JOINT PRODUCT AND PROCESS MODEL ELABORATION BASED ON CONSTRUCTION METHOD MODELS

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ABSTRACT

In practice, the creation of a construction schedule and a related 4D visualization is still a largely manual and time-consuming task. This makes computer-supported concurrent engineering for constructed facilities difficult, since it is virtually impossible to study the impact on project duration and resource requirements for several design and construction method alternatives. We show how construction method knowledge captured in predefined, computer-interpretable construction method model templates supports the joint elaboration of product and process models and allows construction planners to generate design-build scenarios rapidly and to visualize them readily as 4D models.

Keywords: product models, process models, production models, construction method models, hierarchical planning, automation, integration, 4D CAD, AI planning

INTRODUCTION

The construction industry's outputs differ from most manufactured products because they are large, one-of-a-kind facilities and only about one tenth of a facility's initial cost is spent on design and construction planning. In consequence, relatively little theory and computational support exists for concurrent engineering, and professionals rely largely on graphic symbols to represent facility designs and construction schedules. Synthesis of construction schedules from design descriptions and integrated evaluation of design and schedule alternatives, for example, are still mainly manual tasks. In practice, construction planners need to plan and replan projects at several levels of detail and would like to create 4D visualizations to communicate construction schedules. However, the manual and time-consuming nature of the scheduling process makes it difficult to maintain an appropriate and realistic set of plans, schedules, and 4D visualizations throughout design and construction.

In the last ten years, advances in object-oriented modeling have enabled researchers to model designs and schedules as semantic, computer-interpretable models (Björk 1994) (Ford, Aouad et al. 1994) (Augenbroe 1995) (Crowley and Watson 1997) (IAI 1998). Automated synthesis and evaluation of construction schedules is now possible (e.g., Darwiche et al. 1989), enabling concurrent consideration of design and construction constraints. To realize this promise, we need to define the construction knowledge necessary to create and evaluate a schedule and define a common model that integrates design and construction perspectives. The challenge is to formalize the knowledge and models in a general, yet easily customizable way. We need to find what is similar from project to project and generalize the related knowledge and models, and we need to define mechanisms that allow professionals to customize these models from project to project.

4D (x, y, z, t) models combine designers' 3D perspectives with the builders' temporal views in one model. They allow computer-based analysis of constructibility, cost, productivity, temporary support, and other project performance variables dependent on an integrated analysis of time and space (McKinney, Kim et al. 1996). They also generate realistic visualizations of the facility design and its changes over time. Early test cases (Collier and Fischer 1995) have amply demonstrated that 4D models can help to enhance schedule, cost, quality and safety, with potential benefits in the billions of dollars annually for the global construction sector.

To support such analyses, 4D models must represent time explicitly and cannot consist of a simple sequence of 3D model views. However, full 4D models are very time-consuming to generate manually, and cannot currently share their representations with analysis programs. The difficulty and cost of creating and using such models is blocking their widespread adoption. This paper describes research on construction method modeling and 4D modeling that unlocks the potential of 4D models and enhances the facility development process.
We will first give a motivating case example taken from an industrial project and then show how the construction method model template we defined assists a planner in rapidly generating a schedule and 4D production model at various levels of detail.

CASE EXAMPLE

We observed routine planning tasks carried out on a recently completed refinery project. Our observations were focused on the planning tasks associated with the construction of the Deethanizer Unit, one of the process units in the refinery (Figure 1). The main responsibility of the planning team on site was the generation of schedule alternatives. They generated alternatives that represented the application of different "methods" and alternatives that represented activities elaborated to varying levels of detail (it is common practice to refine a portion of a schedule into more detail than the rest of the schedule). An activity network with over 4,500 activities, which was modeled using commercial project management software, was used to plan and monitor the project. A full 3D-CAD model of the refinery was accessible on the project-site and acted as a decision support tool. This setup is typical for projects of this type and size. Three full-time planning engineers and two technicians were responsible for the maintenance of the schedule.

The planning team on this project was continually adding detail to the schedule, monitoring the progress of the project, updating the schedule to reflect the latest status, and replanning activities to account for changes. On one occasion, management asked the planning team to schedule the construction of some of the bays, which are a part of the pipe rack constituting the Deethanizer Unit, in more detail using a spray-on fireproofing construction method. The content of a vessel located on the pipe rack and near those bays had changed to a flammable substance, now requiring the application of fire proofing. Bay1 is one of the bays affected by the decision to fireproof and is used for the remainder of the discussion. Prior to that time, the construction of Bay1 was represented as one activity that incorporated a general productivity rate for the construction of steel bays. Management had requested the detailed planning of the bays in the Deethanizer Unit to assess the overall impact of the "method" change on the project. Figure 2 shows a partial view of the activity network used to manage the refinery project. It shows the activity "Build PR_Bay1" and its direct predecessors and successors. To plan the activity in more detail, the planners relied on a method statement describing the procedures required for the construction of fireproofed-bays and on the 3D CAD model showing the actual configuration of Bay1 (e.g., how many beams make up Bay1). On many construction projects, especially those that are ISO 9000 compliant, critical construction methods are studied and written up as method statements. Method statements serve as directives for the planning team. The planning knowledge in a method statement is general, that is, it is not developed for any particular component or portion of the project.

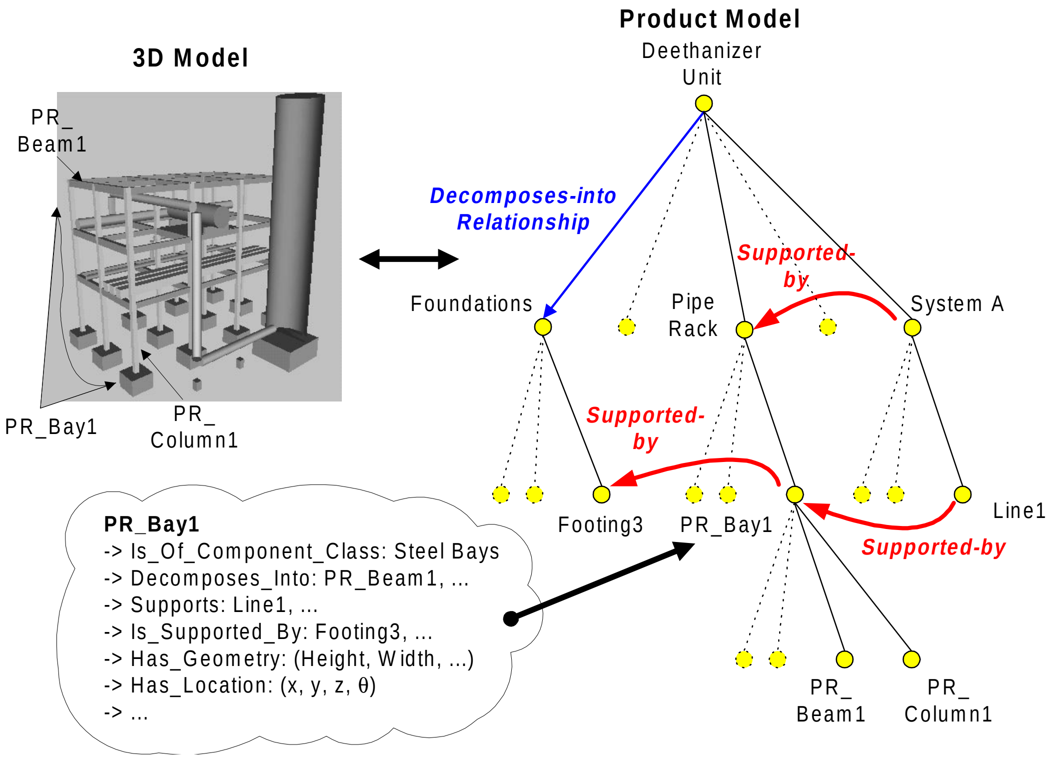

Figure 1. 3D-graphic and symbolic models of the Deethanizer Unit.

The planners created the activities specified in the method statement and interlinked the new activities into the existing network. This specialization of the general method knowledge to the context of the project resulted in the generation of six detailed activities. Figure 3 shows the new network with the more detailed activities to build Bay1. Notice that, even though the detailed activities replace the "Build PR_Bay1" activity, a subnetwork consisting of the new activities could not simply be put into the place of the "Build PR_Bay1" activity. Entirely new sequence links are required. For example, this particular method prescribes that the beams cannot be QC (Quality Control) released until the process systems have been installed to ensure that any blemishes to the fireproofing caused by the installation of the process systems are detected by the inspectors. Each of the new activities generated acts on a component that is part of the Deethanizer Unit. These components can be classified using standard object definitions (IAI 1998) and arranged in a part-of decomposition hierarchy, e.g., according to the RATAS (Björk 1994) model (Figure 1). Note that the resulting activities act on components and systems that are at different levels of detail in the product model, e.g., PR_IBeam1 is a sub-system of PR_Bay1. Finally, a new component, fireproofing, needs to be added to the product model.

The next sections explain how the CMM system automates the generation of activities, the adjustments to the product model required by a particular method, and the sequencing of activities.

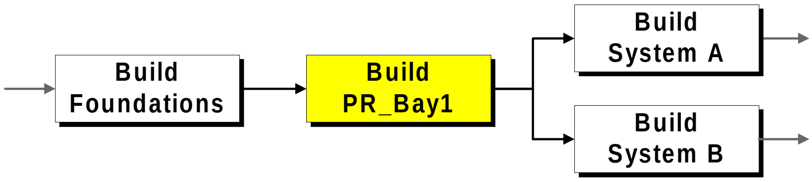

Figure 2. Partial view of activity network used to plan and manage the construction of the Deethanizer Unit.

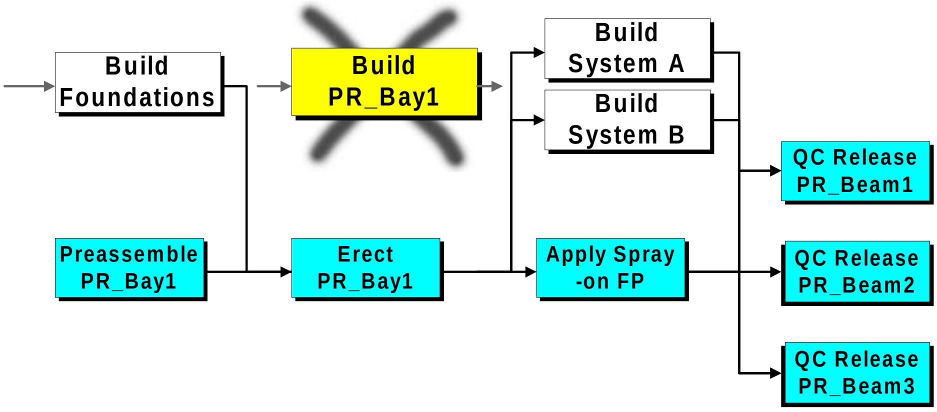

Figure 3. Partial view of activity network after the activity "Build PR_Bay1" has been planned in more detail.

OVERVIEW OF CMM (CONSTRUCTION METHOD MODELER)

Researchers have demonstrated the usefulness of a product model with a decomposition hierarchy and *supported-by* relationships between project components to generate a construction process model automatically (Navinchandra, Sriram et al. 1988) (Darwiche, Levitt et al. 1989). The product model's decomposition hierarchy supports the generation of hierarchical activities, and the supported-by relationships between components enable automated reasoning to sequence the activities. However, the resulting process model is not always a usable or realistic construction schedule, since activities can only be sequenced if elaborated to the same level of detail, and component-based activity elaboration is limited to the original product model. This paper discusses how a customizable and general representation of construction method models supports the transformation of a design-centric product model into a production-centric view.

A formalized hierarchical construction planning process forms the basis of this translation process. The planning process is broken down into method-driven elaboration and hierarchical planning and scheduling steps. User-defined and user-selected construction method models drive the elaboration process by supplying the necessary activity and component elaboration knowledge. The product model undergoes a transformation from a design-centric decomposition to a production-centric decomposition. The elaborated activities are sequenced based on constraints that are passed on to the activities from their construction methods. The output of the planning process is a 4D production model that integrates the product, process, and resource models that were created in this process.

CMM uses an IFC v. 1.5 compliant product model of a designed facility as input. Figure 1 shows the product model and its visualization as a 3D CAD model for the case example. Note that the product model contains information on the types of components in the facility, the size and location of these components, the composition of the facility into various systems, and the supported-by relationships between components and systems. Using construction knowledge stored in construction method model templates (CMMT) and general activity elaboration and sequencing algorithms, a planner is able to select appropriate construction methods for the given project. CMM then automatically generates the required adjustments to the design-centric product model, i.e., it adds components required by the method (e.g., shoring), generates the necessary activities, and sequences the activities. It combines the knowledge in the CMMTs and the product model to determine the appropriate level of detail for each type of activity and to decide on the exact number of activities for a given situation. It uses sequencing knowledge stored in the templates and the supported-by relationships from the product model to sequence the activities. The resulting 4D production model can be viewed as a 4D visualization (Figure 4), CPM diagram, barchart, or resource histogram.

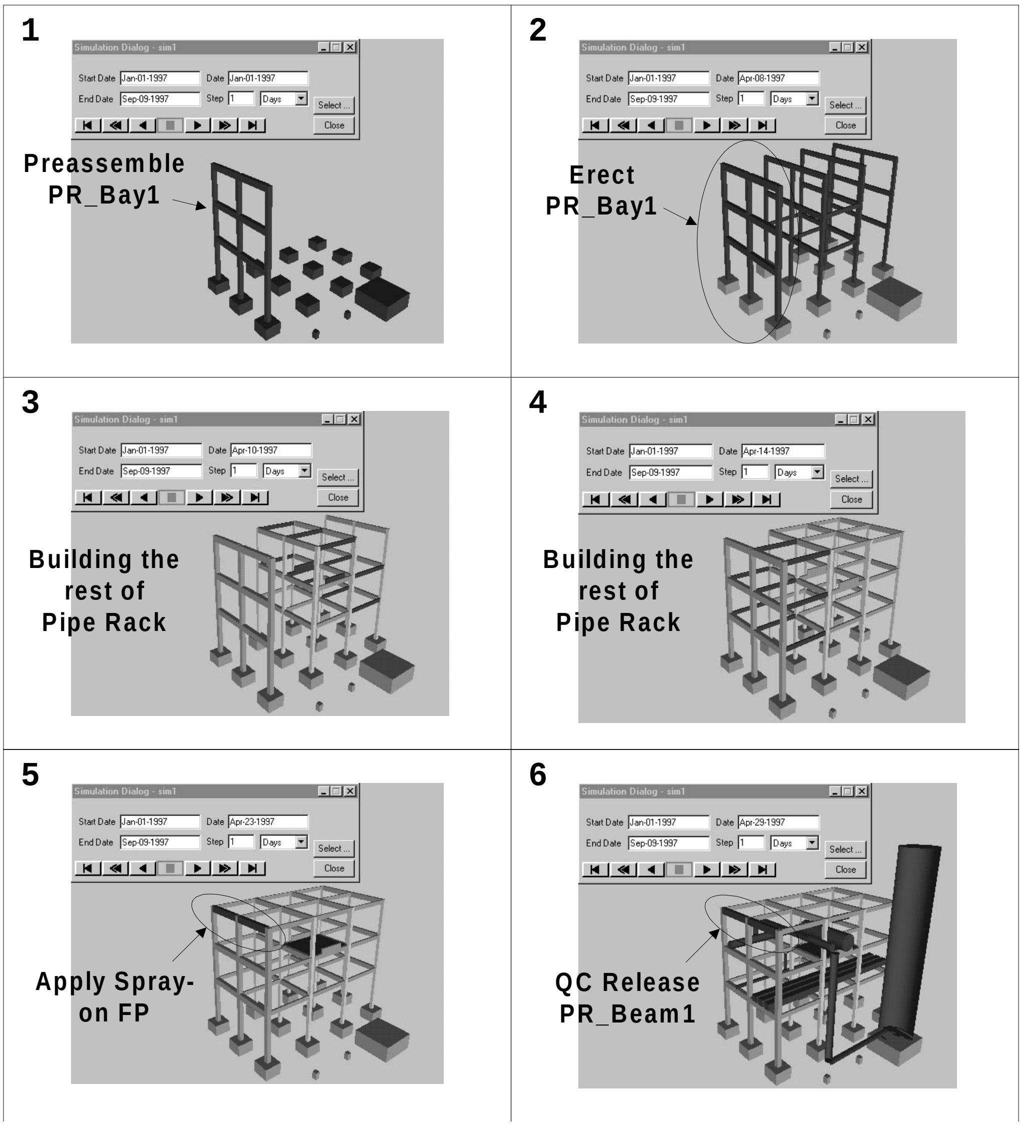

Figure 4. Visualization of 4D production model generated by CMM using Jacobus Technology's PlantSpace^{TM} Schedule Simulator software.

The next sections detail the components of CMM and show how the CMMTs support a flexible, hierarchical planning process.

CONSTRUCTION METHOD MODEL TEMPLATE

We have built on the definitions of a construction method by Froese (Froese, Rankin et al. 1997), Jägbeck (Jägbeck 1994), and Tommelein/Dzeng (Dzeng and Tommelein 1997) and defined the computer-interpretable CMMT (Fischer and Aalami 1996). Figure 5 shows how the CMMT captures a planner's knowledge about the *spray-on fireproofing* construction method. The CMMT uses a planning vocabulary which we extended from Darwiche et al. (1989) to describe each type of activity required by a method. The vocabulary consists of formal specificiations for components <C>, actions <A>, resources <R>, and sequencing constraints <S>. Hence, each activity type is defined by an explicit <CARS> tuple. A particular method always applies to another "higher level" activity. We use an activity's <CA> definition to classify methods and to find applicable methods in a given planning situation. E.g., the "spray-on fireproofing method" applies to the *building* <A> of *pipe rack bays* <C>. We call the activity for which a method applies its domain activity. The template then summarizes the general knowledge about each type of activity required for the method according to the component, action, resource, and sequence constraints for each activity. E.g., the method requires that the <C> *PR_Bay* be <A> *erected* by <R> crew *I-1* after <S> *support* is available and <S> the *bay has been preassembled* (called a technology constraint <TC> and represented as TC1 in figure 5). The CMMT also allows the addition of other relevant information, such as the typical productivity for this crew for this type of activity. It also specifies how the more detailed activities are elaborated <E> from the domain activity. A more detailed activity may refine the level of detail of the component or action of the domain activity; or it may be a hybrid elaboration, adding detail to both the component and action of the domain activity. The CMMT allows planners to reuse general construction knowledge from previous projects. They can also quickly customize a method model for a project or create a new method model. Combined with the knowledge from the product model, the CMMT supports the rapid generation of realistic construction schedules at the desired level of detail. The next section shows how the CMMT for the fireproofing method automates adjustments to the product model, activity generation and sequencing.

Domain-> Action type: Build Component type: PR_Bay

C	PR_Bay	PR_Bay	Spray_On_FP	PR_Beams
A	Preassemble	Erect	Apply	Inspect
R	L-2 Crew	I-1 Crew	C-2 Crew	Ins-1 Crew
S	-none-	Support + TC1	Support	TC2 + TC3
E	Action-based	Action-based	Hybrid	Hybrid
prod	12.0 MHRS/M3	9.0 MHRS/M3	2.5 MHRS/M3	4.0 MHRS/M3
....	....	....	....	....

Figure 5. User defined construction method model template (CMMT) that captures general planning knowledge for the spray-on fireproofing *construction method.*

HIERARCHICAL PLANNING WITH CMM

To start the scheduling process, a planner first creates a seed activity for the project. This activity describes the intent of the project, in our case to build the deethenizer unit. Since there are no specific construction methods that apply generally for deethenizer units, the planner rapidly generates more detailed activities using the "build in components" method. This method simply refines the level of detail of each activity's <C> by moving down one level in the product model and generating a new activity for each of the more detailed components in the product model. This is analogous to the process used by OARPLAN (Darwiche et al. 1989). Figure 6 shows the elaborated product and process model after the activities for the construction of the pipe rack have been elaborated to the level of activities like "Build PR_Bay1". Note that this elaboration process not only generates a hierarchial process model, but also maintains links between the activities in the process model and the components in the product model. This link, made possible through the explicit representation of each activity's <CA>, supports the automated calculation of activity durations based on quantity takeoff information from the product model and the productivity and <R> information from the CMMT. It also supports reasoning required to resolve the sequencing constraints formalized for each activity in the CMMT.

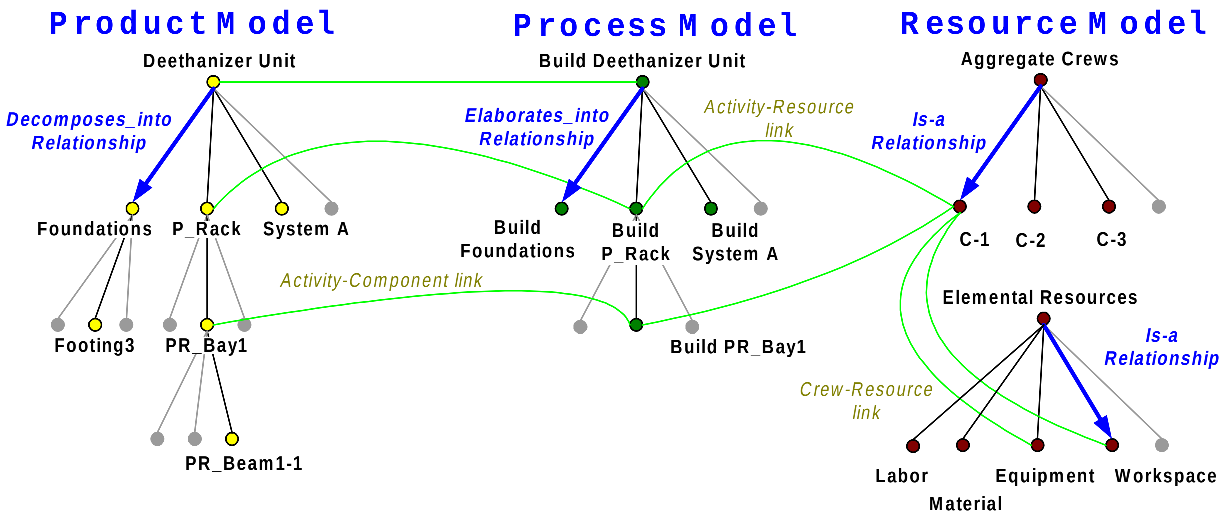

Figure 6. 4D production model after activities for the construction of the pipe rack have been elaborated using the "build in components" method. The 4D production model is composed of linked product, process, and resource models.

If we visualized the process model shown in Figure 6 as an activity network we would see a network at the level of detail shown in Figure 2. We are now ready to apply the specific fireproofing construction method. In the CMM interface window (Figure 7), the planner selects that method "spray-on fireproofing" to elaborate the activity "Build PR_Bay1". Note that CMM gives the planner a choice of methods it knows apply to activities with the action "Build" and the component "Pipe Rack (PR) Bay" based on each method's <CA> tuple. Once the planner has selected the "spray-on fireproofing" method, CMM checks whether it finds all the necessary components specified in the CMMT in the product model. It finds Bay1 and the beams for Bay1, but it cannot find a fireproofing component. Using predefined parametric design algorithms as discussed by (Dharwadkar and Cleveland 1996) or direct user input, CMM adds a fireproofing component to the product model (Figure 8). We have also defined and implemented two other product model adjustment mechanisms to support the creation of a production-centric product model from a design-centric model. They support the addition of new systems, like scaffolding, to the product model and the aggregation of components into zones or work areas. Now that all the necessary components are in the product model, CMM generates activity instances as specified in the CMMT. Note that, since Bay1 has three beams, three QC release beam activities are generated. Also note that CMM is able to generate activities at various levels of detail.

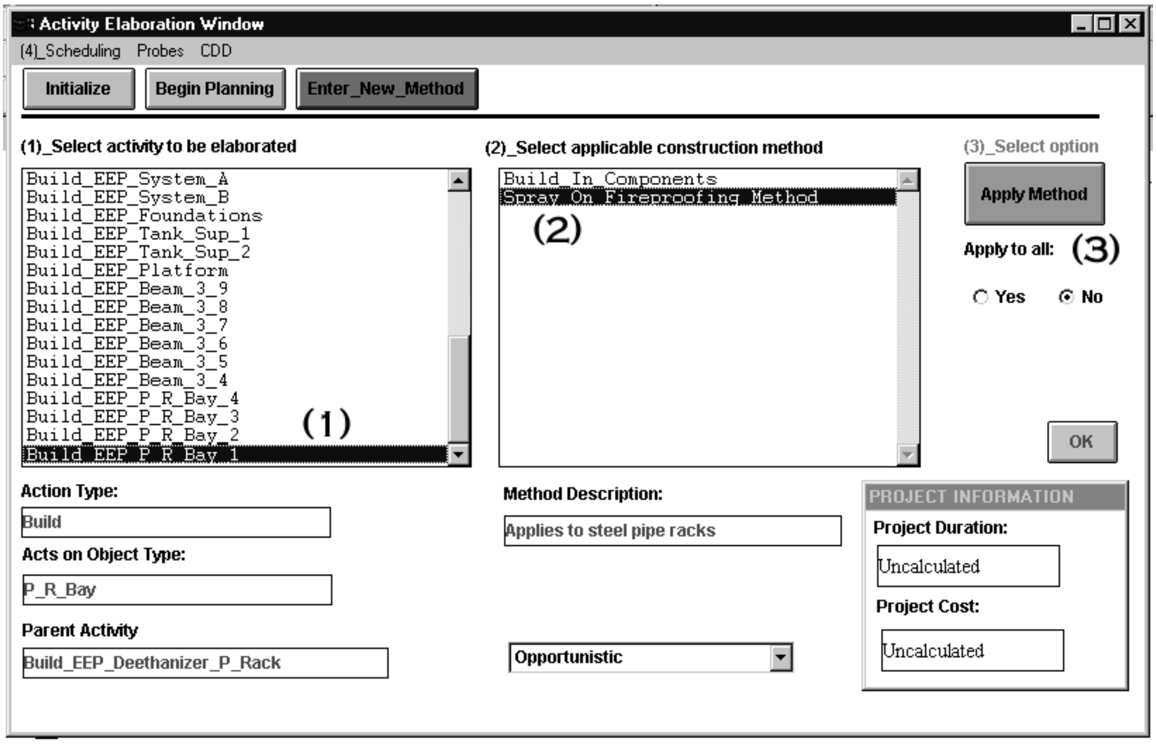

Figure 7. CMM's user interface that is used to elaborate activities in the process model into more detail. Above, the activity "Build PR_Bay1" is selected (1) and the spray-on fireproofing *method (2) is applied to it (3). CMM pre-selects the methods shown in list (2) in accordance with the <CA> attributes of the activity to be elaborated (the domain activity).*

The planners could now elaborate one of the new activities in the process model with a more specific method, e.g., create a more specific plan for preassembling the bay, or refine another activity, e.g., create a more detailed plan for the construction of the foundation. In our case, the planners have created all the activities necessary for the task at hand and asks CMM to sequence the activities and to display the resulting schedule as a 4D visualization (Figure 4). Using the sequencing knowledge each activity instance has inherited from its activity type in the CMMT, CMM creates the necessary sequencing links. E.g., it determines that the preassembly of Bay1 has no sequence constraints to the activities at hand and places it in parallel to the construction of the foundation. To sequence the activity "Erect_ PR_Bay1" it needs to resolve this activity's support constraint and its technology constraint. It goes to the Bay1 component in the product model to find out what provides physical support for Bay1. It finds that Footing 3 supports Bay1. However, there are no activities relating to Footing 3 in the process model. It then moves up one level in the product model to see whether there is an activity that acts at the system level. It finds out that Footings 3 is part of the Foundation. It finds the activity "Build_Foundation" and therefore makes "Build_Foundation" a predecessor to the "Erect_ PR_Bay1" activity. We have defined five mechanisms that formalize the knowledge required for CMM to resolve sequence constraints when activities in the process model act on components at different levels of detail in the product model. The resolution of the technical constraint for the "Erect_ PR_Bay1" activity is significantly more straightforward. The technology constraint <TC1> in the CMMT states that the bay cannot be erected until it has been preassembled. It finds the "Preassemble_PR_Bay1" activity and makes it a predecessor to the "Erect_ PR_Bay1" activity. CMM sequences the other activities in similar fashion using method knowledge and product model information.

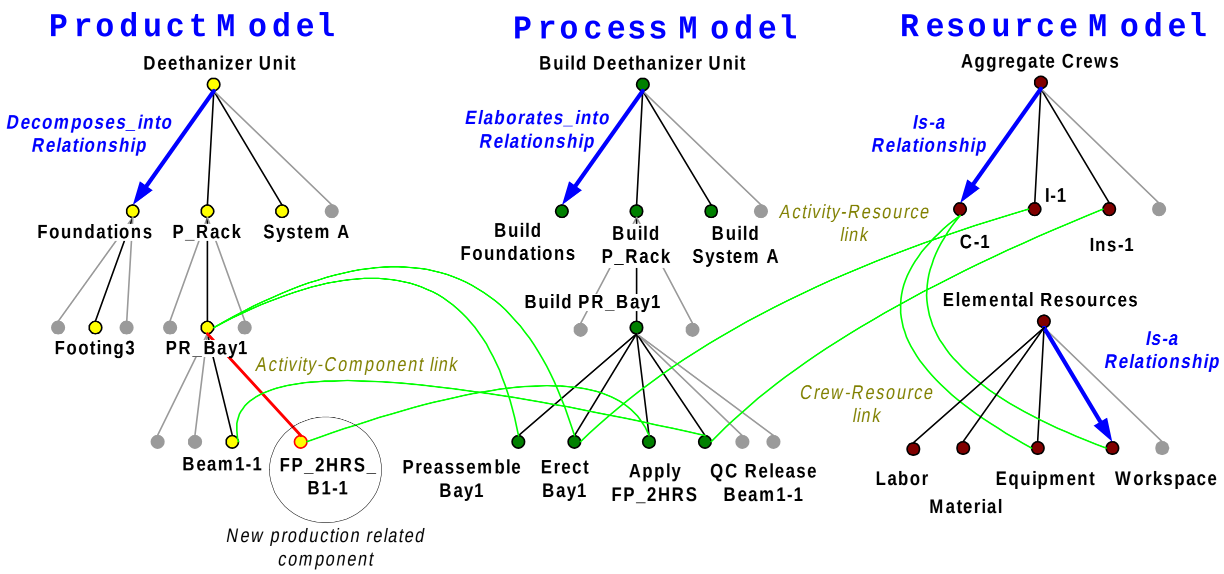

Figure 8. 4D production model after "Build PR_Bay1" is elaborated using the spray-on fireproofing *method. The spray-on fireproofing method invokes the transformation of the product model (addition of fireproofing).*

4D PRODUCTION MODEL

he result of a CMM session is a 4D production model. The 4D production model integrates the designer's and the builder's perspective in one model. CMM allows users to rapidly generate various production models based on design or construction method alternatives. The 4D production model integrates the product model that was adjusted according to the needs of the selected construction methods with the process model and the resource model. It provides the underlying information necessary to support the visualization of each design-build scenario as a 4D model, an activity network, a barchart, or a resource histogram.

IMPLEMENTATION

CMM was implemented in PowerModel™ (an object-oriented programming environment developed by Intellicorp in Mountain View, CA) on SUN Sparcstations running Solaris 3.4. A runtime version of CMM is available for the Windows 95 and NT 4.0 operating systems on PCs. Sample projects and web-based 4D production models generated by CMM can be viewed at http://www-leland.stanford.edu/~florian/florian.htm. So far we have modeled approximately 50 different construction methods and scheduled commercial and industrial projects with up to 3,000 components in the product model. CMM is able to read a product model in the STEP Part 21 format. Its output, the 4D production model, is also created as a file in Part 21 format. We are currently implementing a Java-based method modeler to allow participants in a construction project to capture construction method knowledge in CMMTs interactively on the web. We are also planning to apply CMM on an on-going construction project to test its scalability.

CONCLUSIONS

This paper shows how construction knowledge captured in computer-interpretable construction method model templates and predefined general activity sequencing and elaboration mechanisms support the rapid, user-driven generation of 4D production models. Activity-based method models drive the joint elaboration of the product and process models and customize the product model to the level of detail necessary for production planning. In the pre-construction phase, this gives planners a tool with which they can create multiple design-build scenarios rapidly. They can study the impact of a particular method selection for a detailed part of a project on the overall project schedule (in the case example, management rejected the resulting schedule and selected a different method that allowed for the QC release of the beams before the installation of the process systems). Hence, builders can become active participants in a computer-supported concurrent enginering effort. In the construction phase, CMM supports the rapid replanning of a schedule when changes occur on site. Planners can maintain a detailed, hierarchical schedule that can be used for tactical planning, but that is directly and dynamically tied to the strategic project schedule. We anticpate that the ability to maintain a detailed schedule that is linked to the master schedule and the ability to visualize projects quickly as 4D models will make project schedules more reliable and predictable and will ultimately lead to tighter and shorter schedules (Aalami, Haddad et al. 1997).

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