, changes in site conditions can occur while the project is on hold. Additionally, if a project is held up for any amount of time, the contract with the design firm is most likely terminated. In such a case, as the author experienced, the Navy construction office is in charge of a project with differing site conditions and no architectural support. To add another twist, as is very often the situation, the customer has no additional funds for change orders, so any unforeseen costs require project scope deletion, which is not in the customer's best interest.

Using 3D design, naval personnel could more easily see component relationships and locations by viewing multiple design layers simultaneously, rather than conceptualizing the completed facility mentally. Mechanical, electrical, and structural plans could be viewed concurrently, rather than thumbing through many 2D drawings, to determine if any constructability issues result. When budgets are tight and errors need to be caught earlier, when they are cheaper to correct, one would be at an advantage using 3D tools rather than 2D ones.

3.6 Visualization

"While construction schedules communicate time and the sequence of construction activities, project participants (general contractor, subcontractors, clients, designers, etc.) must mentally associate this schedule information with the description of the physical building. . . . Without a visual representation of this mental 4D model, participants must rely solely on their ability to interpret the abstract schedule and the 2D or 3D design documents. Furthermore, if project information changes, designers and planners must mentally visualize how design or schedule changes affect the overall sequence of construction." (McKinney and Fischer 1998) 4D CAD avoids the differing mental conceptualizations by visually communicating the sequence of building construction. The utilization of 4D visualization allows a more intuitive comprehension of the construction process than traditional 2D drawings and schedule information.

4D CAD focuses on the visualization of the construction product over the period of construction. As time advances, individual components (CAD elements) of the facility are added to the visual model in their final position and form as dictated by the schedule. 4D CAD models convey what physical components are built where and in what time frame. Visualizing the evolving product, involves viewing the interaction of resources as they build the product or perform a support service. The resources include, but are not limited to: temporary structures, materials, equipment, and labor as they create the product.

Various 4D visualization tools can be used to view spatial aspects of a design with virtual walk-throughs, compare lighting schemes in photo realistic renderings, and comprehend the construction sequence with 4D animations during the decision making process. The construction industry typically uses artist's renderings for presentations to owners. Yet, the limitations of the renderings are that they are frozen in time and labor intensive to create. A rendering or physical model requires an artist or modeler to spend a great deal of time on one design idea. Yet there may be additional design alternatives as the project progresses. Any modifications would require more time and resources to generate the new perspective or model. 4D visualization can support frequent and rapid generation of multiple project alternatives using information from existing models and schedules.

4D CAD was used to plan the construction of the Helsinki University of Technology Auditorium project. Being an auditorium, the lighting design was an important feature. The designers used their lighting product database containing about 6000 different lights, 1000 of which were available in 3D format. Upon checking the light distribution curve, rating, installation specifications, and energy requirements for the various lights in the database, they imported the lighting objects into a 3D CAD program. The 3D program then generated photorealistic model scenes of the auditorium with the various lights. The models "provided designers a thorough understanding of the lighting effects and allowed them to refine their design and improve the auditorium's quality of light. At the same time, they became crucial visualization tools that conveyed the design intent to the end-users and the owners for feedback." (Fischer and Cam 2002)

The Computer Science Department at the Helsinki University of Technology has an Experimental Virtual Environment (EVE) where a room of 3 rear projectors, 1 top projector, and several high end computers assemble a virtual reality space. As a result, the Auditorium project team was able to collaborate with researchers at EVE to virtually construct a 3D immersive Auditorium based on the 3D CAD model, including the various lighting scenes. The virtual environment contributed to the stakeholder's comprehension of the design and construction sequence and benefited decision support by improving the client briefing environment. The virtual environment was similar to one created for the Paradise Pier portion of Disney's California Adventure. The contractor for the Disney project was able to hold meetings with groups of eight to ten people at a time in their Computer-Assisted Virtual Environment (CAVE). "The groups could interactively review the proposed design and construction schedule from any perspective and quickly understand the design, schedule, and corresponding constraints." (Fischer et. al., 2003) The CAVE is shown in Figure 2 on the left.

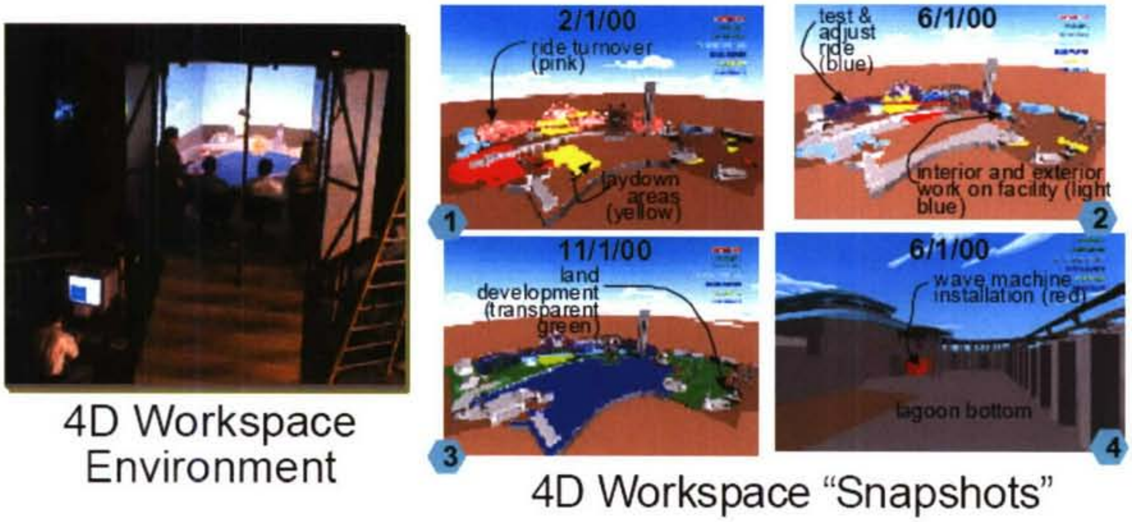


Figure 2: From Liston et. al. (2000), Workspace meeting with snapshots of 4D visualization

3.7 Collaboration

Parties involved in construction projects communicate in a way that is far from the most effective. Communication conflicts result in misunderstandings about responsibilities between parties which can cause problems during construction. Research on the use of 4D models for communication applications was conducted by the Hollandse Beton Groep in the Netherlands. The first application of the technology was the Rotterdam Shipping Center. Before construction began, the project managers held a kickoff meeting to explain the designed construction method to the foremen involved. During the meeting the 4D simulation was shown to the attendees. The foremen were then asked to fill out a questionnaire to get reactions about the application of 4D software on the project. The questionnaire had to be filled out twice: before and after seeing the 4D simulation. Some of the foremen gave the same answers before and after, but others came up with different aspects of the construction process after they had seen the simulation. (Broekmaat and de Vries, 2003)

Another exercise conducted by Broekmaat and de Vries (2003) involved project management employees who were asked to view a construction plan based on a bar chart and a set of 2D drawings. Then they were allowed to view the same project plan in 4D CAD. The result of the exercise showed the benefits of using 4D software: "the support of 4D CAD improved the quality of the analysis within the given time of 10 minutes. People got more motivated to answer the questions (more answers) and were able to do that quicker and more accurately (more correctly answered questions)." (Broekmaat and de Vries 2003)

The increased understanding of the project by viewing a 4D simulation, as shown in the Broekmaat and de Vries' (2003) research, confirms that the technology can aid in collaboration among project stakeholders. In construction, where problems and changes can arise quickly and cause strained relations among contractors, owners, and designers, any collaboration facilitation will most likely be beneficial in getting troubles solved quicker and with less resistance.

Changes in schedule are a common occurrence on construction projects. The causes are numerous: weather, owner directed changes, permitting problems, soil conditions, material delays, accelerations, rework, coordination difficulties, etc.

Changes are challenging to direct because they affect multiple firms, lead to disagreements, initiate cost negotiations, and require coordination to put in place. Mostly, network planning methods, primarily CPM schedules, along with 2D drawings are used to determine responses to changes. However, the limitations of CPM schedules and 2D drawings to evaluate the costs and site conditions under changing conditions limit the project manager's ability to quickly and efficiently resolve responses to change.

Imagine a constrained site where there is barely enough space to move equipment and materials necessary to accomplish on-going work productively. If the project manager is not able to effectively communicate where materials and equipment need to be, productivity can be lost. Fischer and Koo explain:

> Management of site workspace becomes increasingly important when projects are located in urban areas. In some of these projects, project managers can only work on the actual area the building will occupy. In these situations, the project managers need to divide the site into sections so that, while constructing the building for one section, other sections can be used for cranes, backfill, or material storage. The 4D model can make it clear to all affected parties that materials should arrive when, and where they will be stored.

Furthermore, combing 3D models with schedules automatically produces 3D phasing drawings at daily, weekly, or monthly levels depending on the level of detail in the schedule and the 3D CAD model. Contractors can then easily show stakeholders (owners and subcontractors) who is working where, on what, and how the work proceeds over time and through the site. Additionally, the 3D CAD model will automatically reflect schedule updates. As a result, project meetings can be conducted more efficiently since less time will be spent describing what is going on or making sure all present have the same schedule revision.

Construction project teams do consider many types of information when deciding on project problem solutions. Some of the information is available electronically and is visual in nature, but a paper-based view of project information does not readily communicate critical relationships between project information, for example, 2D drawings and a Gantt chart CPM schedule. "Consequently, project teams spend far too much time trying to understand and describe project information to one another and little time actually using the information to support decision-making and solve problems. To illustrate this, consider the following observation of a schedule review meeting:

> On the walls of the conference room (Figure 3) are 2D construction drawings and the project Gantt chart. Each meeting participant has handouts consisting of the schedule, which contains 8000 activities, and the meeting agenda. Participants have brought other types of documents to the meeting such as 'marked-up' schedules, some contract documents, and construction drawings. The meeting begins with the first agenda item, 'Schedule Comments.' This discussion involves the owner asking questions such as: Does the schedule meet contractual milestones? Do these activities adhere to project specifications? Why are you finishing this facility on this date? What if we change this milestone date? What if the equipment is late? Throughout the meeting, project participants are distracted as they shuffle through the schedule sheets searching for activities or as they scan the walls searching for relevant information, trying to understand the schedule and issues at hand. Meeting participants come and go. Some leave to get information such as project specifications or to get updated information. In some cases, a document is passed around for participants to review. By the end of the meeting, twenty types of documents have been referred to or used as participants try to describe, understand, review, and evaluate the schedule. Various people have marked up their schedules or other documents, but no one leaves with the full documentation of the comments, to do items, or issues addressed in the meeting. More importantly, although several problems were noted, no problems were resolved during this meeting nor during the successive three meetings. (Liston et. al. 2000)

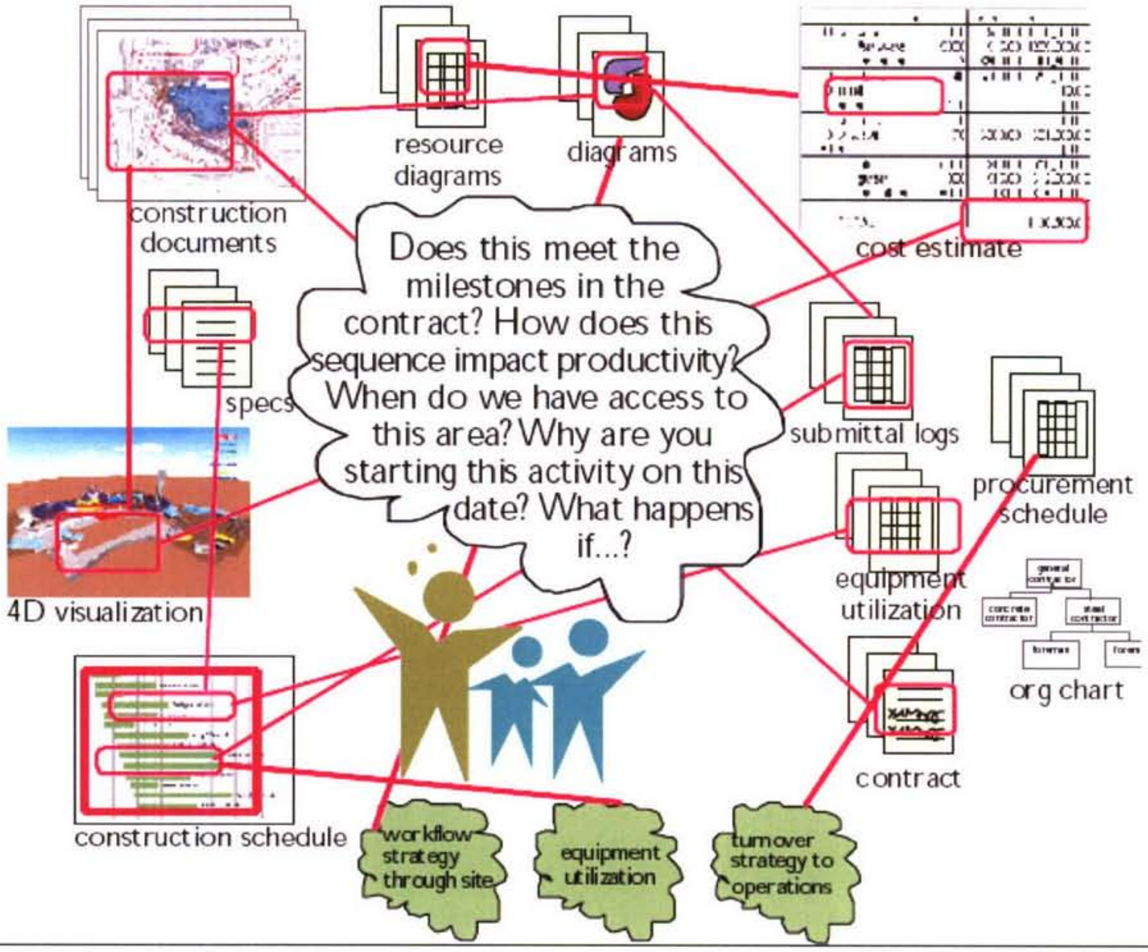


Figure 3: From Liston et. al. (2000), Construction meetings typically involve many types of information and documents for use in the decision making process.

According to Liston et. al. (2000) the team covered the agenda items, but they spent no time solving problems or making decisions. Analysis of the meeting showed that only 10% of the time in the meetings was spent performing predictive tasks (Figure 4).

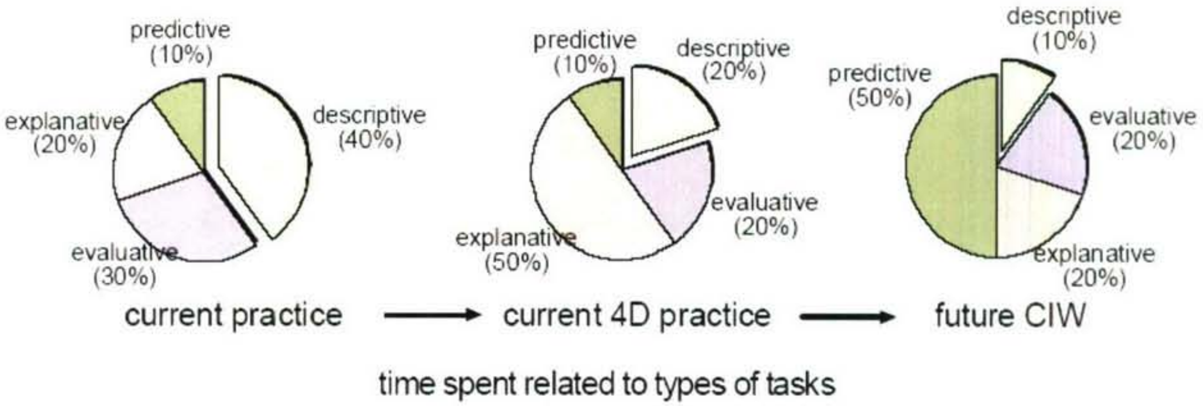


Figure 4: From Liston et. al. (2000), Analysis of time spent performing tasks in current practice and current 4D practice and goal

The researchers (Liston et. al. 2000) also used a 4D workspace, or CAVE environment, for meetings, on the same project, to enable the team to visualize the relationships between the schedule and the 3D model. During the 4D meetings, the team spent more time explaining information than describing it, an improvement over the paper-based meetings. They were able to identify several problems and solve some of them. The 4D environment demonstrated an improved focus due to the reduced clutter of documents and an improved ability to describe and explain project information. As shown in Figure 3 the goal for future "Construction Information Workspaces" (CIW) is to achieve 10% of meeting time devoted to descriptive processes and 50% of the time identifying problems and solving them. Figure 5 shows examples of CAD presentations in CIWs.

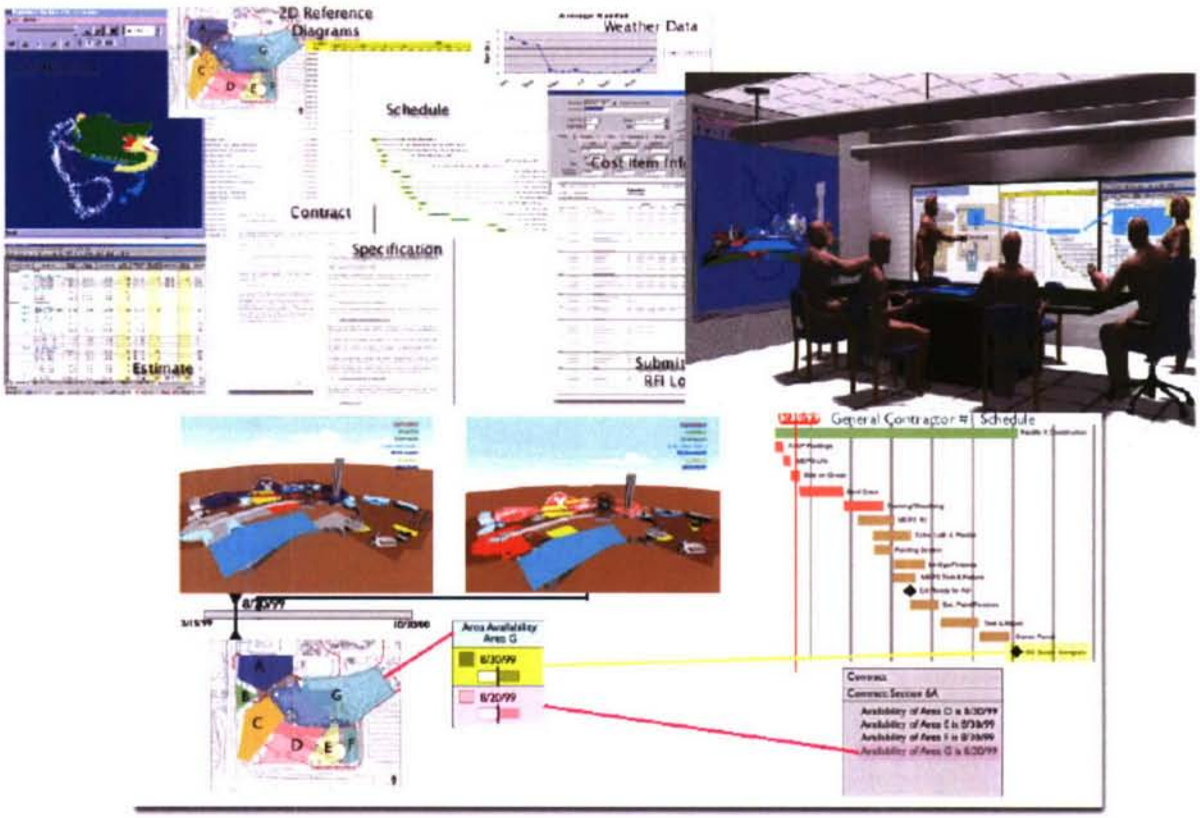


Figure 5: From Liston et. al. (2000), Examples of Construction Information Workspaces (4D-CAD Presentations); Clockwise from top left: past, future, and present

3.8 Training

A 4D model of a facility, showing the interaction of the various systems involved, can allow students to understand the sequential order of how systems must be installed. A model can consist of multiple layers, allowing for the review of each layer in detail, or to view the finished product by superimposing the layers. The model can mimic the actual construction sequence, allowing the user to recognize and identify the different components of the building. A model, in addition to a walk though, can allow the user to access additional information about different building components through linked databases, such as the schedule, technical details, cost details, and visual details from actual construction progress. Overall, a 4D model could be a valuable teaching tool for (but not limited to): construction techniques, construction scheduling, construction safety, construction estimating, construction productivity measurement and improvement, contractual changes and their effect on time and cost, and 3D imaging of construction composition.

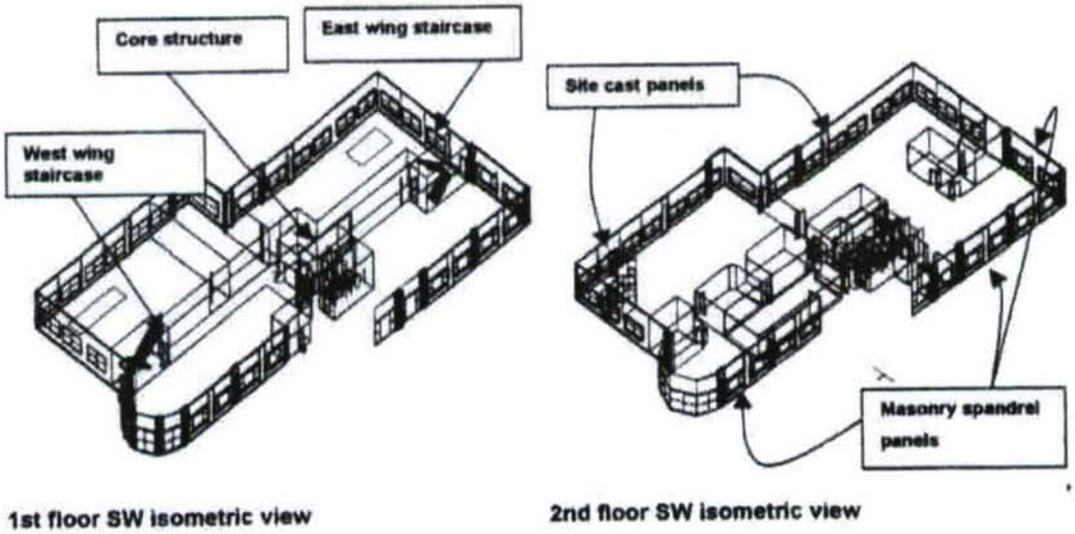
Use of the model would follow the concept "I hear I forget, I see and I remember, I do and I understand." (Oblinger 1992) Oblinger (1992) also documented that humans have a short term retention rate of approximately 25% of what they hear, 40% of what they see and hear, and 75% of what they hear, see, and do. According to Saad and Batie (2002) Use of 4D models in a teaching environment would mirror the way the "human mind thinks, learns, and remembers, by moving easily and freely from words to images to sounds, stopping along the way for interpretation, analysis, and in-depth exploration. It offers a ten to twenty percent improvement in performance over conventional teaching methods, and a one-third reduction in time on task. That can reduce the amount of time a student spends learning by one-third."

Based on the research of the educational benefits of 4D CAD mentioned above, the Navy could implement 4D training at schools for military and civilian personnel working in the construction field. 4D programs could benefit students' understanding of the construction process, construction methods selection, and scheduling through one medium.

3.9 Case Study by Koo and Fischer (2000)

Reasearch by Koo and Fischer (2000) studied the 2D drawings and an as-planned schedule of the McWhinney Office Building project, a small commercial project, to identify potential problems in the proposed schedule. Then they created a 4D model using the initial schedule so the model would virtually show the same sequence. By viewing the model, several problems with the CPM were found that had been previously overlooked. Once the problems were identified, they verified whether any of the schedule problems were encountered during the actual construction. The results showed 4D models increase the comprehensibility of the project schedule, allowing users to detect mistakes or possible problems prior to construction.

Figure 6 shows the configuration of the building: four office spaces on each floor with a core structure in the center with bathrooms and a single elevator shaft. The lobby provides access to the building by elevator and staircase.



1st floor SW isometric view

2nd floor SW isometric view

Figure 6: From Koo and Fischer (2000); Building Configuration of Office Building

Koo and Fischer first looked at the master as-planned Gantt chart CPM schedule to identify problems. They found difficulties in conceptualizing the construction process by viewing the CPM schedule alone. The researchers also found it cumbersome to associate components in the 2D drawings with related activities in the schedule.

Furthermore, each member of the research team had slight variations in interpretation of the schedule. Once the 4D model was simulated the research team was "able to discover inconsistencies in the level of detail among activities in the schedule and identified missing activities. (They) also identified errors in the logic of the schedule, potential time-space conflicts, and accessibility problems." (Koo and Fischer 2000)

Determining whether all activities in the schedule represent an appropriate level of detail, or are on the same level of the work breakdown hierarchy, can be difficult from a CPM alone. Koo and Fischer (2000) realized the discrepancy between the interior and exterior levels of detail, but could not determine what level was appropriate in conveying the overall work flow. Once viewed in 4D, they were able to identify the inconsistencies in levels of detail and determine what level was appropriate. Upon viewing the 4D simulation, they found the schedule did not convey installation of the exterior components of the building in a sequential fashion, rather all the exterior components appeared on the screen at the same time.

The research team could not determine if the CPM schedule was complete by viewing the Gantt chart. However, when viewing the 4D model they could immediately see what components did not have related activities in the schedule. Figure 7 "shows a screen shot of the 4D simulation at the start of the project. Normally, no components should appear on the screen. However, several components are still displayed. This means that these components have not been linked to an activity, i.e., no activity exists to build them. . . . The 4D model is a good way to check if everything in the design (i.e., 3D CAD model) is related to at least one activity." (Koo and Fischer 2000) The interior partition doors and portions of the electrical fixtures (furns, fix strips, and cable trays) were not given activities in the schedule.

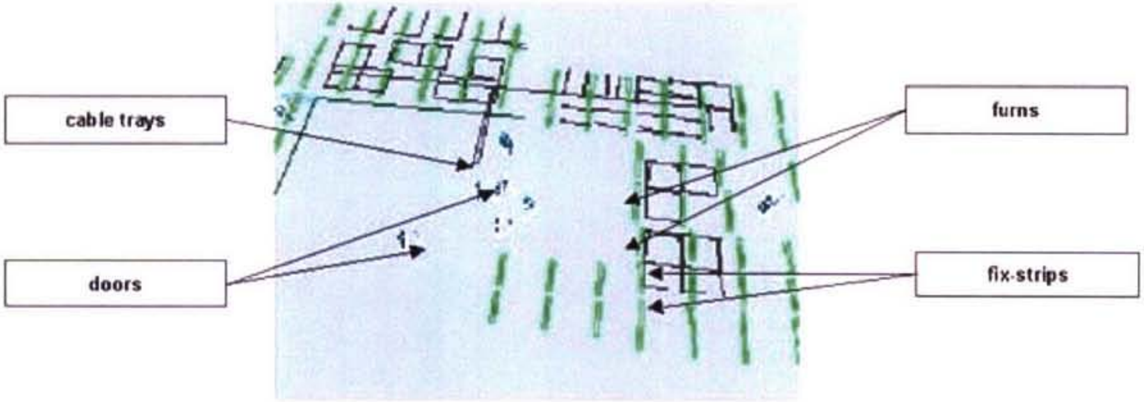


Figure 7: From Koo and Fischer (2000); 4D Model Showing Components Not Related to Activities in Master Schedule

Identifying out of sequence activities is also difficult when viewing the CPM schedule. Since the 4D model displays components when and where they are built, it clearly shows whether the activities in the schedule have been properly sequenced. An overhead HVAC system was scheduled to be installed before the second floor slab and truss frame were completed. As a result there would have been no platform for the HVAC installers to work from. The schedule also showed HVAC and electrical subs working on the second floor while the roof was still being installed. Since the roof was not completed, there was no protection for mechanical and electrical work from the weather even though the execution dates were in the winter season and the project was located in Colorado.

Planners must provide work crews with sufficient workspace. Multiple crews working in a limited workspace may decrease productivity rates, and lead to delays. CPM schedules do not convey time-space conflicts, so crew space problems were overlooked when viewing the Gantt chart. In the 4D model, the research team could foresee that three different crews would have to work concurrently in a limited space.

Possible accessibility problems were also noticed when viewing the 4D model. The lobby staircase was installed early in the project to provide access to construction on the second floor. However, no one could access the second floor while the activity "install lobby stained concrete" was performed. Subcontractors could not use the stairways while the stained concrete in the lobby was being installed. A possible solution would have been to install alternate staircases at the East and West wing earlier than shown in the schedule and before the second floor work begins. In the original schedule the alternate staircases were shown to be constructed after most of the lobby components were already installed.

Upon completion of Koo and Fischer's research they "consulted the project managers and asked about the actual problems they encountered during construction. The two major problems were the congestion in the lobby area and the imbalance of work for the interior phases of the project." As predicted, the installation of stained concrete and scaffolding in the lobby interior delayed drywall contractors from continuing their work on the second floor. Additionally, the time required for each phase was quite different than the planner had scheduled because of the tight workspaces. "The project managers assumed that the allotted spaces would be sufficient for all other subcontractors to work at their expected productivity rates and scheduled the activities accordingly. However, the finish crews working in a horizontal plane (carpet, ceiling grid, and tile subcontractors) required approximately twice the allotted space of each work phase to work at the expected productivity level. The limited space decreased the productivity of these subcontractors, which in turn prolonged their time to install their work for each phase." (Koo and Fischer 2000)

Koo and Fischer's study shows that 4D users can identify problems previously overlooked in the original CPM schedule and verify correctness of the schedule (completeness, consistency, and logic), identify space-time conflict, and anticipate an accessibility problem. The obviation of the need to conceptualize the association between components and activities to comprehend the schedule is a major benefit of viewing a 4D project model. While interpretation of the schedule can vary according to the level of experience, knowledge, and individual perspective of the participants, and create miscommunication among them, the 4D model allows users to view two separate documents through a single medium so all project players can maintain the same understanding. The researcher's explain that a 4D model "shows spatial constraints on the site and in the building. Whereas CPM schedules can only convey what is built when, the 4D model shows what is being built when and where. It therefore allows users to identify whether a component can be physically placed or whether crews can work in a certain location." (Koo and Fischer 2000).

Since the Koo and Fischer (2000) research team was comprised mostly of college students, the research data provided can be linked to possible similar results if adopted by NAVFAC EFAs and EFDs. The basis for the similarity is that a majority of junior officers in construction office positions can reasonably be assumed to have little or no more knowledge of construction than a college student.

4.0 Problems with 4D Models

4.1 Introduction

Although 4D models are beneficial there are some challenges users encounter when using them. Researcher's experience has shown that certain issues are quite common during the development of 4D models, especially when 3D models are created without knowledge of the needs for 4D modeling and construction planning. Furthermore, the construction of a 4D model requires significant project scope and schedule information. Some of the information is precisely the information project participants want to develop or refine through the 4D modeling process, and other information is not available at the time of modeling because of resource or other constraints. Thus, a valuable contribution of the modeling process is identification of where complete scope and schedule information exist and where additional thought is needed. However, the construction of models pose a number of challenges related to the geometry, the schedule, and the linking of the geometry and the schedule. (Haymaker and Fischer 2001)

4.2 Geometry Issues

Most likely, based on past experience of Haymaker and Fischer (2001), 3D models from architects will contain some inconsistencies. For example, an object on the plaster layer should have been on the gypsum board layer. Inconsistencies create extra work when the schedule and 3D model are linked since the 4D modeler cannot easily identify, isolate, and show the scope of work for a particular activity in 3D. (Haymaker and Fischer, 2001)

Besides inconsistencies, a lack of data can cause modeling problems. In 3D CAD, the surface model models only what is seen. For example, a design calls for a wood wainscot to cover the lower portion of a plaster wall, but the architect models the plaster only where the wainscot does not cover it. Even though plaster is under the wainscot, it is not modeled. As a result, in those areas, the surface model does not provide 3D components linkable to schedule activities. (Haymaker and Fischer 2001)

The level of detail in the 3D model often results in 4D modeling problems. Sometimes there is not enough detail in the 3D model. For example, suppose the steel fabricator puts the steel 3D model all in one layer. The contractor may want to split primary and secondary steel into two activities, making necessary two layers of steel. Suppose the architect only models the surface of the building's exterior skin. Yet the skin system requires backing support and clips, which are not modeled, but need to be installed, and should therefore be reflected in the 4D model. Other times there can be too much detail, resulting in sluggish computer performance with large files. For example, the steel fabricator models the 3D steel with all the bolts and holes shown. The information is not needed for the 4D models the contractor planned to create. (Haymaker and Fischer 2001)

4.3 Schedule Issues

As the geometry can be inconsistent with the design intent, the schedule can also contain inconsistencies. For example, the schedule may call for a masonry wall, while the 3D model shows a cast in place wall. The inconsistency must be resolved. The resolution is valuable from a project standpoint, but time consuming for the 4D modeler. Another time consuming schedule requirement is for the simulation of moving equipment. The introduction of activities to control the appearances and disappearances of equipment must be scheduled in order to model their time-space requirements. As a result, there are more activities in the project schedule, and the use of the schedule in the 4D tool is more complicated. Furthermore, some geometry may have no corresponding activity. Again, an activity may be required, but resolving the issue requires more time and resources of the modeler. (Haymaker and Fischer 2001; Broekmaat and de Vries 2003)

To visualize an operation one must see, in addition to the physical components of the facility, the equipment, personnel, materials, and temporary structures required to build it. Furthermore, it is necessary to show the movements, transformations and interactions between the visual elements. The movements and transformations must be temporally and spatially accurate. To depict smooth motion, visual elements must be shown at the correct position and orientation several times per second. Therefore, one must be aware that 4D CAD depicts the state of a completed facility at the end of each unique activity in the schedule. Static CAD models of cranes, temporary structures, equipment, and materials may be included in the snap shots to identify space and layout constraints to increase visual impact, but movement is not simulated in most 4D CAD programs.

4.4 Linking Issues

Often, the geometry is defined in ways conflicting with the schedule. For example, an architect defines the 3D geometry by facility components, but a contractor typically places concrete and steel not by component, but according to sequence. In such a case, the geometry must be broken down and recombined a great deal to get a configuration to match the schedule. (Haymaker and Fischer 2001)

Some geometries are not modeled by the designer. Cranes, lay-down areas, staging areas, scaffolding, and other time-space representations are not part of the architect's design model, but they play a key role on the construction site. The modeler needs to spend additional time to add their geometries to the 3D model. For another example, suppose ductwork was not modeled in the 3D model, but the contractor wanted to know when and where ductwork is scheduled. A 4D modeler must be sensitive as to the best way to communicate the activities associated with non-existing components. One could attach ductwork to a floor slab or ceiling frame, but should be certain to notify personnel involved of the decision. (Haymaker and Fischer 2001)

There have been complaints on certain software where the 3D and/or 4D model can only be used after finishing it completely. Since 3D and/or 4D models can also be beneficial for project analysis in an early stage of a project, more integrated processes are desirable. (Broekmaat and de Vries 2003)

4.5 Only a Model

Although, 4D CAD can be a beneficial tool for construction planning and problem solving one should remember that it is, after all, only a model. Vaughn explains:

> There is nothing magical about having geometry in the computer. The 3D model merely represents the standard of quality that we would like to see:

> it is not a mandate for the final product. Furthermore, building components and parts for the space shuttle are built to two different sets of quality control standards. Losing sight of these facts can mean asking the computer to do too much for you, opening up the possibility that one may be unable to reconcile extreme precision with acceptable limitations in accuracy generated by normal field conditions. (Vaughn 1996)

Vaughn further illustrates his point with an example of a design change for a nursing facility at a hospital. The design change showed rake wall louvers as being five sided, rather than four, and extending up to a gable soffit. The new size and configuration required a precise alignment not previously anticipated. Before the change, rough width dimensions would have been enough to place an order for the louvers, and the dimensions could have been determined from the 3D model. With the new louver configurations, the constructor was unsure of the dimensions because the walls had been modified in the field, possibly altering one of the control points. The constructor had used the rough openings in the rake-wall model to get preliminary bids from the manufacturer, which helped shave a few days off the lead time, but field measurements showed unacceptable variations in the top-of-the-wall-to-soffit dimension of approximately one inch. The constructors finally decided to field measure each opening and not go with dimensions from the CAD model. The negative result was a letdown for the constructor's use of the CAD model, but Vaughn says it drives home an important point, "while the model may be highly precise, it does not always mirror real world conditions. . . . 3D CAD models are accurate electronic documents, but they have practical real-world applications only if one knows their limitations and uses them properly." (Vaughn 1996)

4.6 Case Study by Koo and Fischer (2000)

Koo and Fischer's research did also note some disadvantages of 4D models. They mention that viewing the 4D model alone made it difficult to comprehend the current status of the project. Additionally, a 4D model does not convey all information required to evaluate a schedule since users need to know why activities are sequenced in a certain way. Activities may be sequenced in a certain order because of resource availability or construction method, and 4D models do not inform users of those constraints. Furthermore, a 4D model does not show all the planning information shown in a CPM schedule. For example, a 4D model does not provide information on activities' float or activities with no corresponding 3D CAD components, such as an "inspection" activity. The research team also noted the 4D model becomes "cluttered" quite rapidly if each action on a component is shown with a different color. The research team could not identify whether a work imbalance existed for the interior work crews. They state: ". . . the 4D model does not convey all the planning information that is required to evaluate all aspects of the construction process. It does not show the workspaces required for each activity nor the relationship between production rates among subcontractors. Furthermore, unless the contractor adds scaffolding and other temporary structures to the 3D model, the 4D model does not show the space needs and corresponding potential congestion of temporary works." (Koo and Fischer 2000)

5.0 Construction Management in the Department of the Navy

5.1 Introduction

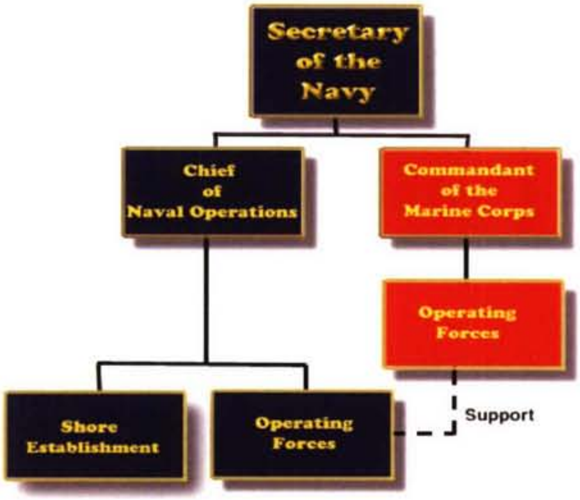
An understanding of how construction is managed by the Department of the Navy is necessary to see how 4D CAD can be implemented by the Naval Facilities Engineering Command (NAVFAC). According to the Navy's Civil Engineer Corps Officer School (CECOS) the Navy does not manage construction it rather administers contracts awarded to constructors. Therefore, throughout the rest of the report the Navy's role in construction management will be referred to as contract administration.

4D programs need to support the mission of the Navy, and NAVFAC in particular, while meeting organization and systems capabilities mandated by organizations NAVFAC is subordinate to for the technology to be beneficial. This section begins with an explanation of how construction contract administration fits into the Navy organization. NAVFAC's organization is then discussed with emphasis on their role in contract administration. The third section discusses the key contract administration positions on a typical Navy construction project.

5.2 Construction Management within the Navy Organization

Table 1 presents an overview of the organization of the Department of the Navy. The Department of the Navy contains three principal components: The Navy Department; the operating forces; and the shore establishment. (http://www.chinfo.navy.mil/navpalib/organization/org-over.html)

Table 1 (from: http://www.chinfo.navy.mil/navpalib/organization/org-over.html): Overview of the Organization of the Department of the Navy



5.2.1 Secretary of the Navy

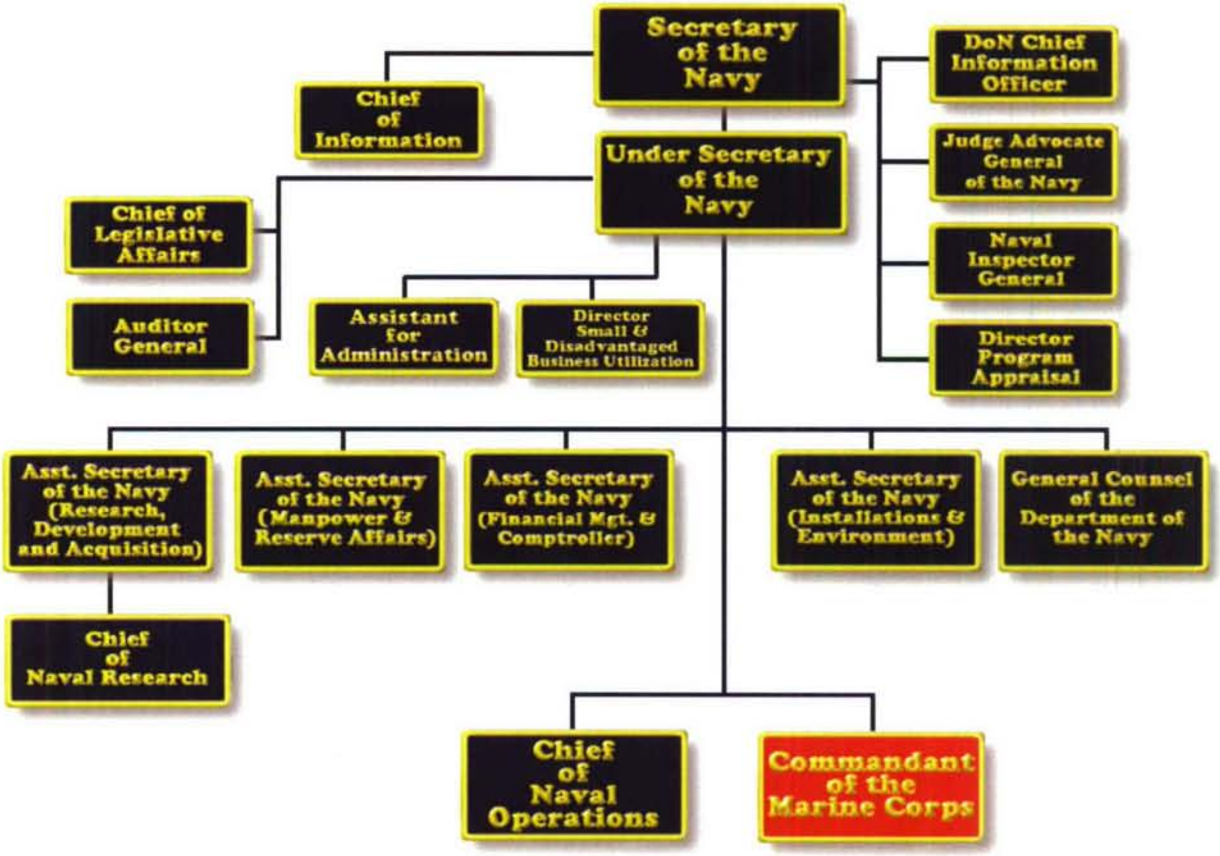
The Secretary of the Navy (SECNAV), a civilian appointed by the Secretary of Defense, is responsible, and has the authority under Title 10 of the United States Code, for conducting the affairs of the Department of the Navy, including: the construction and repair of naval facilities. SECNAV is responsible for formulating and implementing policies and programs consistent with national security policies and objectives established by the President and the Secretary of Defense. Table 2 shows the supporting cast for the Secretary of the Navy. (http://www.chinfo.navy.mil/navpalib/organization/org-sec.html)

5.2.2 Assistant Secretary of the Navy (Installations and Environment)

The Assistant Secretary of the Navy (Installations and Environment), a civilian appointed by the Secretary of the Navy, is responsible for Navy construction and other facilities related tasks. Installations and Environment is responsible to the Secretary of the Navy for, among others actions: construction, operation, management, maintenance and repair of installations, housing and other facilities.

(http://www.chinfo.navy.mil/navpalib/people/assistsecnav/asn_ie/asn_ie-respon.html)

Table 2 (from: http://www.chinfo.navy.mil/navpalib/organization/org-sec.html): Support for the Secretary of the Navy



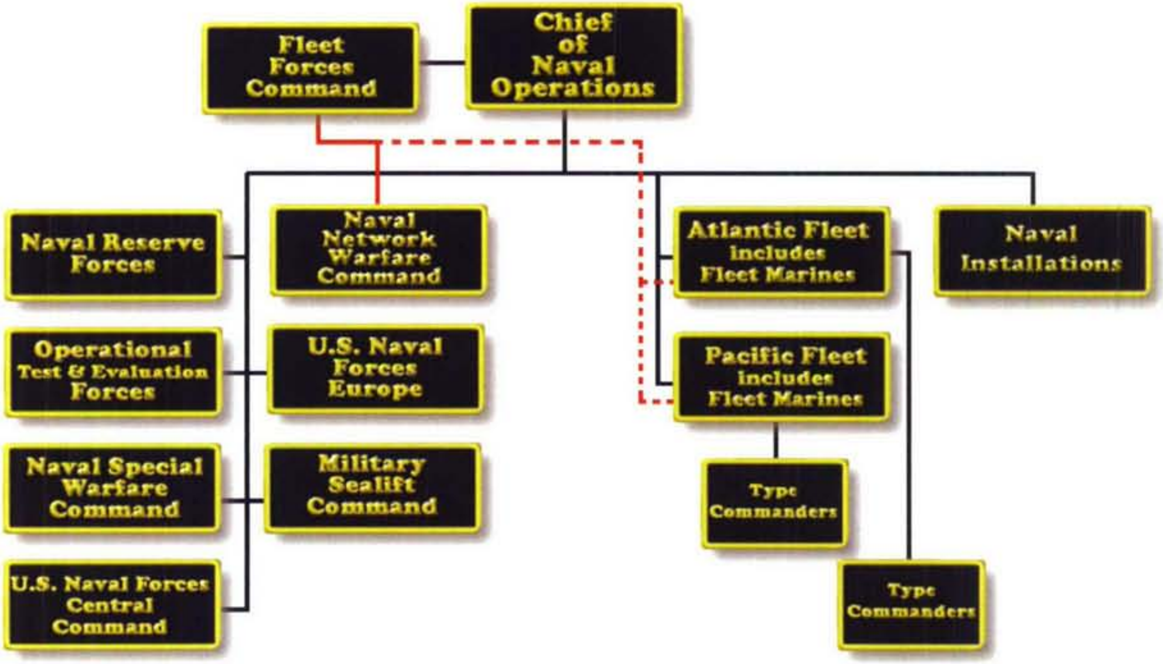
5.2.3 Chief of Naval Operations

The Chief of Naval Operations (CNO) is the senior military officer in the Navy. The CNO is a four-star admiral responsible to the Secretary of the Navy for the command, utilization of resources, and operating efficiency of the operating forces of the Navy and of the Navy shore activities assigned by the Secretary. As member of the Joint Chiefs of Staff, the CNO is the principal naval advisor to the President and to the Secretary of the Navy on the conduct of war, and is the principal advisor and naval executive to the Secretary on the conduct of naval activities of the Department of the Navy. (http://www.chinfo.navy.mil/navpalib/organization/org-cno.html)

5.2.4 Operating Forces

The operating forces commanders maintain a dual chain of command (Table 3). "Administratively, they report to the Chief of Naval Operations and provide, train, and equip naval forces. Operationally, they provide naval forces and report to the appropriate Unified Combatant Commanders." (http://www.chinfo.navy.mil/navpalib/organization/orgopfor.html). The Unified Combatant Commanders are those in charge of designated areas of responsibility around the globe and may be Army, Navy, Air Force, or Marine Commanders. Each operating force commander maintains a budget, which they can use, if they choose, to support construction activities.

Table 3 (from: http://www.chinfo.navy.mil/navpalib/organization/orgopfor.html): Organization of the Operating Forces



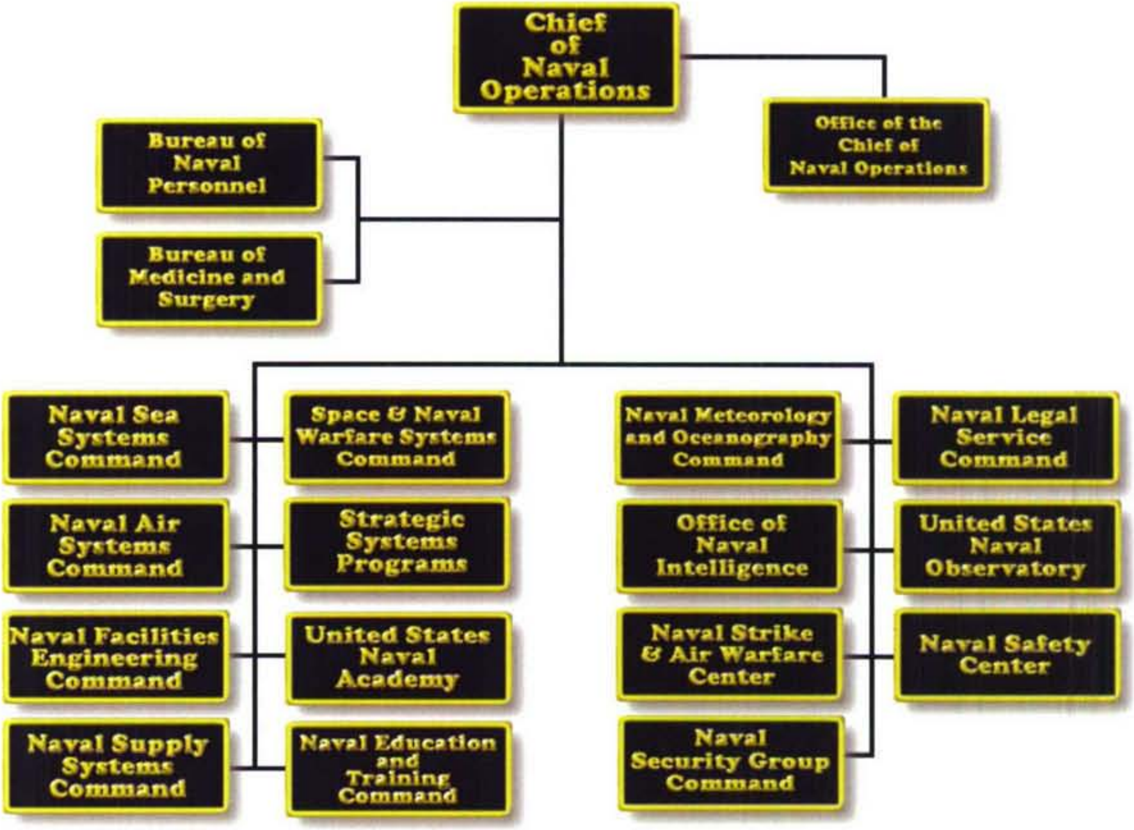
5.2.5 Naval Installations Command

The Naval Installations Command (CNI) is one of the military support arms of the Assistant Secretary of the Navy (Installations and Environment), through the CNO. CNI "is the single responsible office, advocate, and point of contact for Navy Installations, *CNI's mission is to provide consistent effective and efficient shore installation services and support to sustain and improve current and future Fleet readiness and mission execution."* (http://www.cni.navy.mil/mission.html) CNI provides unified and consistent procedures, standards of service, practices and funding to manage and oversee shore installation support to the operating forces. Most importantly CNI provides the funds to support shore establishment military construction (MILCON or MCN) projects.

5.2.6 Shore Establishment, NAVFAC, and Contract Administration

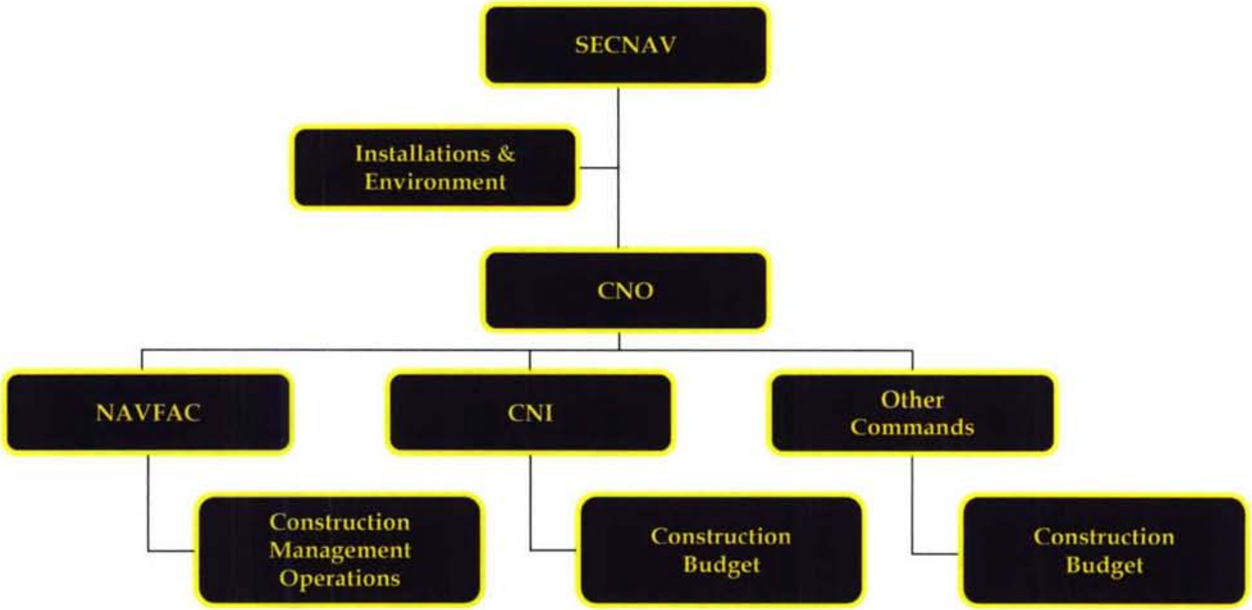
NAVFAC, through the Chief of Naval Operations (CNO), is another military support arm for the Assistant Secretary of the Navy (Installations and Environment) and is one of the commands comprising the Navy's shore establishment (Table 4). The shore establishment is necessary for supporting the operating forces' mission in the form of: facilities; communications centers; training areas and simulators; ship and aircraft repair; intelligence and meteorological support; storage areas for repair parts, fuel, and munitions; medical and dental facilities; and security; among others. Since the shore establishment must support the operating forces they maintain budgets that can include funds for maintaining facilities, besides those provided for by CNI. NAVFAC's mission within the shore establishment is to provide facilities, installation and contingency engineering support, which includes construction contract administration, to the various naval commands from the shore establishment and operational forces. (http://www.navfac.navy.mil/stratpln.pdf)

Table 4 (from: http://www.chinfo.navy.mil/navpalib/organization/org-shor.html): Organization of the Navy Shore Establishment



Based on the overall organization of the Navy, a chain of command for shore establishment construction contract administration can be developed (Table 5). As shown, NAVFAC contributes the actual construction administration expertise to the Navy while CNI and all other commands maintain budgets to fund construction projects. CNI is responsible for facility sustainment, restoration, and modernization (SRM) and military construction (MILCON) project budgets, while other commands maintain their own budgets from which they can fund smaller projects if they choose. CNI supports the operational forces by ensuring SRM and MILCON funding is funneled to the most pressing, mission-critical issues. Once the most pressing, mission critical issues are determined funds are set aside for the award of a design and a construction contract to be managed by NAVFAC. If other commands decide to fund their own construction projects they typically perform design "in-house," since their budgets are typically tighter, and request construction contract administration support from NAVFAC, which they receive for a fee – usually a percentage of the overall project cost.

Table 5: Navy Construction Administration Organization

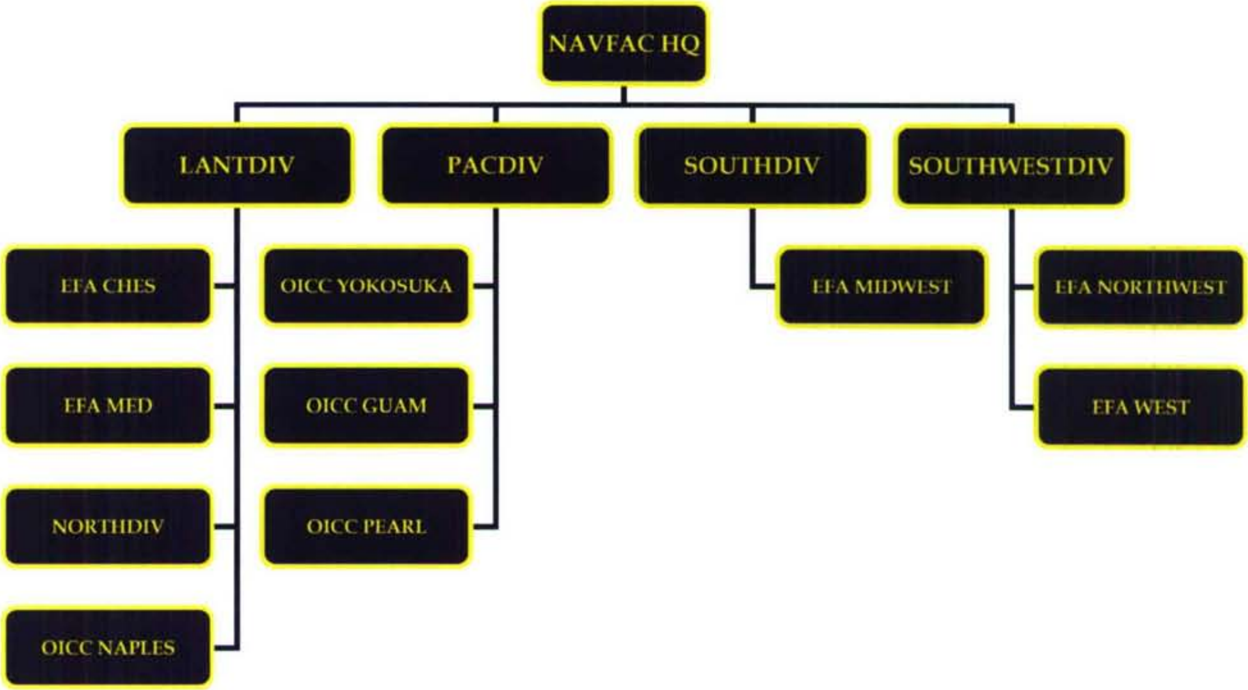


5.3 NAVFAC Organization

As mentioned NAVFAC is the operational manager of construction for the Navy. CNI and other commands provide funds for construction while NAVFAC oversees the work. Since NAVFAC administers all Navy construction projects around the globe, there are many branches to its organization. NAVFAC's organization includes a headquarters element, Engineering Field Divisions (EFD), Engineering Field Activities

(EFA), independent Officers in Charge of Construction (OICC), field offices with Resident Officer's in Charge of Construction (ROICC), and an assortment of support staffs around the United States. A basic organizational diagram is shown in Table 6. (CECOS 2001)

Table 6: Basic NAVFAC Organization Diagram



5.3.1 NAVFAC Headquarters

The NAVFAC headquarters element contains the support staff for all of NAVFAC. The headquarters has its own support staff such as: public affairs, the NAVFAC inspector general, legal counsel, the NAVFAC chief engineer, chief safety officer, and controller. Additionally, NAVFAC headquarters supports the divisions through five groups: the Engineering Operations Group, the Contingency Engineering Group, the Engineering Programs Group, the Public Works Group, and the Engineering Resources

Group. The Engineering Operations Group and the Engineering Programs Groups are the two most involved in construction contract administration, but mostly from the acquisition and funding perspective – they are not involved in the administration of construction operations directly. (http://www.navfac.navy.mil/stratpln.pdf)

5.3.2 Engineering Field Divisions (EFD) and Engineering Field Activities (EFA)

The division level of NAVFAC is where the organization begins to administer construction contracts from an operations perspective. The four Engineering Field Divisions (EFD)s: LANTDIV, PACDIV, SOUTHDIV, and SOUTHWESTDIV are headquartered geographically to cover all Navy construction throughout the world. The EFDs have cognizance over their Field Offices, EFAs, and independent OICCs. The EFD has responsibility for establishing policy and providing resources to its subordinate units. Due to the EFD's responsibility for establishing policy and providing resources it would be the responsible command for implementation of a technology such as 4D CAD. The EFA is a smaller version of the EFD, and is subordinate to an EFD. As a result, the EFD could require implementation of 4D CAD at an EFA to test the benefits before adopting it on a larger scale at the EFD. (CECOS 2001)

5.3.3 Independent OICC

An independent OICC is typically formed by an EFD for the purpose of executing a specific program. Usually the program is both large in cost and technically challenging. New construction of hospitals and bases have historically justified establishment of an OICC organization. An OICC is staffed with technical and support personnel to ensure proper program execution and contract administration. (CECOS 2001)

5.3.4 ROICC Office

The most basic and common EFD or EFA element is the ROICC office, or Field Office. Like the OICC the Field Office is a contract administration organization. Contract administration "is the process of assuring performance of both parties to the contract, i.e. the Government and the Contractor." (CECOS 2001). The ROICC offices assure performance of construction contracts through: quality assurance programs, schedule management, payment processing, contractor / government coordination, labor standards enforcement, site safety monitoring, contract interpretation, equitable adjustments, acceptance, and documentation. Furthermore, as the ROICC office is a government entity it must protect the taxpayers' interest, treat the contractor fairly, protect the integrity of the competitive procurement system, and assure client satisfaction while assuring performance. (CECOS 2001)

The OICC and ROICC offices are where Navy construction contracts are truly administered. If the OICC or ROICC cannot solve a problem they will request additional support from the EFD or EFA. The buck stops with the EFDs though, since they have the resources to solve any construction contract administration problem from legal support, to public affairs and safety.

5.3.5 CECOS

One other very important part of NAVFAC, although not in its organization chart, is the Civil Engineer Corps Officer School (CECOS). CECOS is the school responsible for training the large majority of NAVFAC personnel, both military and civilian. During the 2004 fiscal year CECOS will offer 62 different courses, including four on construction contract administration, and will train every new Civil Engineer Corps Officer in the Navy in construction contract administration.

5.4 Key Players on a Typical Navy Construction Project

Most of the key players for typical Navy construction contracts are located at the OICC or ROICC office since those are the basic units in the organization. This section will explain the duties of the key players in Navy construction contract administration. Please note, the description of the duties of each position will not be all encompassing, since only the basic idea of each position is intended for an understanding of how 4D technology can be implemented, as discussed later on in the report. For example, all members of OICC and ROICC offices should be cognizant of safety issues, but safety responsibilities will not be mentioned for each position discussed. Furthermore, non-contract administration duties will not be mentioned such as collateral duties, evaluation responsibilities, and military responsibilities.

5.4.1 AROICC and ARIECC

The position directly responsible for individual projects is the Assistant Resident Officer or Engineer in Charge of Construction (AROICC or AREICC). The AROICC or AREICC is in charge of day to day matters on individual projects such as: quality assurance programs, schedule management, payment processing, contractor / government coordination, labor standards enforcement, site safety monitoring, contract interpretation, equitable adjustments, acceptance, and documentation. All other members of the organization support the AROICC or ARIECC in performing their duties.

5.4.2 Supervisory AROICC or AREICC

The supervisory ARROIC or AREICC is responsible for ensuring proper constructability review of contract plans and specifications, proper administration of projects by the AROICCs and AREICCs, and preparation of monthly reports for the EFD or EFA. When workloads are heavy some supervisory AROICCs or AREICCs will administer contracts themselves.

5.4.3 Chief Engineer

The chief engineer is a civilian position, second in seniority behind the OICC or ROICC. The chief engineer, as a civilian, typically holds their position longer than the OICC or ROICC and acts as a source of continuity in the office. The chief engineer is responsible for approval of technical changes to construction projects and acceptance of construction schedules. All change orders and contract modifications must be approved by the chief engineer. In some cases the chief engineer will provide assistance on design reviews for office projects.

5.4.4 OICC or ROICC

The OICC or ROICC is the senior person in the office. Usually, the position is held by a military Civil Engineer Cops officer. The OICC or ROICC is responsible for office administration, local construction contract awards, payment approval, and approval of equitable adjustments. All payments, change orders, and modifications must be signed by the OICC or ROICC.

5.4.5 Product Team

The product team is housed at the EFD or EFA and is in place to provide support to the ROICCs for a geographic area. A product team may be responsible for three or more ROICC offices. The product team is a ROICC office's sounding board for recommendations in policy change at the EFD or EFA. The product team can also give assistance to the ROICC office in areas where they need more expertise, such as: safety, claims, or funding matters. The product team will also be the source of funds for change orders, claims, and payments on military construction (MCN) projects.

5.4.6 Naval Installations Command (CNI)

CNI is the source of funds for change orders, claims, and payments on military construction (MILCON) projects.

5.4.7 Other Commands

Any other commands a local OICC or ROICC services will provide their own funds for new construction, renovations, or alterations and will also provide funds for any claims or change orders.

6.0 Navy Implementation of 4D CAD

6.1 Introduction

Section 3.0 mentioned the various benefits of 4D CAD. If the benefits are sufficient, and they outweigh the drawbacks outlined in section 4.0, the Navy could implement use of 4D CAD through a variety of methods. First, use of 4D CAD programs would require persuasion of CNI, and other commands that fund construction, to adopt the use of 3D CAD in the design phase of projects. Using 3D CAD designs may require additional funds from the budgets of CNI and other commands, but the additional funds may be offset by fewer delays, change orders, and claims. Section 7.0 will discuss economic considerations of 4D CAD use, but this section assumes use of 4D CAD to be economically neutral. Second, the magnitude of 4D CAD implementation must be considered. Implementation could take place NAVFAC wide, in one division (EFD) only, in one EFA or OICC office, in one ROICC office, or on one project. Regardless of the degree of implementation, training of personnel in 4D CAD must be available for realization of the technology's success. This section will discuss the need for CNI and other construction funding commands to bless the use of 4D CAD, potential implementation scenarios for 4D CAD at various magnitudes of use, and possible training schemes.

6.2 Bringing CNI and Other Construction Funding Commands Onboard

Persuading CNI and other construction funding commands to adopt 3D design on their projects is a crucial step for implementation of 4D CAD at the construction contract administration (NAVFAC) level. The need to convince CNI and other commands to specify use of 3D CAD in their design contracts is a must for successful implementation of 4D CAD at the NAVFAC level, since changing 2D drawings into 3D CAD is not a feasible task for NAVFAC elements. However, once the design is in 3D, NAVFAC personnel could specify in contracts use of 4D CAD.

To convince the construction funding commands to use 3D design, one would need to explain the potential benefits of using 4D CAD. For the construction funding commands, potential benefits would include: more thorough constructability / design reviews; clarity of project scope; fewer changes, delays, and claims; and increased collaboration. Constructability and design reviews could be performed more thoroughly since 3D plans allow multiple design layers (i.e. mechanical, electrical, and structural) to be viewed simultaneously, allowing for spatial design errors to be spotted more easily. For example, if the mechanical designer planned for ductwork to be installed in the same location as a structural component one would need to see the structural drawing and mechanical drawing side by side in a design or constructability review to catch the error using 2D plans. However, if reviewers are using 3D CAD they could view the structural and mechanical layers together to see the conflict more easily.

Clarity of project scope would be achieved through use of 4D CAD. Once the design is programmed in 4D CAD the clients (NCI and other commands) could visualize the project on a computer screen from various angles and at various stages of completion. The extent of the clarity can be the choice of the command funding the project. For example, if specific architectural details need to be understood prior to construction the command could use programs similar to the lighting database explained in section 3.6. An increase of scope clarity would better ensure clients of receiving what they truly "have in mind."

Section 3.4 discusses research by Fischer et. al. (2003) that shows using 3D designs reduces the number of requests for information (RFI) during the construction phase. If there are fewer RFIs during construction there are fewer changes and delays, and fewer changes and delays result in fewer claims and ultimately fewer costs.

Section 3.7 discusses the collaboration benefits of using 4D CAD. As mentioned in section 3.7, 4D CAD can be used in project meetings to put everyone on the same agenda and increase communication through better understanding. Achieving increased communication in project meetings would be extremely beneficial for project clients, such as CNI, since they are not continually involved in the day to day construction administration. The visual aids provided by 4D CAD would ensure all project stakeholders are on the same level of understanding of the project's progress and status. Clients' questions could be more thoroughly answered and potential problems could be more easily foreseen.

6.3 Potential Implementation Scenarios for 4D CAD at Various Magnitudes of Use

There are numerous possibilities for implementation of 4D CAD within the NAVFAC organization. This section will focus on three possible implementation ideas: use in a OICC/ROICC office, use throughout an EFA or EFD, and use throughout all of NAVFAC. The three formats were chosen based on the process of contract administration within NAVFAC and the structure of the NAVFAC organization. Since contracts are administered at the OICC/ROICC level of the organization, the first proposal is to implement 4D CAD at only one OICC/ROICC office to measure its benefits. Since the NAVFAC organization is supported by four basic elements (headquarters, EFD, EFA, and OICC/ ROICC), use by each of the four, from the bottom up, is a natural means of implementation. For example, 4D CAD could be implemented at the most basic element – the OICC/ROICC office, or at any of the other hierarchically senior elements to include the more junior ones. In this section implementation of 4D CAD at the EFD and EFA levels will be explained concurrently since their organizations are very similar.

6.3.1 Use in OICC/ROICC Office

Since construction projects are administered at the OICC/ROICC office level, 4D CAD could be specified for particular projects deemed to benefit from the technology. The decision to specify use of 4D CAD in the contract documents would be based on whether a project exceeded a certain cost threshold or when certain conditions or constraints effect a project.

Initially, the technology would not have much “in-house” support. The first project to use 4D CAD would certainly be a learning experience for the AROICC/AREICC and the OICC/ROICC office administering the contract. Software and hardware required for the 4D CAD system may need to be installed professionally, and training would probably need to be provided outside the Navy organization. Use of the technology on the first few projects should be well documented for future users to benefit from.

The specification section outlining the use of the 4D CAD system would need to be thoroughly reviewed by the AROICC/AREICC overseeing the project. As mentioned in section 2.4 there are three ways of programming 4D CAD software: batch process, linking process, and interactive process. The contractor would receive the 3D CAD plans from which a schedule would be developed; most likely the contractor would be using linking process software to link the schedule to the design components. The AROICC/AREICC would then receive the linked file from the contractor for review. The file received by the AROICC/AREICC would or should be a batch type file since the file itself would not need to be changed. If the AROICC/AREICC spots schedule errors in the review the file would simply be returned to the contractor with comments on what to change. Use of an interactive program would not be needed since neither the contractor nor the AROICC/AREICC would be able to change design components.

6.3.2 Use throughout an EFA/EFD

Since construction contracts are not directly administered at the EFA level only certain policy decisions and support units would be developed at the EFA. One policy decision concerning 4D CAD at the EFD/EFA level would be to mandate its use on a certain size or type of project throughout the EFD/EFA. Another possible policy decision at the EFD/EFA level could be to provide the field offices with 4D CAD experts at the EFD/EFA headquarters for troubleshooting any problems at the field offices. Besides the troubleshooting team, the EFD/EFA resources could be better used if the field offices could email 4D CAD files to allow for better communication between the field office and headquarters.

Mandating the use of 4D CAD on certain sizes and types of projects would need to be based on some economic analysis stating what project cost threshold needs to be exceeded before 4D CAD becomes and economic advantage. Certainly, one would not benefit from using 4D CAD to build a $20,000 garage, but maybe one would save money using 4D CAD on a $30 million hospital renovation. The economic analysis in section 7.0 will discuss in more detail what the possible threshold may be.

Implementation of 4D CAD throughout an EFD or EFA would undoubtedly result in some technical or educational problems. Therefore, the EFD or EFA could develop a policy to establish a 4D CAD support team. Some field offices may not have the technical staff to set up a 4D CAD system. In such a case, the EFD or EFA headquarters could provide the field office with experienced personnel to assist in the set up of the required software, hardware, or peripherals needed to achieve the results specified in a certain contract. Other field offices may lack trained personnel in 4D CAD tools at the time of specified use. In this case, the EFD or EFA could either send a mobile training team to the field office, send field office personnel to a Navy run training center (if available), or send the field office personnel to civilian training centers. Training will be further discussed in section 6.4.

Besides policies concerning use of 4D CAD throughout an EFD or EFA, the use of 4D technology would benefit the command. Since many OICC and ROICC offices are located outside of the local area of the headquarters, use of expert resources at the command go unused by the outlying field offices. Mostly the failure to use headquarters' resources is due to the difficulty of communicating problems based on bulky 2D plans and overwhelming schedules back to the EFD or EFA. However, with implementation of 4D CAD, files could be emailed to the EFD or EFA to explain the concerns. Since the headquarters sees many more problems with construction projects than the field office does, the EFD or EFA may be able to propose a solution based on their past experiences.

The policies stated here could be implemented throughout an EFD or EFA once the benefits of 4D CAD have been established at a smaller scale, like the OICC/ROICC office. Immediate implementation at the EFD or EFA level would not be wise because costs may increase if 4D CAD use is not an economic advantage over 2D drawings.

6.3.3 Use NAVFAC Wide

Establishing use of 4D CAD throughout the NAVFAC organization would be the final step of the implementation process. Certainly, as in the case of implementation at the EFD/EFA, the technology would need to prove beneficial at the lower levels of the organization. If lower level use does reveal benefits, widespread use throughout NAVFAC could provide many benefits. Benefits to the organization could include increased customer satisfaction, achievement of cost and time growth goals, and a better equipped workforce.

Really no new additions would be needed at the NAVFAC headquarters level since 4D CAD implementation and policy would be handled at the division level. Therefore, once 4D CAD showed success at one EFD, NAVFAC headquarters would only need to set the policy for command wide use. Since the success of the technology would have already been established NAVFAC would merely reap the benefits.

6.4 Training Considerations

Training of NAVFAC personnel, mostly AROICCs/AREICCs, would be a consideration for implementation of 4D CAD systems. According to the proposed implementation plan in section 6.3 – start with the smaller elements and grow to the larger ones if 4D CAD proves successful – training would follow a similar course. As 4D CAD is first implemented on construction projects few people will require training. If 4D CAD proves successful, and it is adopted by EFDs and EFAs, more people will require training and training methods may need to change. If command wide use of 4D CAD is ever decided upon the training method may again need to change. This section will propose training methods for the three implementation schemes proposed in section 6.3.

6.4.1 Training of Individuals Assigned to 4D CAD Projects

When the first few contracts incorporating 4D CAD programs are awarded, as far as the Navy is concerned, only the AROICC or ARIECC administering the contract, and an alternate, need to be trained. Any other Navy personnel needing information from 4D CAD can learn from the AROICC or AREICC educated in using the program. Since few people would require training when 4D CAD is first implemented, those AROICCs and AREICCs needing education could attend training sessions provided by the software company. Most 4D CAD software companies do provide training sessions on the use of their programs. For example, Commonpoint provides both full day and half day training programs for those using their software.

6.4.2 Training of an Entire EFA or EFD

If an EFA or EFD decides to adopt the use of 4D CAD technology, the training methods should change. The EFAs and EFDs maintain personnel at the headquarters to support their field offices. Therefore, an EFA or EFD could send headquarters personnel to 4D CAD training and set up a mobile training team. The personnel selected for the mobile training team would attend training provided by a software company and obtain any materials required to teach the course. Then whenever a project is awarded that specifies 4D CAD the mobile training team could travel to the field office and train the required personnel. This method would require only a small group of headquarters personnel to attend "out-of-house" training, while allowing for an unlimited number of field office personnel to receive the same training "in-house."

6.4.3 Training of the NAVFAC Organization

If 4D CAD proves successful at the EFD and EFA level, NAVFAC may see value and decide to implement its use command wide. Command wide use should again change the training methods. If NAVFAC decides on 4D use then there would be a potential for every NAVFAC AROICC or AREICC to use the technology. In such a case, NAVFAC should move to train every new AROICC and AREICC in using 4D CAD programs in their indoctrination courses. Most AROICCs and AREICCs are indoctrinated at CECOS, so CECOS could maintain a staff member trained to teach 4D CAD. Thus, every member of the NAVFAC team with the potential for using 4D CAD would already have training in its use.

If a course in 4D CAD is developed at CECOS the technology could also be used to benefit construction management courses by allowing students to see the sequential order of how systems must be installed, visually on the computer. The various benefits of 4D CAD in training construction management students is discussed in section 3.8.

7.0 Economic Analysis

7.1 Introduction

Generating a 4D model involves significant work hours and creates additional up-front costs. Therefore, a 4D model must be able to provide information to save time and lower the total cost of construction. A 4D model can reduce costs by supporting early detection of problems, such as time-space conflicts, safety issues, and site workspace restrictions. As a result, planners can formulate realistic schedules and cost estimates. It also allows construction planners to decide on the construction method most appropriate for the design and site. The potential for cost savings is usually greater earlier in the project during the design and pre-construction phases. Thus, 4D CAD has the potential for great gains in productivity by providing a construction simulation model with accurate site and design data from the CAD files.

Demands for more productive and lower cost delivery of facilities are ever increasing, especially on Navy contracts, where budgets are tight and the mission is critical. One of the largest barriers to implementation, however, is that 4D CAD technology requires three dimensional engineering designs as models, something currently uncommon on Navy projects. Research has shown that 75 to 80 percent of a 4D model's cost involves creation of the underlying 3D model (Sheppard 2004). Yet when the design team works in 3D, the additional cost becomes a project benefit - as shown in section 3.4. Model costs on large projects may run as low as one-half a percent of the project budget, but investments can be returned 50 to 100 times over in project savings. On the other hand, if project participants don't clearly establish a 4D model's scope, purpose, and level of detail prior to its modeling, the cost-benefit ratio decreases. (Sheppard 2004)

This section will provide a cost-benefit analysis of 4D CAD models' use on U.S. Navy construction projects administered by NAVFAC. Analysis will begin with a breakdown of the costs involved in implementing 4D CAD technology on Navy projects, followed by the potential return on investment. The analysis will focus on determining the minimum size and type of project scope needed to profit from 4D CAD's benefits.

7.2 Costs of 4D CAD Use on Navy Construction Projects

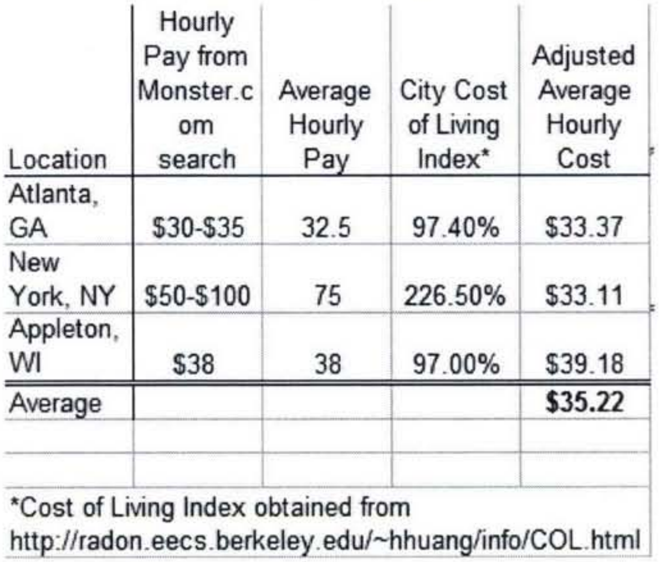
Costs involved with 4D CAD include the software, viewer, training, conversion to 3D design, and the linking of the schedule to the design. The software, viewer, and training costs can all be determined from pricing information supplied by 4D CAD manufacturers and is therefore easy to quantify. However, costs for conversion to a 3D model and linking the schedule to the design will vary based on project complexity, personnel experience, and design style.

Some projects are more complex than others, resulting in some projects with few components and others with many. The amount of components requiring a link to schedule activities will be directly proportional to the amount of time required to create a 4D CAD model. The project planners' experience using 4D CAD software will also impact the amount of time needed to link components to schedule activities. A first time user will need time to make mistakes and learn, while an experienced user will be able to rely on previous lessons learned. As mentioned, 75 to 80 percent of a 4D model's cost involves creation of the underlying 3D model (Sheppard 2004), and this depends on what type of design one is working from. If the design documents are 2D paper based drawings the 3D model creation will typically take more time than if the design is already available in 3D CAD. Most designs today are typically not performed in 3D CAD. Therefore, development of a 3D model can be time consuming. However, if the design is in 3D to begin with, some modifications may still be necessary for conversion to 4D. For example, all the footings may be on the same layer in the 3D CAD file, but the schedule plans to place the spread footings at one time and the continuous footings at another. Therefore, the 4D scheduler would need to put the spread footings in a separate layer from the continuous footings.

Since the variability of the costs associated with both building the 3D CAD model and linking components to activities complicates quantification, their cost analysis will be supported by past experiences of 4D model development. Based on ten years of experience implementing and developing 3D-based technologies in the construction industry, Kathleen Liston, the current chief technology officer of Commonpoint Inc, says 3D model development and activity / component linking typically takes from 100 to 250 man-hours (interview 6/24/04). A search of Monster.com gave hourly rates for construction schedulers in three cities: Atlanta, New York, and Appleton, WI. Table 7 shows the hourly wage rate for construction schedulers in the three cities, the cost of living index for those cities, the adjusted hourly wage and the overall adjusted average hourly wage. Since hourly wages were only advertised for three cities and the variation was reasonable this report will assume the adjusted hourly wage rate of $35.22 reasonable for cost analysis.

The time required for model development and activity / component linking ranges from 100 to 250 man-hours. The actual time will fluctuate within the range based on project complexity, personnel experience, and design style; as previously mentioned. For the purpose of this report, the average time of 175 man-hours will be used to present the analysis. Based on an hourly wage rate of $35.22 and an average time to complete a 4D model of 175 man-hours the labor cost to develop a 4D model would be $6165.25.

Table 7: Average Hourly Pay for Construction Scheduler



Location	Hourly Pay from Monster.com search	Average Hourly Pay	City Cost of Living Index*	Adjusted Average Hourly Cost
Atlanta, GA	$30-$35	32.5	97.40%	$33.37
New York, NY	$50-$100	75	226.50%	$33.11
Appleton, WI	$38	38	97.00%	$39.18
Average				**$35.22**

*Cost of Living Index obtained from http://radon.eecs.berkeley.edu/~hhuang/info/COL.html

The remainder of the cost of 4D model development includes the software, viewer, and training. The Appendix is a table, acquired from Commonpoint Inc, of 4D CAD software currently on the market. Table 8 is a condensed version of the appendix showing the prices for software, viewers, and training on six of the products listed.

Table 8: Average Total Cost of 4D CAD Setup

Brand Name	Balfour	Bentley	Common Point	CSA	RCT	Navis	Avg. Cost
Software Price	$36,000	$3,795	$7,900	$6,000	$67,500	$8,000	$21,533
Price of Viewer	$79	$0	$499	$4,000	$0	$0	$763
Training Cost	$1,000	$2,200	$0	$20,000	$10,000	$2,450	$5,942
Total	$37,079	$5,995	$8,399	$30,000	$77,500	$10,450	**$28,237**

If 4D software is specified by the Navy, the contractor will likely have the option to choose which program to use. If one liberally assumes each product is used an equal number of times the average cost would be $28,237. If interested, the reader can use the Appendix to see how many projects each program has been used on to weight each software / viewer / training package for a more accurate cost, but for the purpose of this report assume each program will be used equally.

Now that the average labor and material costs involved in implementing 4D CAD on a single project are calculated, one can determine the average bid markup associated with using the technology. If typical markups of 5% for sales tax, 30% for direct labor, 10% for field office overhead, 3% for home office overhead, 8% for profit, and 1% for the bond premium are included, the Navy's cost of specifying 4D CAD can be found according to Table 9.

Table 9: Navy's Cost of Using 4D CAD

1. Direct Materials	▨	$28,237	▨
2. Sales Tax on Materials (5% of line 1)	5.00%	$1,412	▨
3. Direct Labor	▨	$6,165	▨
4. Insurance, Taxes, and Fringe Benefits (30% of line 3	30.00%	$1,850	▨
5. Subtotal (Add lines 1-4)	▨	▨	$37,664
6. Field Overhead (10% of line 5)	10.00%	$3,766	▨
7. Subtotal (Add lines 5&6)	▨	▨	$41,430
8. Home Office Overhead (3% of line 7)	3.00%	$1,243	▨
9. Profit (8% of line 7)	8.00%	$3,314	▨
10. Subtotal (Add lines 7-9)	▨	▨	$45,987
11. Contractor's Bond Premium (1% of line 10)	1.00%	$460	▨
12. Total Cost (Add lines 10&11)	▨	▨	**$46,447**

The reader should note that the cost determined here is based on the assumptions of average software prices, hourly wage rates, and typical markups for Navy projects. This section merely provides a method for determining the cost of implementing 4D CAD on a Navy construction project. A similar analysis should be performed for each specific project, and different assumptions should be based on the type of project and its location. Larger projects may require more man-hours for model development while smaller projects may require less. The location of the project will drive wage rates, tax rates, and overhead and profit markups.

7.3 Return on Investment

Once the costs are determined the breakeven point is known. Therefore, if the Navy chooses to implement 4D CAD on a project, savings in the amount of $46,447 would need to be realized for the investment to breakeven, not considering the time value of money. Also, the project would need to be in a location where a scheduler would earn approximately $35.22, the sales tax on software is 5%, and overhead and profit markups are the same as those in Table 9. Furthermore, the project size would need to be such that a scheduler would take about 175 hours to compile the 4D model. If any of the variables are different the number will change.

The only research considering return on investment was obtained from an interview on June 24, 2004 with Kathleen Liston. She stated that using 4D CAD software can "avoid up to 45% of change costs, leading to 4-6% overall project costs savings or more." Her statement was based on ten years of experience implementing and developing 3D-based technologies in the construction industry, as the current chief technology officer of Commonpoint Inc, and as a PhD in Construction Management from Stanford University.

An assumption of 5% cost savings is reasonable for Navy construction projects. The Atlantic Division of NAVFAC, when the author worked there from 2001-2003, was setting goals of 8% cost growth and 12% time growth on construction projects. If using 4D CAD technologies can reduce cost growth from 8% to 3% on particular projects, the investment should pay for itself.

If a cost savings of 5% is assumed, one can determine the minimum project dollar value required to cover the cost of using 4D CAD:

$$\$46,447 / 5\% = \$928,940$$

In words, if the costs of setting up a 4D CAD system are $46,447 and the anticipated project cost savings due to using a model is 5%, the minimum project dollar value required to breakeven is $928,940. Therefore, once 4D CAD is implemented the total project cost would be $975,387. The savings would be $46,447 and the investment would breakeven.

However, this analysis is assuming the quantification of many variables that could be very different on any given project, regardless of how accurate the assumptions are. Construction projects are very unpredictable, and therefore a factor of safety should be considered. Due to the number of variables and the irregular nature of construction a factor of safety of at least 3 would not seem unreasonable. A factor of safety of 3 would increase the minimum dollar value from $928,940 to $2,786,820, or would assume 1.67% cost savings instead of 5%; once a few projects implement 4D CAD the factor could be adjusted based on experience.

7.4 Cautionary Note

Although this analysis places a number on when 4D CAD use would be cost effective, one must realize that the type of project will impact the degree of cost savings. For example, the construction of a facility that is fairly straight-forward with no complexities and few site constraints would see fewer cost savings than a project with many complexities and site constraints. Project planners should very carefully consider how complex a project is and whether or not the benefits of 4D CAD would profit the project in question. Additionally, planners should perform their own analysis using numbers suitable to their situation. For example, a project being performed in San Francisco would not use $35.22 for the hourly wage of a scheduler.

8.0 Conclusion

4D CAD is a tool with many potential benefits for the construction industry as a whole, and for NAVFAC in particular. As it was first implemented only ten years ago, 4D CAD is still in its developmental stage. There are many kinks still to be worked out, but none are so difficult to work out as to prevent 4D CAD from benefiting constructors, owners, and designers in a big way. Use of 4D CAD can potentially catapult the construction industry past bulky 2D drawings and overwhelming CPM schedules, into a more streamlined, integrated, collaborative process – involving all project stakeholders from the designer to the end user. Designers can potentially receive more informative input from constructors and owners, while constructors and owners can potentially use 4D CAD to conduct more productive meetings.

A major consideration of using 4D CAD, from an owner's perspective, such as NAVFAC, is how to implement its use. One possibility is to start small and grow with each success. NAVFAC, with its hierarchical organization, can begin implementation 4D CAD at the most basic levels, and if the technology proves successful, let it spread and eventually grow to the next level. As the technology is implemented throughout the organization, policies can be rewritten to provide guidance on when and how it should be used and how personnel should be trained. If it does prove successful in the NAVFAC organization, training of personnel at CECOS in 4D CAD could provide increased benefit to the organization by providing instructors with a medium to better educate AROICCs and AREICCs.

Besides developing a plan for implementing 4D CAD, one must also construct a method for determining when to use it. When to implement, however, is a highly variable decision. In construction there are many different types of projects, project locations, and project stakeholders – no two projects are ever exactly the same. Therefore, project planners must consider each project separately, and perform their analysis with cost and savings factors suitable to their situation. Then, once an economic analysis is performed, or even before, an analysis of how 4D CAD technology would be used and benefit the project in question. If there are no foreseen benefits by the project stakeholders then implementation of 4D CAD should probably not be considered.

Recommendations for future work on this topic would be to further develop the implementation of 4D CAD in the NAVFAC organization by providing position descriptions incorporating 4D CAD. For example, the chief engineer is responsible for schedule acceptance; would he also accept 4D CAD models? Another recommendation for future work would be to further develop the economic analysis of 4D CAD for specific types of projects. For example, would 4D CAD be beneficial for a new road project? A road repair project? New construction? Renovation? Tunnels? Bridges? Another related topic would be what other types of owners / constructors / designers would most benefit from 4D CAD?

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APPENDIX

Comparison of Software Costs and Applications

Company	Name of program	Availability	Price of 1 seat of software	Price of viewer	Typical installation cost (including training)	# of projects used to date	Type of projects
Balfour Technologies	fourDscape	Download browser, license server	$79 for browser avg. $2000/mth for server subscription	$79	$0-$10,000+ (on-site training @ $1000/day)	>20	Transportation
Bentley Systems	Bentley Navigator	Download, CD-ROM	$3,795	$0	(On-Site Training) 2day - $6,600 + expenses 1day - $2,200 + expenses	500+ ranging from small to large projects worldwide.	Architectural, Commercial, Transportation, Process, Power, and offshore plants and facilities
Common Point, Inc.*	Common Point 4D	Internet Download, CD-ROM, Off the Shelf	$7,900 (includes training, 1 Producer, 5 viewers) $5,900 for additional seats Free to educational institutions Maintenance/upgrades for 1 year included	$499	$2-4 hours included in cost	>60	Commercial, Transportation, Industrial, Master/Urban Planning, Historic Reproduction
Construction Systems Associates	PM-Vision Module of Plant/CMS	Consulting, off the shelf	$6,000	$4,000	Starting at $20,000	16 projects, largest project over 36,000 activities	Semiconductor fabrication facilities, power plants, commercial facilities
Intergraph Process,	SmartPlant Review	Off the shelf	$12,000 includes base viewer and all	$5,500	Typical construction	Hundreds (4D with	Process, Power, and

Power & Offshore, div. of Intergraph Corp.			6 modules. Leasing options available		site $5,500; Typical engineering design office $25,000 concurrent license	construction sequencing)	offshore plants and facilities.
Reality Capture Technologies, Inc.	ConstructSim	off the shelf	$13,500 / seat. $22,500 for the VPM integration server. Leasing options available	$0 included	Starting around$10at,000 (multiple seats used primarily at the construction site)	2	Industrial facilities / Process / Power/ Offshore
Navis Works	Pro Project Pack	Off the shelf	5 Seats for $12,500	$0 included	$2450 for annual maintenance and email support	??	

*Acquired by Reality Capture Technologies

Comparison of Software Functionality

Name of Program

Feature	fourDscape	Bentley Navigator	Common Point 4D	PM-Vision	Intergraph SmartPlant Review	ConstructSim
Hardware requirements	PC/Laptop HW-accel OpenGL graphics card 128MB - 1GB+ mem	Intel Pentium(or equivalent)processor.Minimum of 128MB RAM	250MB Ram, 500 Ghz Processor, OpenGL Workstation or Laptop compatible, MAC with Virtual PCcard	PC compatible system	Standard Laptop with standard OpenGL graphics card; 32 MB RAM	Laptop or PC with OpenGL graphics card; 1 GB Ram;; 1.7 Ghz processor
Software requirements	Windows 2000/NT/XP	Windows NT 4.0,	Windows System	Windows NT/2000/XP	Windows NT/2000/XP	Windows NT/2000/XP

	or Linux/Unix	2000, XP				
Easy to update model	Import schedule and models	Import Schedule and models	Update 3D and Schedule	Yes	Can be manual or automatic and transparent to the user	Automatically
Model size (# polygons)	5-10 million polygons for interactive update rates	Unlimited model size, based on available virtual memory. No software limit to the number of polygons and triangles.	1 million polygons per 500 MB Ram	Over 70 million triangular polygons	Unlimited model size, based on available virtual memory No software limit to the number of polygons and triangles	Unlimited model size while maintaining high frame-rate for user interactivity
Types of CAD adapters	AC3D, Design Workshop, OpenDX, Multigen OpenFLT (preferred format), VRML, 3DStudio, LightWave, Wavefront, terraPage. Through import utilities can display: Microstation, AutoCAD, XGL, Inventor, CATIA, IGES, ESRI GIS	PlantSpace Design Series, Intergraph PDS, Rebis OMNI-series, AutoPlant, Pro-Series, MicroStation, AutoCAD	Adapters for: AutoCAD, ArchiCAD, Microstation, VRML Via VRML/Utilities: FormZ 3D Studio/VIZ XSteel, Katia, Wavefront, Multigen, GIS via utilities	AutoCAD, Microstation, PDMS, PDS, PASCE, VRML, IGES, Unigraphics, and several others. An interface to schematic 2D drawings (P&IDs) also exists.	Intergraph 2D and 3D PDS (Plant Design System); FrameWorks Plus; SmartPlant P&ID; 2D and 3D MicroStation; AutoCAD; SolidEdge SAT;	PDMS, PDS, Autoplant, AutoCAD, ArchiCAD, PASCE, VRML, MicroStation; Also has an interface to P&IDs

Schedule integration	Any spreadsheet format from Primavera, MS Project, Excel, etc.	Primavera Project Planner v3.1 Microsoft Project v98, v2000, and v2002	P3, MS Project, Excel, Comma-delimited and tab-delimited files	Primavera, Microsoft Project, Microsoft Excel spreadsheet, Sugar, ODBC	SmartPlant Foundation; direct import and export of Primavera and MS Project; ODBC; Microsoft Access; Excel,	Primavera P3,MS Project, Excel, ODBC, Microsoft Access
Output	JPEG file sequence at specified quality for .MPG or .AVI creation, image snapshots	.BMP file snapshots and industry standard .AVI's for detailed simulations.	Viewer, Movie Files (AVI, MPEG), Snapshots/Images, 3DS Max/VIZ, VRML (Animated), MultiPage TIFF Print Report/Layout	Movies (.avi, .mov, .mpg)	Screen, printer, import and export of all standard movie and still image formats	Viewer, Movie, Snapshots/ Images Weekly work package assignments with a bill of materials for the weekly work package
Analysis	Data output of ANY analysis tool or simulation can be configured for temporal & spatial visual analysis.	Powerful navigational tools, static and dynamic clash detection, queries, construction simulation and detailed object motion	Time-Space Conflicts, Incomplete, Interference detection, Cash Flow Analysis (by activity flow), Field/Quantity cumulation by day	The system has a number of diagnostic facilities to verify and check the schedule	Robust data and graphic navigation and analysis including query, static and dynamic clash detection, object motion and construction simulation	Conflict, queries, clash detection, weekly work package assignment and sequencing with crew resource analysis, material trial allocations against weekly work packages to

						query the availability of materials on-site
4D playback options	Time slew, speed, direction, visual perspective, tethered eyepoint	frames per weeks, frames per day, frames per hour, frames per minute, frames per second,	Speed, Interval, Activity Types, Overlay Text, % Complete, Critical Path, Switch between planned/actual, start, stop pause, backward, forward, go to start, go to end; go to date; query; color, shading, wire frame; highlight; visibility, pre-defined views, in progress transparency, clipping/sectioning	Yes	Speed, Intervals, frames per day; days per frame; loop; start, stop pause, backward, forward, go to start, go to end; go to date; snapshot; query; % complete; critical path; color, shading, wire frame; highlight; visibility;	Speed, Interval, Color Types, Overlay Text, % Complete, Critical Path, Switch between planned and actual 4D representations
Color-coding options	RGB ColorMAPS, RGB ColorRAMPS, & Transparency dynamically assigned to desired object attributes	Define your own color schemes to show critical path versus non-critical path activities in different colors.	True color, transparency options, textures, simple lighting	Dynamic color assignment	True color, materials and textures, wire frame, transparency, by task or object	By resource, activity-type, work-package, crew, availability of materials on-site, customized queries, ability to display activities not yet complete, system-by-

						system for testing and turnover
Automation	Object motion & speed controlled by internal scenario spec. or external dataset.	yes	Yes. Manual/automatic linking between named components and activity, automatic activity type assignment	Generate activities from the model according to activity templates. Provide assignments of construction quantities and cost. The quantities are calculated automatically from the model database.	Yes. Includes several options for manual and automatic task and object association such as match substring of task name or group name	Yes, automatically generates a detailed level-4 task database (with time and cost estimates) from a level-1 master schedule; Also performs automatic assignment of model components to schedule items through component ID, material type, material size and other custom associations, manual and highly automated task and schedule detailing; material take offs
Supports reorganization Of 3D data	3D models organized into a visual hierarchy tree, creating	Yes	Yes - automatically via attribute/field association,	System reorganizes the "engineering	Yes. Modifications to schedule or model can	Yes. Performs automatic re-organization of the CAD

	new visual groups/subgroups as desired		manually via drag and drop with flexible re-organization hierarchically	model" to construction format, including construction zones, disciplines, contracts, process systems, etc.	be updated independently of each other	model by discipline, pipe spools, construction areas and systems for turnover and testing. Can also be grouped and organized by any model attribute A sheets / spools and
Supports subdivision	Yes	Yes. Use grouping functions to create groups of 3D model components, or subdivide large groupings into smaller sets of objects that represent the way materials are actually manufactured and handled in the	Limited	Yes	Yes. By area, zone, system, work package, etc.	Yes, using zones; systems, work package, sheet or spool, and discipline

		field.				
Can add 3D temporary components	Yes	No	Yes	The system has powerful 3D modeling functionality which is based on parametric libraries.	Yes. Temporary or permanent, such as Scaffolding, welds, lay down yard, cylinders or spheres for sound, radiation, or explosion simulation; with user definable attribution and association to schedule	Yes Scaffolding, welds, lay down areas, and crane simulation
Supports animation, path planning	Yes	Yes	Yes	Yes	Yes	Yes
Types of graphics	Wireframe, shaded lighting effects, photo-realistic textured faces	Wireframe , solid, mixed, lighting effects	Basic shade mode,	Shaded, Hidden-line, Wireframe, Texture mapped,	Wire frame, full range of shading modes, hidden-line, texture mapping, photo-realism; environment box, etc.	Basic shading, dynamic lighting control, wire-frame, texture mapping, and environmental model support
Annotation	Overlay Text, 3D Text in model	Yes. Ability to create text messages within the view.	Dynamic Overlay text, Snapshot Annotation for print/reporting, 2D and 3D text labeling, 3D highlights and	Yes	Yes. Automatic 2D and 3D labeling; tags with text and saved views	2D and 3D text labeling, 3D highlights and arrows, document hyperlinks,

		Accurate measurement of dimensions between two selected points.	arrows, document hyperlinks, embedded photos and images, safety notes, and saved views, including 4D model state 2D and labeling; feedback of objects and activities to CAD and schedule		in a database; drag and drop any file into the viewer for automatic association	embedded photos and images, safety notes, and saved views, including 4D model state 2D and labeling; feedback of objects and activities to CAD and schedule
Other unique features	Supports remote collaboration thru fourDscape portals and remote GUI capabilities	With additional Bentley technology users can have controlled access to review up-to-date models for authorized individuals. Plus model check in/check out capabilities. View attached documentation from	Easy to learn, Build first model in a few hours Hierarchical 4D components for flexible matching of 3D model with schedule at several levels of detail Educational program with free educational licensing Bi-annual user conferences focusing on 3D/4D modeling	Integrated with XDCAD technology, supporting Plant Lifecycle applications and Plant Information Asset™ databases. Able to handle schematic drawings (P&IDs). Reviews construction quantities and cost with the schedule. Identifies engineering changes, DCN's, and other object	Easy to use and can run on low-end laptops or high-end desktops. Can be configured for the most casual user yet robust enough for the 3D expert. Can be linked to more than the project schedule but can include the entire engineering framework and asset database. No other product is as well	Allows detailed work packagesCAD Neutral platform. Easy to be assembled for weekly work planning. Easy-to-use avatar abased walkthrough with safety review analysis; CAD vendor neutral platform that utilizes open and extensible XML data model which integrates not only with

		industry-standard applications and keep track of maintenance schedules, reports and P&ID drawings.		related documents with the activities.	integrated with PDS, INtools, MARIAN, SmartPlant Foundation, and SmartPlant 3D.	the schedule but also with materials management systems and earned value reporting systems for detailed quantity estimation and task tracking; Allows multiple engineering datasets. Unique line following and recordingcapabilities. er, and component attributes to be added to the model through spreadsheets and databases in addition to those provided in the 3D CAD models; Linking across multiple datasets, incorporates a dynamic change

						management system that provides attribute cross-checks and data validation reporting. Incorporates a unique line following and recording capability. Additional modules support operator, training, procedure development and validation, plant mechanical integrity inspection; and as-built modeling.