COST-LOADED PRODUCTION MODEL FOR PLANNING AND CONTROL

Cost-loaded production model

M. FISCHER and F. AALAMI
Department of Civil and Environmental Engineering, Stanford University, Stanford, USA
C. KUHNE and A. RIPBERGER
Institute for Tunneling and Construction Management, Technical University Munich, Munich, Germany

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Abstract

This paper describes a cost-loaded production model that supports integrated project planning, scheduling and estimating and real-time cost and schedule control. The production model integrates product, process, and resource information between all levels of detail and within each level of detail of construction management information. It describes and calculates project schedules and cost estimates explicitly at any level of detail desired by project participants. A hierarchical construction planning, scheduling, and estimating process and corresponding software prototypes assist the user in generating and updating the cost-loaded production model. The main contributions of this work are the consistent representation of component, action, resource, and sequence constraint objects at all levels of detail and the formal planning, scheduling, and estimating processes and mechanisms. These are the two essential components that make the cost-loaded production model possible. The production model enables construction managers to work from general project information to detailed project information, generate detailed what-if scenarios rapidly and control and manage a project's progress on a frequent and precise basis.

Keywords: Project planning, project control, product modeling, process modeling

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1 Introduction

"Was man nicht weiss, das eben brauchte man, und was man weiss, kann man nicht brauchen." (J. W. Goethe, Faust)

Loosely translated, Faust says: "What one does not know is exactly what one needs to know, and what one does know one cannot use." This quote reminds us of experiences on construction projects, where a lot of information about the project was available for crew and project management, but it seemed that we were always missing just the right information necessary to make a well-informed decision. Typically, someone created construction planning and cost estimating information to answer a specific question (e.g., what will be the overall project duration?). At a later time, someone else needed to answer a different question (e.g., how many laborers will we need next week and where will they work?) related to the first question. To answer such questions, we continuously needed to recreate information, aggregate detailed scope, cost, schedule information, and generate more detail as required by the decision at hand. Often, we would quickly make a plan, schedule, or cost estimate to answer a new question. For example, on one project, the project management team created over one thousand separate hand-made and paper-based three-week look-ahead schedules. The main problem is that construction planning and cost information exists in many different forms and places (in planners' minds, on paper, in computer files) and is neither integrated nor easily accessible.

Today, it is still common practice in the construction industry to view cost estimating, construction scheduling, detailed work planning, etc. as separate functions for project execution. The systems used for each function are simply not compatible, and their integration often creates additional work and data and increases the complexity of the project management system. Most proposed mapping schemes (Rasdorf and Abudayyeh 1987, KLR Bau 1990, Gehri 1992) only work in certain situations. The detailed underlying information and the estimating and scheduling assumptions are lost when, for example, detailed cost information is mapped onto cost control accounts and onto master schedule activities. It is difficult to show the interaction between cost and schedule, and to maintain an integrated scope-cost-schedule model when the project design or schedule changes. One can control the cost of concrete, e.g., but it is impossible to manage individual production processes proactively.

In this paper, we present a production model, which considers the needs of planners and builders and supports the creation of cost and schedule models that reflect the realities of project execution more closely than the approaches used in practice today. We propose an integrated planning and estimating process and a computer-interpretable model that support activity generation and sequencing and the estimation of material and time-dependent costs.

We are interested in understanding and modeling the production process of buildings. The production process consumes resources to create a product. The consumption of resources requires time and creates costs. Therefore, the production model integrates a product model, process model, and resource model. Since it models the relationships between product components, process activities, and material and labor resources it avoids the data redundancy found in the approaches used in practice. The hierarchical product, process, and resource models, in addition to the underlying coherent data structures, enable project participants to create individually designed views that focus on the information of interest to them. This paper gives an overview of this project planning and estimating system, summarizes the underlying information model, and contrasts the proposed model with others in the literature. It places particular emphasis on the cost elements of the production model. The work presented here was developed at Stanford University and at the Technical University of Munich. The group in Stanford focused on the construction planning side and developed the Construction Method Modeling (CMM) prototype. The group in Munich focused on time and cost control of construction projects and developed a prototype called POP (Process-Oriented Planning).

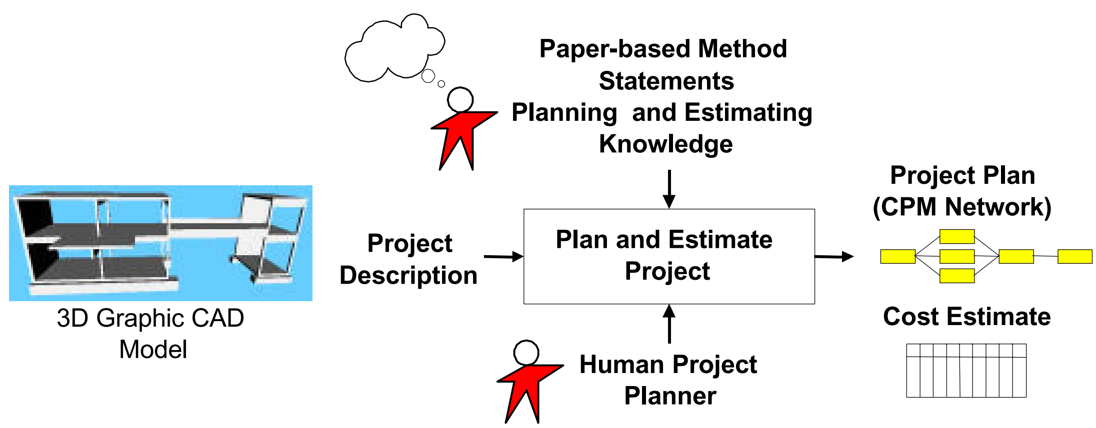
2 Production planning needs

Construction planning, scheduling, and cost estimating are important parts of any construction project. The planning and estimating process and the resulting construction plans, schedules and cost estimates need to support the following needs:

1. Inform project managers about *who* needs to do *what*, *when* and *where*, i.e., determine the *resources* <**R**> required for a particular *action* <**A**> on specific *components* <**C**> or set of components under certain *sequencing constraints* <**S**>.
2. Provide different project parties, e.g., owners, general contractors, and subcontractors, with <**C**> <**A**> <**R**> <**S**> entities and their relationships at the appropriate level of detail. For example, represent <**C**> entities at less detail for owners (e.g., buildings) than for subcontractors (e.g., temporary structures).
3. Support the rapid generation of alternative schedules and estimates based on the exploration of different design and construction method choices.
4. Rapidly estimate and re-estimate the costs for various sets of design and method choices to determine the most cost-effective allocation of resources. Related cost estimates need to be available at several levels of detail.
5. Provide the basis for project control to contrast budgets and target schedules with actual costs and schedules.

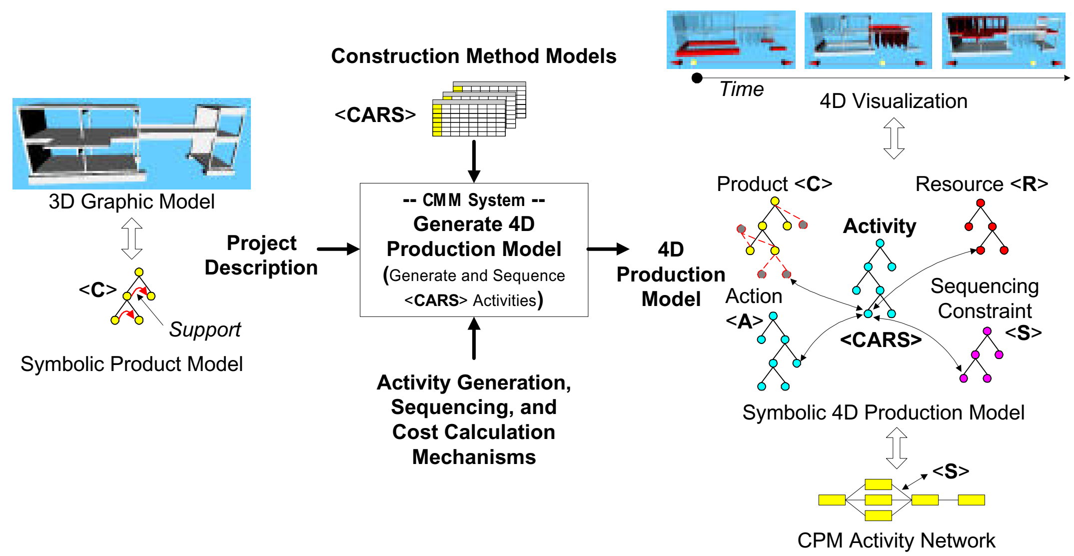
Today, planners base the generation of project plans and estimates on 2D or 3D drawings of a project (Figure 1.a). They use personal planning and estimating knowledge and construction method information to generate the necessary activities and estimate items manually. Software is essentially used to document the decisions and work of the planners and estimators. Typically, commercial project management tools represent schedules as Critical Path Method (CPM) networks and cost estimates in spreadsheets. The current project planning and estimating process and project management software do not address the five needs listed above. The main problems lie with the representation of the output and the planning process.

The output of current systems does not represent *who* does *what*, *when* and *where* in a formal and computer-interpretable way. Furthermore, cost estimates and schedules are usually not integrated, making it difficult to perform real-time progress control or to recalculate the cost of a project rapidly due to a schedule or method change. CPM tools allow planners to model activities with descriptive activity names (Build Foundation) and to associate sequencing relationships (Finish-Start [FS] to Build Wall), work quantities (concrete volume), and resource and cost information (Crew F-3 with its productivity rate) with each activity. With this information, a CPM system calculates activity durations and schedules the project. A planner then interprets the schedule to find out *who* does *what*, *when* and *where*. However, CPM systems represent each of the <**CARS**> entities of an activity as a name or value only. Therefore, a computer system cannot interpret and reason about <**CARS**> entities to support the planner in revising and updating activities and their relationships and costs. A planner must manually adjust a plan and estimate to reflect changes in design, construction method, or level of detail. Likewise, an estimating spreadsheet has descriptive names for estimating items but does not contain the information in a computer-interpretable way to support the planning needs listed above.



a) IDEF∅ diagram representing current project planning and estimating process

Fig. 1: Comparison of current and proposed planning and estimating processes. IDEF∅ diagrams representing project planning and estimating in current practice (a) and using CMM (b)



b) IDEF∅ diagram representing synthesis of 4D production model from a symbolic product model in CMM

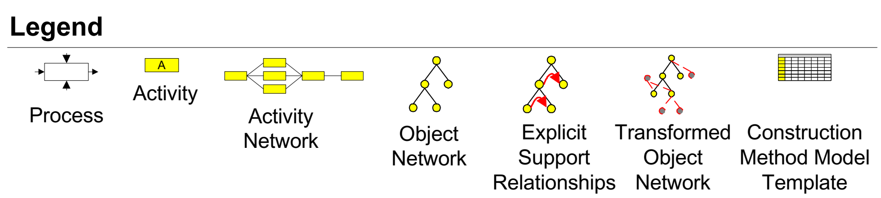


Fig. 1 (cont'd): Comparison of current and proposed planning and estimating processes. IDEF∅ diagrams representing project planning and estimating in current practice (a) and using CMM (b)

3 Related research and point of departure

Several other researchers have formalized an activity as a <**CAR**> tuple and used the <**CAR**> conceptualization to support the generation of activities (Navinchandra et al. 1988, Darwiche ET al. 1989, Jägbeck 1994, Dzeng and Tommelein, 1997). They use the <**CAR**> conceptualization to generate appropriate activities for each building component in a product model, to link component, action, and resource information, and to automate activity sequencing. However, prior construction planning prototypes do not maintain explicit objects for *components* <**C**>, *action* <**A**>, *resources* <**R**> and *sequencing constraints* <**S**> at all levels of detail in their product and process models. This makes it difficult to calculate and aggregate costs in a consistent manner on a project and from project to project.

Other researchers have described models that integrate the information necessary for construction management. Froese (1996) gives an excellent overview and discussion of these models. Typically, these models are based on the same classes of objects we have used for the cost-loaded production model (products, activities and resources). They also show the relationships between these construction objects (e.g., an activity uses a resource). Typically, they do not describe how the models will be populated with project-specific information, and how users will update and maintain an up-to-date scope, cost, and schedule model. Without such mechanisms it is, in our experience, almost impossible to enter and maintain the thousands of data items needed to manage a project at several levels of detail.

Building on the <**CAR**> abstraction and on the conceptual construction information models described in Froese (1996), we formalized a Construction Method Model Template (CMMT) that allows planners to model the activities required for a particular method (Aalami et al. 1998a). Planners define each activity in a CMMT with <**CARS**> entities. CMM implements a hierarchical method-driven planning process (Aalami 1998b). With CMM, planners can now generate detailed 4D production models from a product model by selecting and applying CMMTs (Figure 1.b). The input to CMM is a design version of a product model. CMM uses the planning information in the selected CMMTs and information in the product model to generate activities with explicit <**CARS**> entities automatically. The planner controls the levels of detail of the activities CMM generates. For this process we formalized four bodies of planning knowledge: activity elaboration knowledge, activity sequencing knowledge (Aalami et al. 1998c), product model transformation knowledge (Fischer et al. 1998), and cost estimating knowledge. This paper focuses on the essential elements necessary for cost estimating. Prior publications have focused on the planning and scheduling aspects (Fischer and Aalami 1996, Aalami and Fischer 1998).

CMM is implemented with PowerModel by Intellicorp (Mountain View, CA). We tested CMM on several construction projects to verify that it was able to generate production models (viewed as a CPM diagram or a 4D model) that are realistic. The largest test case was carried out in 1998 on a hospital project in Palo Alto, CA. Based on a product model describing over 3,000 steel components of the structural system for the hospital and based on steel erection method knowledge obtained from the steel erector, CMM planned the steel erection work correctly and automatically (Katz 1998).

4 Description of planning and estimating process and information models

Users generate and elaborate cost-loaded activities for the production model with the following planning and estimating steps (Figure 2). For a particular activity (e.g., Build Product at the beginning of planning or Build Wall Pos. 2 after some activities already exist), users choose the construction method they would like to apply by selecting the appropriate CMMT in the methods database. The CMMT knows what detailed activities are necessary to complete the original activity. Each detailed activity knows what component in the product model it acts on, what type of action it carries out, what crew and material resources it needs, what sequence constraints it has, and what one-time costs and productivity rate it has. With this knowledge and with the project-specific information in the product model, CMM generates the detailed activities in the production model (e.g., Place Concrete Wall Pos. 2). It calculates the activity duration by extracting the material quantity information from the product model following the ActsOnComponent relationship (1), by looking up the applicable productivity rate in the CMMT, and by using the duration calculation algorithm for the activity's action type (2). It then calculates the time-dependent costs by multiplying the duration with the crew unit costs stored in the resource library (3). It computes the material costs by multiplying the quantity information from the product model with the material unit cost in the resource library (4). It can now calculate an activity's total cost by summing the material and crew costs and adding eventual one-time costs (e.g., set-up costs) from the CMMT (5). The user can now look at the total project cost or at the cost of producing a particular portion because the system can roll up the activity costs to any desired level (6).

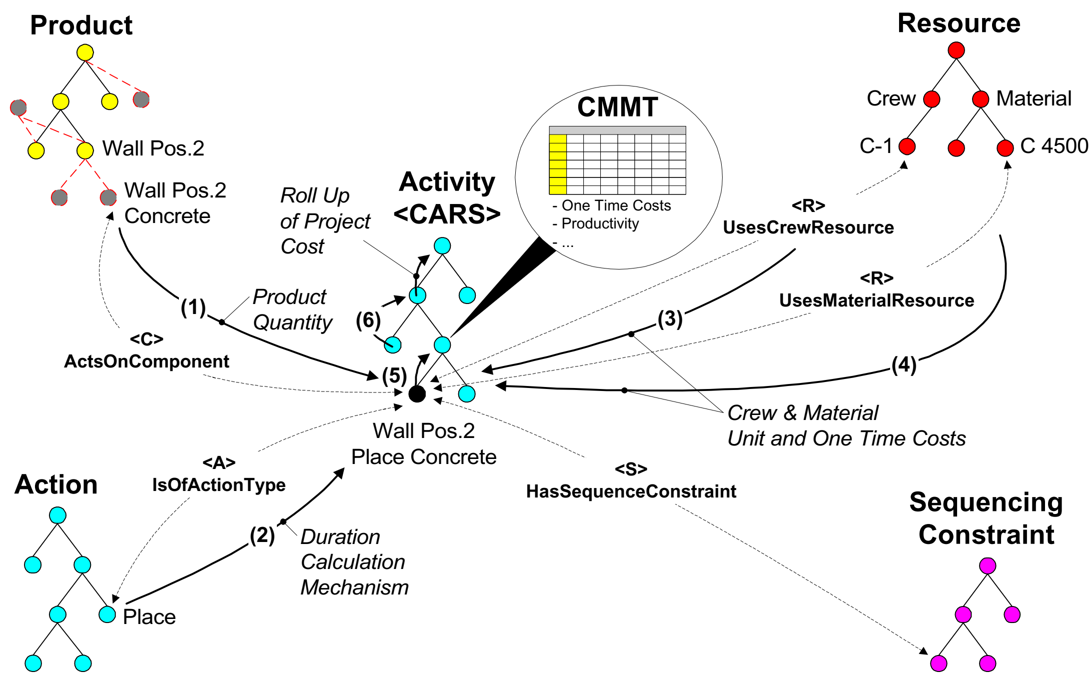


Fig. 2: Generation of cost-Loaded activities for production model

Table 1 illustrates the key attributes for an activity object. It contains the typical attributes one finds in scheduling software (only a few like duration, earliest start and finish are shown here). It contains the attributes necessary for the various types of cost described in the previous paragraph and includes the relations and methods that integrate the product, process, and resource models and calculate the costs of production. Note that this activity model supports an integrated production model that combines scope, cost, and schedule information. Software tools available on the market today only link some of these data items (Staub et al. 1998). For example, one can transfer the quantity information in a 3D CAD model into an estimating spreadsheet at one level of detail. This does not create an integrated production model where a user can generate cost-loaded activities that have explicit bi-directional links to product and resource objects at several levels of detail.

Table 1: Main attributes, relations, and methods of an activity

Activity		
Attributes:		Values:
Id:	LongInt	-
Name:	String	Wall Pos.2 Place Concrete
UnitOfMeasure:	String	M3
ProductQuantity	Extended	10
Duration:	Extended	1 [d]
EarliestStart:	String	01.09.99
EarliestFinish:	String	01.09.99
CrewProductivity:	Extended	1 [h/M3]
CrewUtilization:	Extended	100 [%]
CalculatedTotalCosts:	Extended	9600 [$]
AggregatedTotalCosts:	Extended	-
TimeDepCosts:	Extended	1600 [$]
QuantityDepCosts:	Extended	3000 [$]
OneTimeCosts:	Extended	5000 [$]
:		
Relations:		Values:
<C> ActsOnComponent:		Wall Pos.2 Concrete
<A> IsOfActionType:		Place
<R> UsesMaterialResource:		C 4500
<R> UsesCrewResource:		Crew Type C-1
<S> HasSequenceConstraint:		FS Wall Pos.2 Place Formwork
:		
Methods:		
(1) GetProductQuantity!		
(2) CalculateDuration!		
(3) GetCrewResourceUnitAndOneTimeCost!		
(4) GetMaterialResourceUnitAndOneTimeCost!		
(5) CalculateCost!		
(6) RollUpCost!		
:		

Once users have generated a cost-loaded production model with CMM, the production model can be transferred with an ISO 10303 Part 21 file (STEP Physical File or SPF) into POP (Process-Oriented Planning) developed at the Technical University of Munich (Kuhne et al. 1998a, 1998b). We coordinated the output from CMM and the project information needed in POP to allow users to generate the necessary planning information quickly and to explore several alternatives and update the production model rapidly. POP supports users in monitoring and controlling a construction project. By building on the hierarchical production model described above it supports the typical aggregations used for cost and schedule control while maintaining the original detailed information. This enables real-time cost and schedule control because the cost and schedule information is available at the level of detail and composition needed. The cost-loaded production model allows a user to construct any desired view of the scope, cost, and schedule information because the detailed production information is maintained, product, process, and resource information is integrated at all levels of detail, and each item of information knows from where it originated. POP was tested on a recent freeway project in Germany (Lippert 1999). With little additional effort for data entry (about 15 minutes per day) the site management team was able to monitor and control cost and schedule performance on a daily basis. Because of this real-time and integrated view of cost and schedule, the site management team was able to identify areas of concern while it was still possible to take corrective measures. This was possible because POP models the scope, cost, and schedule information at the level of detail at which site managers collect daily reports from foremen. With its aggregation mechanisms and with its detailed and integrated cost and schedule information, POP can quickly contrast actual cost and schedule data with planned or budgeted cost and schedule data at any desired level of detail.

5 Impact and significance

The production model proposed in this paper is a coherent model that integrates the main production information used to plan and manage a project. This information is grouped into compatible and related partial models describing the building product, the activities or production processes and the resources. This organization eliminates redundancy of scope, cost, and schedule information and allows construction managers to work with subsets of the production information as needed by a particular task while maintaining and using a consistent overall model. As other authors have also noted, the basic relationships between the production model objects are simple. However, the resulting model is highly complex system with a high connectivity between objects and attributes. It is unlikely that software tools will be able to maintain all of these relationships over the course of a project. However, as presented, computer tools can automate many of the routine data generation, integration, and calculation tasks. Our collaboration on this research project and our tests on site have also made it clear to us that information standards like the Industry Foundation Classes proposed by the International Alliance for Interoperability will greatly facilitate the practical use of such integrated information models.

Specifically, some potential benefits of this work for industry practice are:

- Availability of an integrated model that answers *who* does *what when* and *where* at multiple levels of detail
- Rapid generation of cost-loaded production models for different design and construction method alternatives
- Reuse of scheduling and estimating information as projects progress and planning and control needs change

- Availability of "intelligent" schedules and estimates where each activity knows *why* it exists, *how* it relates to other activities, and *how* it calculates its costs

The hierarchical method-driven planning process and the formalization of construction method, planning and estimating knowledge can potentially bridge the gap between site offices and the head office of construction firms. On many projects there is a disconnect between the information the project management team generates and the information generated by the site management team. This is a pity since the experience of field personnel is clearly needed to produce a realistic construction schedule and estimate. No tool exists, however, that allows field personnel to model their knowledge and use it to generate project schedules and estimates with computer software. Today, it is also impractical or maybe even impossible to generate and link plans, schedules, and estimates to the level of detail needed on site on a day-by-day basis. Hence, it is difficult to incorporate field knowledge into a plan useful at the project manager's level. As a result, today's master plans and schedules are often unrealistic and fail to predict activity start and end times and resource needs (Katz 1998). Crews may work on the wrong activities in the wrong areas, slowing overall project progress and increasing project cost.

Given that field personnel in construction are skilled enough to build complex facilities and based on our field tests, we believe that, with the appropriate tool, field personnel would be motivated and able to produce detailed schedules that link to the other schedules at their level of detail and to summary-level schedules. With CMM and POP, superintendents can build detailed cost-loaded production models instead of paper-based look-ahead schedules. Since a model at the day-to-day work level exists they can now match the progress data they already collect on a daily basis with a plan. This should greatly improve the assessment of project progress in a timely manner and simplify payment applications for completed work. They can use information on what happened today to plan tomorrow's work and understand the impact of changes in their scope of work on other disciplines and overall project completion and cost. They can rapidly explore the impact of changes in material and labor availability and study the effect of design changes. The cost-loaded production model also allows them to communicate a schedule as a visual 4D model which helps to identify interference between crews. In summary, CMM and POP help understand the impact of overall project decisions (e.g., a change in completion date) on day-to-day resource allocation and assist in showing the effect of day-to-day progress on overall project progress.

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