MODEL-BASED CONSTRUCTIBILITY ANALYSIS:

THE MOCA SYSTEM

Martin Fischer, Assistant Professor
and Florian Aalami, Graduate Research Assistant
Department of Civil Engineering, Stanford University
Stanford, CA 94305-4020, USA

Abstract

The recent years have seen the development of several knowledge-based scheduling systems that facilitate the integration of design information with the generation of construction schedules. They have demonstrated a remarkable progress over manual planning systems. For example, these systems are able to generate a set of activities from a project description and to reason about support and enclosure information to determine the sequencing of activities. In a research project sponsored by the Center of Integrated Facility Engineering (CIFE) at Stanford University, we extended the idea behind these planning and scheduling systems by adding detailed models of construction methods. Such knowledge is needed in model-based form to enhance the practicality of the schedules that are generated, and to overcome some of the limitations of heuristic systems. While the use of product models to represent design information has been well documented over the last few years, the formalization and implementation of detailed models of construction methods still represents a major challenge and opportunity. When interacting with a product model, such construction method models are able to generate construction schedules and cost estimates almost instantaneously. This will enable project participants to explore more alternatives to a greater level of detail in less time. This will lead to projects that are more constructible than some of today's projects. This in turn will lead to a reduced total delivery time and cost for constructed facilities. This paper describes the current status of the MOCA (Model-based Constructibility Analysis) system which uses formalized construction method models to automate the generation of schedules based on product models.

1 INTRODUCTION AND RELATED WORK

"The ideal virtual product or service is one that is produced instantaneously and customized in response to customer demand" Davidow and Malone write in their book "The Virtual Corporation" (Davidow and Malone 1992, p. 4). In construction, we are used to produce customized products. We are, however, still far away from instantaneously customizing them in response to customer demand. Market pressures on buyers of construction services, e.g., reductions in time-to-market for new products, will force the architecture-engineering-construction (AEC) industry to respond more rapidly to customer needs. This means that the time from conception to completion for a facility will have to decrease significantly. This will require changes in organizations, rethinking of work procedures, and improvements in technologies. Over the last few decades, significant productivity improvements of individual engineering tasks have been achieved through computer-based automation. In recent years, many researchers and practitioners have focused their efforts on integrating the data produced by these islands of automation (Harmon 1992) and on augmenting these computer applications with knowledge-based systems, e.g., (Sriram et al. 1989, Fenves et al. 1990, Gero 1990). These researchers have demonstrated that knowledge-based computer applications improve the decision support available to engineers. The advent of object-oriented software tools and model-based reasoning (Kunz et al. 1989) has further enhanced the usefulness of artificial intelligence tools to the engineering community. Object-oriented, model-based representations of engineering artifacts will likely be the representation of choice for engineering tools of the future (Gielingh and Tolman 1991, Froese 1992). In fact, such tools are already entering the market place (Levitt et al. 1991). Increased integration, powerful software paradigms, and the order-of-magnitude reduction in cost per computer cycle achieved every few years[1] will allow us to design and plan constructed facilities much faster than we can today. This increased speed will be a key component in achieving the rapid customization required in the future. To harness the full potential of these new tools, formal models of engineering processes must be developed and implemented. The research project described in this paper explores the application of model-based software tools to provide rapid feedback on the constructibility of a facility under design.

1.1 CONSTRUCTIBILITY IN THE DESIGN PROCESS

The importance of constructibility as a project objective (Tatum 1987) and its potential to improve cost effectiveness have long been recognized (CII 1986). The interrelationship between a product and its processes has also been noted, e.g., (Allen 1987). However, few systems exist that attempt to make constructibility input to design explicit and systematic. Some companies have established formal constructibility review processes. Researchers at CERL though have found that even with these processes constructibility input often comes too late to have a significant impact (Kirby et al. 1989). Some practitioners have summarized their constructibility knowledge (Anthony 1985, Boeke 1989), and industry associations publish guidelines with respect to the constructibility of structures, e.g., (CRSI 1988). Some researchers have built prototype systems that assess the constructibility of a proposed design alternative (Barone 1990, Fischer 1991). These systems generally use heuristics to represent constructibility knowledge and often base their reasoning on a geometrical model of the design (Fischer 1993). These heuristics provide rapid constructibility feedback on very specific design decisions. They do, however, not support an in-depth analysis of cost and schedule implications of these decisions. We must, therefore, be able to generate cost estimates and construction schedules from design information much more rapidly than today.

1.2 AUTOMATED GENERATION OF CONSTRUCTION SCHEDULES

"Based on a detailed study of job requirements, planning establishes what is to be done, how it is to be done, and the order in which it will proceed. A detailed time study of the resulting planning network is then conducted in the scheduling phase" (Clough and Sears 1991). In practice, scheduling is still a very manual tasks. Many software tools are available to represent, store, and manipulate schedule data. These tools are typically based on the Critical Path Method (Fondahl 1962) and automate all the scheduling calculations, e.g., Primavera. However, the data input for current scheduling programs is still largely a manual task. A scheduler must break down the project into appropriate areas or zones, define the necessary activities and sequence these activities. This requires an understanding of how construction methods relate to a design description. Commercial software tools can now manage this link between a design description in CAD format (ASG), estimating data (Timberline) and scheduling data (Primavera). Other tools provide a link between CAD data and a schedule to visualize the construction sequences (Cleveland 1992). However, the user must still manually specify the links for all these systems.

Several researchers have augmented scheduling environments with knowledge-based systems (Darwiche et al. 1989, Navinchandra et al. 1988, Waugh 1990, Zozaya-Gorostiza et al. 1990, Kartam and Levitt 1990, Cherneff et al. 1991, Echeverry et al. 1991). Kähkönen (1993) classified and characterized activity dependencies. Early successes of these efforts indicate that knowledge-based tools support automated generation of activities and sequencing of activities. These plan and schedule generators are usually linked to a model-based description of a design, but use only very basic construction knowledge to generate activities of the type "Build-Column1". They typically reason about topological relationships of design objects to sequence corresponding activities, e.g., schedule a column on the first floor before one on the second floor. They lack, however, the specific construction knowledge needed for realistic cost and schedule feedback.

To provide rapid and realistic constructibility feedback, we must, therefore, develop computer-based models that formalize construction planning, scheduling, and estimating for specific construction methods. Such construction method models will have to interact with design product models to automate the generation of plans, schedules, and estimates as much as possible and will have to lend themselves to be maintained and updated easily. These models could then perform an important role in the integration and automation of tasks in the project delivery process.

1.3 RESEARCH OBJECTIVES

Within the larger goal of formalizing construction process models, the research described here developed a prototype tool that demonstrates the feasibility of formalizing construction process models and the practicality of generating realistic project schedules through the interaction of such process models with product models. Specifically, our objectives were as follows:

- formalize knowledge and data about particular construction methods that is relevant for scheduling,
- represent these models in a computer system,
- develop the mechanisms that allow these models to create activities based on knowledge about a construction method and a description of a facility,
- develop mechanisms that sequence these activities,
- develop mechanisms that estimate the resource use and duration of individual activities,
- implement these mechanisms in a computer system, and
- test the prototype system on small sample facilities.

2 CURRENT STATUS OF MOCA

2.1 FORMALIZATION OF CONSTRUCTION METHODS

From previous research (Fischer 1991) and by observing industry practice, we realized that construction methods consist of a key technology or concept (e.g., a concrete placing method such as "pump concrete", a formwork system such as "slipform") and require a certain set of activities to be performed by one or several crews using some equipment. We also realized that some construction methods can be applied for a number of structural components (e.g., concrete can be pumped into columns, beams, slabs, and walls) and others can only be applied for one or two components (e.g., mainly walls—and to some extent columns—can be slipformed). Furthermore, construction methods are generally only applied for one type of material (e.g., cast-in-place concrete). Thus, to generate realistic construction schedules, we needed to represent all of these aspects of construction methods in symbolic models.

These models of construction methods allow the system to prompt the user (scheduler) to enter the various methods which he or she would like to use to build a given project. They give the user the flexibility to use different methods for different components (e.g., pump the concrete for slabs and use crane and buckets for placing concrete in columns). This allows a scheduler to generate a schedule for one set of construction methods and to compare it with the schedule for another set of methods in a matter of minutes. It should therefore enable a scheduler to explore a variety of construction approaches to a project and to give designers feedback on the constructibility of their designs.

It is also possible to change the description and level of detail for a certain method or to add a new method to MOCA. All the rules and methods that make use of the information in the databases used by MOCA have been written in a general way to allow the addition, deletion, inclusion, exclusions, and modification of methods, activities, and resources as desired by the user.

2.2 AUTOMATED GENERATION OF ACTIVITIES FROM A PRODUCT MODEL

The models of construction methods and the selection process by the user described in the previous section make it easy for the system to match the methods and their activities with the relevant components in the product model (the design). MOCA simply generates a list of the methods chosen for each type of structural component in the area of the project for which the system should produce a schedule (e.g., "pump beam") and generates the activities needed by a method to build the components.

2.3 AUTOMATED SEQUENCING OF ACTIVITIES

At this point, MOCA has determined what activities need to be carried out to complete a project. The next scheduling task now is to sequence these activities. Previous research, for example (Darwiche et al. 1989) has shown the usefulness of using the support relationships between components of a structure to sequence activities on lower story columns before activities on slabs that are supported by these columns. Since no previous research was available that uses explicit construction method knowledge for the sequencing of activities, we needed to find an approach to automate the sequencing of activities. After careful analysis we found that all activities can be grouped into three distinct categories based on two attributes: core activities, non-location specific auxiliary activities, and location-specific auxiliary activities.

First, an activity is either location-specific or non-location-specific, i.e., it needs to be performed at the location of the component it acts upon or it can be performed anywhere. For example, forms can be prefabricated anywhere, but they have to be placed at the location of the component (e.g., beam between gridlines D4 and D5).

Second, an activity is either a core activity or an auxiliary activity. While all activities need to be finished to complete a project, some activities are more essential to the sequencing of a project than others. For example, the placing of forms is essential ("core") to the construction of a component at a specific location, whereas stripping the forms is essential for the completion of the project, but—assuming, for the time being, no resource limitations—impacts the completion of a component and thus the sequence of activities to a lesser degree than placing of the forms. It is, therefore, an auxiliary activity.

For example, to complete a beam, the following activities might be needed: fabricate form, place form, fabricate reinforcement, place reinforcement, place concrete, strip forms, cure concrete, and vertical and horizontal finish of the concrete. Of these, fabricate forms and fabricate reinforcement are non-location-specific activities, i.e., they can be done anywhere. The other activities are location specific, i.e., they must be done at the location of the beam on the project. Some of these location-specific activities are more essential to establish the structural integrity (and thus the support for other components) than others. For example, vertical finish of the sides of a beam can be done after construction proceeds elsewhere; the same is true for "strip forms" which can—theoretically—happen anytime after the beam has cured[2]. The other activities (place form, place reinforcement, place concrete, horizontal finish[3], cure concrete) are essential in establishing the structural integrity of the beam. Structural integrity is needed to exploit the concept of supported-by relationships to sequence activities between various zones or construction areas (e.g., from floor 1 to floor 2).

To summarize, the addition of the two attributes (location specific vs. non-location specific, core vs. auxiliary) allows us to sequence activities derived from construction method models in a realistic way. MOCA first schedules core activities[4] for components in a zone and then inserts non-location-specific, auxiliary activities before the activities that depend on them (e.g., "fabricate form" before "place form") and inserts location-specific, auxiliary activities after the activities that they depend on (e.g., "strip form" after "cure concrete")[5].

We expect that other construction methods (e.g., for steel construction) can also be represented in this way to automate the generation of realistic schedules from a product model.

2.4 RESOURCE USE, DURATION AND COST CALCULATIONS

We represent the resources required for each activity and their production rate in a (simulated) database. From interviews with concrete subcontractors (e.g., with Peck & Hiller, Mountain View, CA) we found that production rates vary from crew to crew, from activity to activity, and from component to component. This requires a detailed breakdown of resource and productivity information in the database. For example, Crew C-20 is a crew that places concrete with a pump, and that places about 40 cubic yards of concrete per day for beams.[6] This information is used to calculate the duration for an activity in a construction area (zone).

We are currently implementing a cost estimating system that combines information from the product model (material quantities) with unit prices for materials to calculate material costs, and information from the schedule (activity and project duration and crews used) with daily costs for crews and supervision to calculate direct and indirect labor and equipment costs. This gives a more realistic cost estimate than current unit-price methods and integrates time and cost management (Rasdorf and Abudayyeh, 1991).

2.5 CURRENT IMPLEMENTATION

Currently, MOCA uses the concepts and ideas described above to generate a detailed construction schedule for small reinforced concrete structures. Given a product model and some user input about the use of construction methods, MOCA determines the construction activities required to complete a very simple project, sequences these activities, calculates the duration of individual activities, and performs CPM calculations. It, therefore, serves as a small proof-of-concept prototype for the goals and ideas outlined above. MOCA is implemented on top of Design++ and is linked to AutoCAD to visualize the geometry of the product model and to Primavera to visualize and manipulate the scheduling output.

3 CURRENT LIMITATIONS OF MOCA

The first phase of this research project has shown the potential of model-based construction planning and provides a starting point for the investigation of a number of additional aspects that are germane to the scheduling (and estimating) of construction projects. We are in the process of addressing all of these aspects in a second prototype.

3.1 MODELING DOMAIN AND TESTING

Currently, MOCA only deals with a few small structures. While we have verified our methodology by hand to replicate the generation of a construction schedule for a three-story, 600-car parking structure, we recognize the limited modeling domain with respect to components, construction methods, and types of structures, and thus the limited testing of our scheduling methodology.

3.2 ZONING CAPABILITIES

Currently, MOCA only deals with one zone (construction area). To be useful for practitioners, a system like MOCA must be able to handle several (user-defined) zones (Winstanley and Hoshi, 1992). This would require the addition of two functions to MOCA. First, a graphical interface to allow the user to define zones (e.g., by pointing, clicking, windowing in AutoCAD) needs to be implemented. Second, the system needs to know how to sequence activities from zone to zone.

3.3 MODELING OF RESOURCES

In its current version, MOCA uses production rates of resources to calculate activity durations and cost. MOCA assumes that there are enough resources to build the project as scheduled. However, as was shown by Waugh (1990), a schedule based on logic constraints, such as supported-by relationships, does most likely not allocate resources in the most economical fashion. Thus, resources need to be modeled more explicitly to give the user the ability to specify resource limitations and have the system consider these limitations when scheduling activities (without putting a logic dependency relationship between affected activities, though!) to arrive at a realistic schedule that considers the requirements of the structure (support), the requirements of construction methods, and limitations of resource usage with respect to the schedule. This would enable a project team to explore the costs and benefits of, e.g., doubling the amount of slab formwork available on a project.

4 SUMMARY OF MOCA

Using MOCA and given a symbolic product model of a design, users can rapidly develop a schedule and cost estimate for specific construction methods. They can then change the design or the method to study various alternatives in an integrated fashion. They can use pre-defined construction methods or define a construction method on the fly by aggregating crews and activities and sequencing the activities. Such a system allows users to evaluate constructibility rapidly with respect to schedule and cost advantages for particular methods and designs. These rapid feedback cycles in turn enable a project team to develop a project faster and more accurately.

So far, initial tests have confirmed the feasibility of this approach. Similar approaches have been reported in (Ikeda et al. 1991, Jin et al. 1992). Significant future research will be needed to explore the scale up of this approach and to gain a fundamental understanding of the underlying engineering processes in construction planning.

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[1] At a meeting of the Semiconductor Industry Association, John Young, former president and chief executive officer of Hewlett-Packard Company made the following prediction: "The cost of the computer cycle by the end of the decade will be about one-hundredth of what it is today. This is going to change in very fundamental ways how we organize information and how we work" [Young 1992].

[2] Of course, because of resource requirements, contractors are usually interested in stripping forms as soon as possible. As stated by John Fondahl (1962), such resource requirements should, however, not impact the logic sequencing of activities.

[3] We assume that the beam is part of a beam-slab system and thus requires horizontal finish of the top of the beam. As pointed out earlier, the inclusion or exclusion of such activities is left to the discretion of the scheduler.

[4] Note that core activities are always location specific.

[5] It is interesting to note that non-location-specific activities are always auxiliary activities that precede core activities (that is the nature of construction, we suppose) and that auxiliary, location-specific activities always follow the core activities that they depend on.

[6] The actual numbers used might not be realistic at this point, but could be adjusted quite readily to reflect actual project data. Note also that productivity information at this detail is easily obtainable from daily job reports.

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