Abstract
Collaborative AEC technologies centering around component-based CAD models support architectural and structural perspectives. The construction perspective is often neglected because an important dimension for construction—time—is missing. Construction planners are forced to abstract CAD model building components into schedule models representing time. 4D-CAD (3D-CAD + time) removes this abstraction by linking a 3D building model and schedule model through associative relationships. Adding time to 3D-CAD models extends the use of CAD tools from the design phase to the construction phase. This paper discusses requirements for CAD tools to support construction planning and evaluation.

Motivation
A construction manager’s primary role is to develop a construction plan that meets a client’s cost and time requirements, communicate that plan to project participants, and prevent costly construction errors. Typically, the primary tool for this communication is a construction schedule which abstracts design documentation (2D or 3D drawings and specifications) into a set of activities and sequential relationships (Fig. 1-B). While construction schedules communicate time, they are difficult to associate with the description of the physical building. In addition, design and schedule information often change, and it is a challenge to update the separate documents (CAD model, schedule) in a consistent fashion.

4D-CAD removes this abstraction by representing time (the schedule) and space (the 3D building model). One form of 4D-CAD is a 4D animation (Fig. 1) which is a visualization (movie) of the construction process. A 4D animation is created in several ways:

1) orchestrated series of 3D images [4D CAD 1994],
2) batch process linking CAD layers to a schedule activities [Collier and Fischer 1995], or
3) interactive process dynamically linking CAD graphic entities with an ‘activity’ objects [McKinney et al. 1996; Jacobus Technology 1996].

At the Center for Integrated Facility Engineering (CIFE) at Stanford University we have been studying the creation and use of 4D animation. In some cases, the process of creating a 4D animation, regardless of the method, helped...
identify potential construction problems [Collier and Fischer 1996, Novitski 1996, Goldstein 1995]. In other cases, 4D animation was an effective tool to visually communicate a construction plan since it replicates construction processes more accurately than current scheduling tools [4D CAD 1994]. This interaction with industry demonstrated the value of visualizing the construction process with 4D-CAD. Industry feedback also highlights key issues preventing the current and frequent use of 4D-CAD as a planning tool:

1) **Representation of time is not enough.** 4D-CAD addresses one concern of construction managers—time. However, 4D animations do not represent the cost, constructability, or safety of a proposed construction sequence.

2) **Creation and manipulation of 4D models is time consuming.** Construction planners typically start with a set of 2D drawings and specifications from which they create a 3D-CAD model. They create a schedule with a scheduling tool and then use a 4D tool to link the two sets of information. If the planner wants to make any changes, he/she must edit the original CAD and schedule content.

3) **Visualization should include more than just the graphic representation of the building.** Construction planners viewing 4D animations want to see equipment, staging areas, scaffolding, and work areas. These elements are just as important to the planner as the building elements. Furthermore, planners want to see other process information such as interferences and congestion.

This paper discusses issues related to the development of CAD based 4D tools which provide the functionality necessary to overcome these limitations. We have identified the following CAD features needed to support the use of 4D-CAD for construction planning:

- extraction of CAD geometry and relationships
- component definition
- elaboration mechanisms
- generation of temporary items
- representation and manipulation of 4D content
- visual feedback mechanisms

We discuss these requirements based upon our 4D-CAD work [Novitski 1994; Collier and Fischer 1995; McKinney et al. 1996] and our interaction with contractors. Although we focus on our work at CIIFE, we cite other academic and industry efforts related to the use and development of 4D tools. Before starting this discussion we briefly introduce relevant 4D concepts and terms.

**Background: 4D Models**

A **4D model** contains graphic and schedule information and their associations or **4D content**. 4D content refers to graphic and schedule information which are assigned meaning within a 4D context. For example, a 3D-CAD model contains CAD information such as lines, surfaces, or solids and a schedule model contains activity information such as duration or predecessors. A **graphic 4D model** is created by implicitly linking these two models with a 4D tool and is represented in a 4D animation (Fig. 1). This linking process involves the implicit assignment of content to the graphic information by referring to specific graphic information as a building component such as ‘roof tiles’ or ‘metal deck.’ The resulting 4D animation simulates the construction process with implicit associations between the construction schedule activity and the graphic content it acts on.

A symbolic 4D model, on the other hand, explicitly represents 4D content with an underlying symbolic description of a **4D component**. A schedule model represents the installation of the tiles with an activity object titled ‘install tiles’ (Fig. 1-B). A graphic 4D model references this CAD and schedule content. That is, the graphic 4D model merges the 4D content and stores only the information relevant to producing a 4D animation. This prevents the planner from manipulating the underlying CAD or schedule content.

A symbolic 4D model, however, symbolically represents the graphic entities as **4D product components** (Fig. 1-C); and the schedule information as **4D process components** (Fig. 1-D). Relationships between these components are also explicitly described and defined. 4D tools which store information graphically and symbolically make it easier to manipulate 4D content.

Transforming 3D-CAD information into symbolic 4D content, however, is not easily achieved with today’s CAD tools. Nor do CAD tools support representation of symbolic 4D content. This paper discusses our efforts to improve 4D data modelling with CAD modelling tools. Various research efforts propose data modeling methodologies for representing building design information for various domain purposes, i.e. product modelling or process modelling [Eastman and Siabiris 1996, Phan and Howard 1993, Molina et al. 1995, Aouad et al. 1995]. These efforts, however, do not explicitly address how AEC designers perform the process of data modelling. This paper presents a test case with various scenarios describing how construction managers might perform 4D modelling. We demonstrate the use of 4D tools from a construction perspective by providing a context and purpose for the 4D modelling. Furthermore, we highlight current limitations of 4D tools—specifically with respect to CAD based 4D tools.
Test Example

We use a construction project case example to illustrate how construction planners could use 4D-CAD models to support construction planning. The construction project consists of three campus buildings distinguished by steeply-pitched roofs (Fig. 2). Right before roof installation contractors realized that the gutter could not be installed since the assembly piece for the gutter had not been detailed. The roof, sheet-metal, and stucco subcontractors were forced to produce a new solution to start their work. The roofer, sheet metal, and stucco contractor had to mutually decide on the new sequence of construction by considering the following issues:

- **what kind of connection piece should be added** — a single c-channel to support the gutter and roof tiles or a two piece c-channel
- **who installs the new connection piece** — roofer or sheet-metal subcontractor
- **who uses the scaffolding and when** — scaffolding is needed by both the sheet metal and stucco work crews
- **how to prevent damage to the stucco** — damage occurs when tiles are installed after the stucco due to bending of the supporting steel structure

In the following sections we discuss 1) how 4D models can store information and knowledge about the project to help planners evaluate alternative roof construction schedules, 2) how planners interact with the 4D model content and 3) how the project team could have used visual feedback of a 4D model to identify problems during construction planning and to communicate advantages and disadvantages of alternatives. We describe planning scenarios in three task sets.

1. **Knowledge tasks** include: analyzing a 4D model and representing knowledge in 4D components. The goal of these tasks is to evaluate a schedule based on a 4D analysis of cost, damage, and temporary support.

2. **Interaction tasks** include: manipulation of 4D content and generating 4D content with single and multiple-user input. The goal is to facilitate input from multiple sources and improve interaction and manipulation of 4D content.

3. **Visual tasks** include: viewing 4D model content in a 4D state (Fig. 1), 4D animation, or 4D component. The goal of these tasks is to enable planners to communicate a proposed construction plan and various evaluation criteria, e.g. cost, time.

In each section we describe how existing 4D tools’ and CAD tools’ features and functionality support these tasks.

**Knowledge**

We’ve identified three 4D tool functional requirements for enabling the representation of project knowledge within a 4D model: 1) defining components, 2) extracting CAD geometry information and 3) acquiring functional, associative, and semantic relationships.
FIGURE 4: Partial Component Definition for a 4D Component

Component Definition and Extraction of CAD Geometry Information

In the test case example, planners must weigh various evaluation criteria such as cost and time. A criteria they cannot ignore is whether a proposed construction sequence satisfies ‘temporary support’ conditions. For example, the initial roofing schedule (Fig. 3) does not satisfy support for gutter installation since there is nothing installed prior to gutter installation to support the gutter. Unlike standard support analysis such as structural analysis, ‘temporary support’ analysis requires information about the order of construction of the building elements.

Temporary support, then, requires information about building components and their ‘support’ relationships with other components; and sequencing information to know when the component is installed. The ability to analyze ‘temporary support’ conditions is dependent upon the ability to represent this information in 4D product and process components. We refer to this as component definition. For example, the 3D-CAD entities representing the gutter must be represented as a 4D product component containing the gutter’s location in space and its relation to other building components.

Component definition, then, is a description of the information needed to represent and reason about a component. The component definition of a 4D product component representing the roof tiles might include geometric attributes such as length, thickness, and width. Additionally, the tile component definition contains relational attributes associating the 4D product component with other 4D components (product or process). For example, the roof tile 4D product component would contain an attribute describing its relation with the 4D process component ‘install tiles’.

If components are defined and represented appropriately, 4D models can help planners evaluate a proposed construction plan. In our current 4D work at the Center for Integrated Facility Engineering CIFE (http://gaudi.stanford.edu/4d-building-blocks) we are developing information models to evaluate cost, damage, and support for a given construction sequence for problems like the roof construction example (Fig. 3). Consider this scenario:

The general contractor builds a symbolic 4D model representing a 3D model of the gutter detail and a proposed construction sequence (Fig. 3). The contractor selects the ‘check support’ evaluation tool. The planner observes the virtual simulation of the gutter detail and as the tile is virtually constructed a message notifies the planner that the tiles need additional edge support.

The 4D product component representing the tiles is shown in Figure 4. The attribute check_edge_support contains the value ‘NO’. This indicates that the tiles do not have sufficient support along one of its edges. As the simulation took place, each 4D product component is checked for various kinds of temporary support. Then, unlike a static analysis, this ‘temporary’ support analysis checks to see whether those components have been virtually constructed.

For example, the tile component requires ‘edge support’, ‘continuous support’, and ‘structural support.’ Each of these support conditions must be analyzed. The need for ‘edge support’ is determined by two factors: 1) the angle of the roof (attribute ‘angle’) and 2) coefficient of friction of the roof tiles. The 4D analysis first determines whether edge support is required. If so, the analysis continues and searches for components which may satisfy the static ‘edge support’ condition. The attribute ‘edge support’ lists the potential candidates. In this example, the value is ‘null’ since no component in the model satisfies the ‘edge-support-for’ relation. If the attribute ‘edge_support’ contained a component, such as a c-channel, then the analysis would check to see if the component was ‘virtually’ constructed.

4D tools should enable the ability to view the 4D component definitions and easily manipulate the 4D product or process component content. For example, a component browser showing the ‘tile’ component definition allows planners to access the symbolic information within a CAD-based 4D environment rather than in a knowledge-based 4D tool environment. The planner can then make changes to the graphic or symbolic content.

Acquiring Functional, Associative, and Semantic Relationships

For 4D analysis to work, we must have knowledge about ‘supported-by’ [Darwiche et al. 1989], ‘connected-to’, or ‘edge-support’ relationships. This knowledge can be acquired in several ways:

1. Derive relationships through geometric algorithms and knowledge-based reasoning.

This method is possible at small scales but is difficult to employ for a general all-purpose
derivation of relationships. For example to determine 'supported-by' relationships, reasoning can be used to geometrically determine potential vertical support relationships between CAD components. However, accounting for a variety of support conditions (as demonstrated in the example) is difficult.

2. **Manually interpret 3D-model and assign relationships.** Interpretation is a useful method for assigning semantic or functional meaning to graphic content [Clayton et al. 1994]. This method provides the most flexibility yet also requires construction planners to understand the purpose and process of assigning relationships. For a small detail like the test case example, this method is feasible. For the entire construction project, however, manual interpretation simply increases the amount of work required to build a 4D model.

3. **Capture relationships as 3D model is produced.** Some CAD tools [ProEngineer®, IDEAS®, Ashlar Vellum®] capture geometric relationships between graphic entities or components in the form of constraints. These tools however, are more widely used in the mechanical domain and define relationships specific to that domain. Additional research efforts have explored the use of drawing constraints in general drawing and architectural drawing tools [Maulsby et al. 1992, Gross 1990]. Developing mechanism to capture and represent 'supported-by' or 'edge-support-for' relationships is a quick and easy way for construction planners to store and maintain relationships. This method, although ideal for planners, requires a CAD tool which supports the creation and maintenance of relationships and constraints.

Creating relationships and maintaining them is key to advancing the use of 4D tools for evaluation of construction schedules. Research defining the appropriate definition of those relationships and acquisition of those relationships is needed.
**Interaction**

Interaction occurs on two levels: 1) interaction with other people such as subcontractors and project designers and 2) interaction with the 4D content. To support these interactions CAD environments must provide the ability to elaborate and to manipulate 4D content.

**Elaboration**

The previous section discussed how a 4D planner could use a 4D tool to evaluate a proposed solution at a specified level of detail and content. Furthermore, we assumed that the person using the 4D-tool consolidated information from various sources: subcontractors, estimators, design drawings, and specifications. Producing a 4D model of the gutter, however, requires input from multiple people and multiple levels of detail. Consider the following scenario:

A construction planner starts with a model of the campus buildings project (Fig. 2) and wants to use a 4D tool to plan the project. First, the planner breaks the building into twenty work packages: excavation, foundation, steel, sheet metal, roof, etc. The planner then provides the subcontractors responsible for each work package with relevant design documentation and access to the project 4D model. Each subcontractor produces a detailed 3D model and schedule model of his/her respective portions of the construction project. For example, the roofer builds a detailed graphic model of the roof components (Fig. 5-C) and a detailed schedule (Fig. 3). When each subcontractor finishes, they submit a 4D model to the general contractor who links the more detailed 4D models with the master 4D model.

Realizing this scenario requires developing mechanisms to support elaboration graphically and symbolically. At the knowledge level this is represented by 'part-of' [Nederverdeen and Tolman 1996] relationships or 'is-a' relationships. Graphically, however, CAD tools do not support these kinds of relationships except through layering referencing. Layering is an organization mechanism and referencing is creating associations between drawing models but not drawing content. In the above scenario, the planner will want to view and access 4D content at various levels of abstraction. That is, from the high-level roof graphic, the contractor will want to access more detailed 4D model content provided by the roof subcontractor. This functionality requires graphic and symbolic multi-representation.

An example of multi-representation is shown in Fig. 5. The zoom-in view of the building represents the roof as a single entity (surface) (Fig. 5-B). In Figure 5-C the roof is represented by multiple graphic entities: metal deck, insulation, gutter, etc. Each of the figures represent a different 'graphic' view of the 3D-CAD model. Multiple-representation is a mechanism which enables representation and interaction with multiple-views of a [Nederverdeen and Tolman 1996, Fruchter et al. 1993] of a project.

**Manipulate 4D Content**

Requiring each participant in the construction project to produce 4D content is not feasible with today’s 4D tools. Planners are already struggling to use CAD, estimating, and scheduling programs effectively. Current off-the-shelf 4D tools require planners to use CAD, a scheduling tool and a 4D tool [Jacobus Technology 1996, Williams 1996]. Furthermore, changes to 4D model content are not easily made with these 4D tools since the 3D-models are not represented explicitly. That is, one cannot edit or revise the graphic content in the 4D environment.

In our research at CIFE we have developed a prototype interactive 4D tool [McKinney et al. 1996]. Planners using this tool can make changes to the 3D graphic and schedule information within a CAD-based environment. In the test case example this kind of interaction is necessary since planners need to revise the schedule information and the 3D-model.

Additionally, in the process of creating 4D models, planners need to interact with the ‘relationships’ between various model components. With today’s 4D tools, planners adjusting sequences for the gutter schedule need to manually enter data and assign associations with graphic components. Our prototype enables more direct interaction with the 4D model. This gives planners the opportunity to generate and evaluate alternative 4D models.

In demonstrating our research prototype and 4D tools, we observed planners attempting to interact with the 4D animation (Fig. 1). Our prototype 4D tool does not allow planners to stop or rewind the animation. Viewing a 4D animation of the gutter, then, requires planners to repeatedly show an animation to observe subtle differences and absorb the content of the 4D animation. Recently we have been using Jacobus Technology’s Schedule Simulation environment which allows planners to view the 4D animation in a movie window and control its speed, pause it, or rewind. However, when the planner stops the animation to show a 4D state (Fig. 1), a planner cannot manipulate or adjust the graphic model content since the Jspace viewing environment does not provide functions or commands to edit or create geometry.

**Visual**

Today, viewing 4D content is typically done with a 4D animation. However, this content is limited to representation of the ‘designed’ 3D building components. Planners, though, are concerned with additional kinds of information: 1) non-building components and 2) evaluation feedback.
**Representation of Non-Building Components**

Consider the following scenario:

*The subcontractors and general contractors have finished building the 4D model and have reached a solution. Then, the sheet metal subcontractor asks who pays for the scaffolding and when the scaffolding will be constructed? The roofing subcontractor then realizes that the 4D model doesn’t show where he can stage the tiles and additional roof supplies.*

Non-building components such as temporary structures, equipment, staging or supply areas, are just as critical to the schedule as the permanent building components. However, since they are not part of the permanent building structure they are often not represented in a 3D or 4D model of the building. 3D or 4D CAD based tools should either supply a template of these temporary construction components for planners to add to 3D models or provide mechanisms to automatically generate these components. The Interactive Visualizer research project at Georgia Institute of Technology is exploring ways to visualize construction equipment within a CAD environment [Goldstein 1995]. Incorporating features like this into a CAD-based environment will provide a more accurate visualization of a construction schedule.

Additionally, representing work spaces or laydown and staging areas are critical for planners to coordinate subcontractors on site. The location and size of these areas often change throughout a construction project. For example, accurate representation of the roof construction includes the area where the roof components are being installed and the area where the roofers are storing the roofing materials. The location of this area is related to the location of roof work and is therefore best represented with 4D-CAD. Planners should be able to assign functional uses of outlined areas. The roofers may require a clearance area for safety. This area, then should be constrained to exclude any other construction work. However, an area for staging materials may be less restrictive. A 4D animation, then, Planners, then, can view the impact of work spaces and storage areas on the project construction.

**Visual Feedback**

Communicating the evaluation results to the construction planners is critical. Currently, 4D tools provide visual feedback based only on a critical path method evaluation. As the animation plays, planners can see when a component is under construction, complete, or on the critical path by the color of the component. This feedback is useful for the planner to evaluate problem areas within the construction project.

In the scenario described in Section 2.1, the planner can view 4D analysis results during a 4D animation.

‘Temporary’ problems such as ‘damage’ when shown in the context of time and space help the planner evaluate a schedule. For example, as the tiles are constructed virtually, a flag or warning symbol communicates to the planner temporary support problems. Additional kinds of feedback include ‘interference checking’, ‘crew congestion’, or a ‘dollar counter’. Like colorful images showing stress ratios on structures, well-designed visual cues will enable the planner to quickly identify problem areas.

**Conclusion**

Representing the construction perspective in a CAD-based environment is an ongoing effort for our 4D-CAD research group at CIFE. We are trying to extend the use of 4D-CAD from a communication tool used by a single contractor on a limited number of projects to a planning tool used by the project team. Overcoming the limitations described in this paper is a step in this direction. Our future research includes examining mechanical feature-based CAD tools such as ProEngineer and IDEAS; developing 4D tool prototypes which demonstrate some of the concepts discussed; and ongoing case studies with industry involving the use of 4D CAD.

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**References**


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