CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Construction Planning and Manageability Prediction

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SUMMARY
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Title: Construction Planning and Manageability Prediction

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1. Abstract:

The Construction Planning and Manageability Prediction (CM) System builds a master plan and schedule that explicitly represent planned construction methods and resource utilization. The system simulates the schedule and identifies potential resource bottlenecks and material handling difficulties. An automated diagnosis procedure analyzes the simulation results to identify potential risk factors in the plan and schedule and to help a project manager to assess project manageability. This paper also discusses the results of simulating some aspects of a real construction project. Low management influence in a given time span appears to cause later low manageability. Furthermore, simulation results show that the number of problems increases after periods of low management influence and decreases after periods of high management influence.

2. Subject:

• What is the report about in laymen's terms? This report describes a computer technique for assessing ease or difficulty of managing a proposed construction project.

• What are the key ideas or concepts investigated? Construction CAD models, planning, scheduling, resources, risks and ease of construction management.

• What is the essential message? The research suggests that computer tools can give early insight into management risks associated with a given master plan.

3. Objectives/Benefits:

• What benefits does the research have to CIFE members? The research suggests that computer tools can give early insight into management risks associated with a given master plan. It shows the use of symbolic modeling in the analysis tools.

• What is the motivation for pursuing the research? Help add "manageability" as an issue to consider in master planning.

• What did the research attempt to prove/disprove or explore? The research tested the idea that computer tools can give early insight into management risks associated with a given master plan.

4. Methodology:

• How was the research conducted? Symbolic model with simulation; field observation for validation.

• Did the investigation involve case studies, computer models, or some other method? Case studies included a simple one built on Takenaka experience and a more detailed one based on experience of a CIFE member. Computer models were build.

5. Results:

• What are the major findings of the investigation? The research suggests that computer tools can give early insight into management risks associated with a given master plan.

• What outputs were generated (software, other reports, video, other): a computer system, report, video

6. Research Status:

• What is the status of the research? Ongoing at Takenaka

• What is the logical next step? Extensions using a more detailed test case.

• Are the results ready to be applied or do they need further development? Need further development

• What additional efforts are required before this research could be applied? Model extension and validation.

Construction Planning and Manageability Prediction

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Table of Contents

Abstract

Engineers now routinely use planning tools to prepare and document master plans. However, the tools do not evaluate plan feasibility or how easy or difficult plans will be to perform, i.e., their manageability. Further, engineers do not carefully evaluate plan feasibility and manageability because of time and resource limitations during pre-construction design and planning. Thus, construction managers often encounter unanticipated problems during construction and startup. Such problems might be avoided by changes in design, building methods or the master construction plan. The Construction Planning and Manageability Prediction (CM) System builds a master plan and schedule that explicitly represent planned construction methods and resource utilization. The system simulates the schedule and identifies potential resource bottlenecks and material handling difficulties. An automated diagnosis procedure analyzes the simulation results to identify potential risk factors in the plan and schedule and to help a project manager to assess project manageability. This paper also discusses the results of simulating some aspects of a real construction project. Low management influence in a given time span appears to cause later low manageability. Furthermore, simulation results show that the number of problems increases after periods of low management influence and decreases after periods of high management influence. We infer that the project status at any time depends on a balance between the severity of the problems and the influence of management. The research suggests that computer tools can give early insight into management risks associated with a given master plan. Future project managers will use extensions of these computer tools to identify design, construction methods and planning assumptions that lead to manageability problems.

1 Introduction

1.1 Background

For many years, civil engineers have developed project designs, plans, schedules and cost estimates and then used these products of the pre-construction phase to guide project construction and startup. In practice, designs and plans rarely include explicit assessments of how easy or difficult they will be to perform, i.e., their manageability. This research demonstrates the potential of using computer tools to build construction plans and schedules automatically, and to assess the manageability of a planned project, given its design, construction plan and schedule. This manageability assessment would be done during the pre-construction phase, so an engineer could change the design, plan or schedule to improve manageability. To clients, quick planning and early analysis of manageability should lead to better anticipation and management of construction problems. Better management anticipation should in turn lead to a higher likelihood that projects complete on-time, on-budget, with higher quality for users, and with higher profit for all involved.

[Fischer] reports work in Civil Engineering to predict the constructability of a design. Levitt and Kunz [Levitt 85] discussed a technique for changing the predicted durations of planned future activities if certain risk factors applied to one activity and there was reason to expect that the risk factor would continue to affect subsequent activities.

Careful pre-construction master planning and scheduling are prerequisites to later success in the construction phase. Ideally, the planning and scheduling processes will produce plans (sequences of activities) and schedules (sets of activities that have assigned start times, durations and resources) that builders can execute effectively. A good project manager can identify potential risk factors of a plan and schedule: conditions that might go wrong during construction and cause problems with successful project execution. For example, the manager might suggest that changing staff levels cause coordination requirements that may be difficult to meet and that, if not met, will lead to delays in activity completion; significant site space constraints may cause problems; use of novel construction methods or equipment may be difficult. Such risk factors have causes: basic properties of resources and activities. They have potential effects: increases in activity durations and requirement for additional training, setup or coordination activities.

Successful construction master planning produces plans and schedules that are both feasible and reliable. Feasibility is largely a technical issue: given a building plan and a set of construction methods and resources, a builder can (or cannot) build a plan. Reliability is largely a management issue. It describes the predictability of a plan, or its susceptibility to being adversely affected by the risks that inevitably occur. Reliability is the basic issue of our research on manageability.

Highly reliable, or manageable, projects have few unexpected problems that construction managers must solve after construction starts. Unreliable projects are at risk of not making due date, cost, quality or safety objectives. An unreliable schedule might require management attention to try to level swings of resource levels, simplify complicated material movement, facilitate safety, or improve relatively inefficient resource utilization. While we do not have quantitative survey evidence, it is our experience and impression that most projects have relatively large numbers of unanticipated problems concerning timely availability of resources, ability to manage materials and resources safely, quickly and effectively, and finding workarounds for incomplete or erroneous or suboptimal designs[3]. Project managers spend large amounts of time "fighting fires" and rather less administering a planned routine.

This project will lead to definitions of risk factors that affect project reliability and theories of how to assess their presence. We hope that these definitions and theories will lead ultimately to procedures and tools that will help project managers to control their construction projects more successfully because they will have more reliable construction management plans.

1.2 Objectives

Construction managers and engineers must consider so many factors in making a master plan and schedule that the work may be incomplete and include errors, even after significant investment of time. The difficulty of building feasible and reliability plans led us to the following two major objectives:

- *Help automate the master planning and scheduling processes.* Our conjecture is that computer tools will help human planners to produce feasible plans and schedules faster and more consistently.
- *Improve master planing and scheduling reliability.* Our conjecture is that carefully conceived computer tools will help human planners to produce plans and schedules that more consistently consider issues such as constructability, safety, effective resource movement, and impact of construction on neighbors. We want to identify specific risk factors in construction, to formalize procedures to identify them, to identify their causes and potential effects on activity and project reliability, and to identify specific activities in plans and schedules that these risk factors could affect if they are active during construction. The theory should produce procedures to assess plan reliability and feasibility and to identify specific issues that may make plans unreliable.

This project is a research activity because of the current lack of planning and operational theories and proven standard practice for assessing construction risks. In addition, there is a lack of effective tools to make feasible construction plans and schedules automatically and to assess risks in construction plans and schedules for manageability.

The processes of planning and scheduling are well-established in both practice and theory, comparing to the process of diagnosis. Our specific purpose in this research is to formalize risk factors, their fundamental causes and possible effects, and the process of identifying them.

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3 The first author has a number of years as an on-site project manager.

To meet these objectives, we (1) formulated a detailed theory of master planning and scheduling, including definition of risk factors and a description of their potential effects on construction outcome; (2) implemented the theory in the computer; (3) tested the theory using realistic test cases.

1.3 A force field metaphor

A force field is a suggestive metaphor for the process of project management. Managers and engineers exert a control force to push a project along a planned trajectory toward a goal. There is always an opposing problem force (sometimes named "Murphy") that pushes against the control force. The balance of the control and problem forces will determine construction project progress. An assumption behind our work is that a control force is more likely to be effective when it can predict the opposing problem force.

It is very common to have many problems during a construction project, even given a feasible plan: the problem force always seems to operate. For instance, workers may not come on time because of poor cooperation or reluctance to work with an unfamiliar subcontractor, especially during uncomfortable weather. Sometimes there is need to use low skilled or poorly motivated teams, even though their expected work safety, duration or quality is less than desired.

In this research, manageability describes the ease of executing of a project plan. Manageability describes how easy or hard is it for the project team to follow a feasible plan.

1.4 Scope

Figure 1 shows a schematic representation of the process of pre-construction master planning. Using project and design information, project planners use engineering knowledge to plan construction methods, create a construction plan, and build a schedule. They then attempt to predict potential problems and assess project manageability.

Normally, busy engineers use corporate experience and standard methods such as CPM to do method planning, construction planning and scheduling. Manageability assessment, if done at all, is informal. Thus, the assessment made at planning time will include implicit assumptions, for example about design rationale, that are not usually passed explicitly to the field construction manager.

Project information used in objective setting includes:

- Financial, physical, regional, social and other environmental conditions and objectives that characterize the local building environment.

Design information used in planing and scheduling includes:

- 3D CAD design or, more typically, 2D plan, elevation and section drawings;
- Facility requirements, some of which are explicit such as space volumes and requirements for functional performance. The reasons for many requirements are, however, normally implicit.

Manageability analysis is also normally implicit in the mind of a project manager, and again managers rarely perform it explicitly because of lack of theory, time and tools.

The Construction Planning and Manageability Prediction (CM) System builds a master plan and schedule that explicitly represent planned construction methods and resource utilization. The system simulates the schedule and identifies potential resource bottlenecks and material handling difficulties. An automated diagnosis procedure analyzes the simulation results to identify potential risk factors in the plan and schedule and to help a project manager to assess project manageability..

Figure 2 shows the CM system logic flow. The system implements six steps as follows:

- Build symbolic model: Given a 3D CAD model, the CM system builds a symbolic conceptual building model that describes the features in the facility, i.e., geometric forms, (e.g., columns, beams), relationships among features (e.g., Supports, Surrounded-By). The geometric model defines some simple attributes (e.g., dimensions of lines). Since they are not now necessary for symbolic reasoning, they are not now imported into the symbolic model.
- Methods Planning: infer activities and resources needed for construction of the designed building.
- Process Planning: infer precedence relationships among inferred activities.
- Scheduling: builds a scheduling chart based on the results of planning phases.
- Problem Simulation: simulate problem occurrence on the planned project.
- Manageability Analysis: analyze each activity and identify conditions that will make the activity easy or difficult to perform.

The implementation of the CM system assumes the following limits:

- Small buildings that have 2 or 3 above-ground floors;
- Building methods now consider only basic framing work, including required temporary work such as creating forms. The system now does not consider any other work, such as finish or underground work or design and construction of functional systems such as HVAC.
- Use of a common structural system: (e.g., Steel, Reinforced Concrete, Steel Reinforced Concrete);
- Common site and project conditions;
- Conceptual 3D CAD design: the system does not now handle design details.

A test case for this research is a small apartment building that has two floors, as shown in Figure 3. This figure shows an example test case that we used for system validation, including a CAD drawing of the simple building and part of the description of the corresponding symbolic model that was built automatically by interpreting the 3D CAD model.

2 Construction Planning and Scheduling

This section describes the first four steps performed by the CM system, i.e., building design through scheduling. The next section describes the simulation and manageability analysis.

The CM system includes symbolic models of both the building to be built and the processes of master planning and manageability analysis. These symbolic models have explicit representations of form, function and behavior, based on the approach to symbolic modeling described in [Kunz]. Section 5, Discussion, describes the knowledge representation of these models in more detail. This section introduces the model.

Form describes the basic conceptual elements of a model. In this project, the form of the building includes geometric forms such as beams and columns, and relationships among these building elements such as *Supports* and *WorksWith*[4]. The form of the master planning and manageability analysis includes conceptual entities in project management, such as activities and risk factors. Activities have standard CPM predecessor/successor relationships. In addition, they have a *SupportingActivity* relationship to identify necessary support activities. For instance, "Erect framing steel activity" has "Maintain cranes activity" as a *SupportingActivity*.

Functions describe the intent of designers in using specific forms. In the case of the building, the function is simply to provide space. Other possible functions include maintaining particular temperature and lighting levels, resisting lateral and gravity loads, and providing access to allow occupants to move from one space to another. In the case of master planning and scheduling, functions include various activities as summarized in Table 1.

Behavior describes the way in which forms actually behave, or their physics. Behavior normally includes the way in which form elements are intended to behave, given their functions, and it may include additional behaviors that might be benign, beneficial or undesirable. In the CM system, resources have behavioral attributes, including descriptions of the way in which they may or may not perform intended activities as planned.

In the Artificial Intelligence literature, the term "structure" is often used to describe what we mean by form; we choose the latter term to avoid confusion with the former term that has specific meaning in structural engineering.

2.1 Building Design

Construction planning requires understanding the building elements of a design, such as the beams, columns, slabs, walls. In addition, each of these elements has properties such as dimensions, features, material, and construction method. Finally, these elements have relationships with each other, such as "Supported by"

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[4] We use italics to indicate relationship names used in a symbolic model.

and "Surrounded by." Typical CAD systems use very simple graphic primitives (e.g., extruded rectangles). These simple primitives must be interpreted to identify the higher level components to be constructed, such as walls and beams, and to identify the properties and relationships of each physical element. The first step in the CM system, as shown in Figure 2, is Building Design. It involves creating a 3D CAD model of a building and identifying the structural engineering and construction features in the drawing.

The prototype CM system now includes slabs, beams and columns as building features because these features are used directly in construction. Later extensions will include walls, windows, footings, etc. The CM system now shows a menu of features to the AutoCAD user, and currently the user manually interprets selected graphic elements as an instance of one or more of the predefined construction features. Automated feature interpretation, while potentially valuable, was outside the scope of this project.

In addition to interpreting construction features in a graphic building model, the user also identifies the structural engineering features of the building model. Thus, a user might interpret a particular column as a steel (S), a reinforced concrete (RC), or as a steel and reinforced concrete (SRC) structure.

2.2 Construction Methods Planning

The second step in the CM system, as shown in Figure 2, is Construction Methods Planning. It involves selecting the methods to use to construct each construction element and then identifying the construction materials, resources and activities.

The CM system now considers three kinds of construction methods:

- Building Method, e.g., steel or reinforced concrete structures;
- Process Method: Precedence of construction steps, e.g., jointless[5] or floor-by-floor construction;
- Production Method: Means of constructing each building object or part, e.g., use of prefabricated concrete or site-built methods.

The CM system infers applicable methods for each building feature to be constructed. When multiple methods are possible, the user selects a preferred method.

The CM system infers activities and resources the following way.

- Identify building materials needed to construct each building object, given chosen construction methods. (For instance, use of the Steel Reinforced Concrete (SRC) structural system leads to need for framing steel, reinforcing bars and concrete.)
- Identify subsidiary materials required by the main materials and methods. (For instance, forms are subsidiary resources of concrete that is placed using a cast-in-place method.)

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[5] Jointless columns reach the entire building height. A jointed method, such as floor-by-floor, is appropriate for large and some shorter buildings. It requires joining shorter columns.

- Identify activities required to place main materials. (Main materials require activities to place themselves.)
- Activities required to place and remove subsidiary materials. (Subsidiary materials, e.g., forms and scaffolds, require activities to place and remove themselves.)
- Infer "works with" and its inverse, "works for," relationships among activities. For example, an activity to place elevated objects or resources also requires an activity to place scaffolding. A place-scaffold activity WorksFor some associated place-object activities, and they in turn *WorkWith* the place-scaffold activity.

The CM system includes descriptions of building objects, any of which may require other building objects. Starting with these building object descriptions, the system generates resource and activity requirements recursively. For example, a building requires a column that requires concrete that requires a form and form erection. Eventually, CM generates all activities and resources needed for construction of a designed building. The CM system calculates activity durations based on unit times (e.g., time to pour a yard of concrete) and the volume of each building object being processed by an activity.

In the CM system, construction planning activities include providing resources, site maintenance, placing and removing temporary resources such as scaffolding, external coordination, and actual construction activity.

2.3 Process Planning

Process planning, the third step in the CM step as shown in Figure 2, involves creating the precedence relationships among the activities to perform in construction. The CM system uses the OARPLAN planner [Darwiche]. OARPLAN uses two basic intuitions:

- Actions build Objects using Resources. Thus, activities are defined as action-object-resource triples.
- The planner uses basic engineering relationships to sequence activities. For example, if one object supports another, then one activity places the first object, and a successor activity places the second object. Normally, these ordering relationships are implicit in a design.

CM infers predecessor activities of generated activities using structural constraints such as the *"SupportedBy"* structural relationship and physical constraints such as the *"SurroundedBy"* physical relationship. For instance:

- Activities that place objects on the first floor are predecessors of the second floor activities because second floor objects are supported by first floor objects;
- Column placement activities are predecessors of beam placement activities when a beam is supported by a column.
- For a SRC structure, reinforcing bars surround framing steel, and concrete surrounds the reinforcing bars in a SRC column. Thus, activities that erect framing steel have precedence over activities that place reinforcing bars, and those activities have precedence over activities that pour concrete.

CM infers a precedence for some activities by considering their role as placing a subsidiary material or providing a supporting activity. For instance,

- Placing forms is a predecessor of placing concrete because forms are subsidiary materials required by concrete.
- Removing forms is a successor of placing concrete.
- Placing scaffold is a predecessor of placing reinforcing bars because the activity placing reinforcing bars works with a supporting activity managing scaffold.

Figure 4 shows the way that the planner infers plan activity precedence using the *SupportedBy* structural relationship. Thus, step 1 of this figure assumes a floor-by-floor construction method in which the first floor construction precedes second floor construction ("1F -> 2F") because upper floors are supported by lower floors. Columns are also constructed before beams ("Column -> Beam") because beams are supported by columns. The planner assigns precedence relationships among all activities based on the *SupportedBy* structural relationship of the objects associated with the activities. Step 2 of this figure shows use of the *SurroundedBy* physical relationship. The planner assigns precedence to activities that place framing steel over activities that place reinforcing bar, based on the *SurroundedBy* relationship between framing steel and reinforcing bar. Then, as suggested in step 3 of the figure, the planner assigns appropriate precedence relationships to activities that place and remove subsidiary resources such as forms, based on the *SurroundedBy* relationship. Finally, as suggested in step 4 of the figure, the planner assigns appropriate precedence relationships to supporting activities that support the activities for both main and subsidiary materials, based on the *WorkWith* relationships.

2.4 Scheduling

Scheduling, the fourth step in the CM step as shown in Figure 2, uses the CPM algorithm to create a schedule for the construction activities. A Gantt chart displays the schedule. Users can change activity durations interactively on the schedule chart, such as the one shown in Figure 8, and it automatically updates dependent activity start and end times.

2.5 Case Example

We used the design of a small apartment house as a test case, as shown in Figure 3. We chose a Jointless method as a construction process, so in Figure 8, the plan and schedule first do all the framing steel work, followed by a set of activities to place forms and concrete for each floor. The project finishes after removing all forms and scaffolds. CM system built a feasible project plan and schedule as the result of planning phase, according to the design of the building, and the user's choice for construction methods.

3 Manageability Diagnosis

Section 1 discussed the necessity of manageability diagnosis for successful construction management. Section 2 discussed the steps performed by the CM system that set up the input to the manageability analysis. This section discusses the mechanism by which risks become management problems, and it develops a theory to predict the manageability of a planned construction project, given its design, plans and schedule.

3.1 Generic causes of risks

Figure 6 lists some kinds of construction site risks. Inexperienced construction engineers often have not developed the skill to anticipate and manage these risks consistently and effectively. Highly skilled managers and engineers seem to formalize their specific experiences, such as those shown in this figure, into more general categories of knowledge, and eventually, to anticipate potential problems in projects and to make plans to avoid them.

We categorized a relatively large number of risks, such as those shown in Figure 6, into the set of five categories shown below.

- Mistakes, e.g.,
    - Mistake of manufacturing of <framing steel>
    - Incorrect placement of <framing steel>
    - Incorrect position of <anchor bolts>
- Low quality, e.g.,
    - Low quality of <framing steel>
    - Inaccurate <framing steel> placement during erection
- Conditions that enable other risks, e.g.,
    - Impossible to deliver <framing steel products>
    - Impossible to set <steel beams>
- Accidents, e.g.,
    - Workers fall when <erecting framing steel>
    - Collapse of <frame> during <erection>
- Scarcity, e.g.,
    - Project delay caused by lack of <labor>
    - Project delay caused by lack of <material>

A problem such as "Incorrect placement of framing steel" might have the same root causes as a problem "Incorrect position of anchor bolts": inaccuracy of human action and difficulty of the work.

After extensive consideration of the causal mechanism of specific construction problems such as those shown in Figure 6, we propose that there is a cascade of effects by which general behavioral properties of resources can sometimes lead to actual occurrence of problems. Figure 5 shows our description of this problem cascade.

- Essential Attributes are basic properties of resources and actions. These attributes may lead either to positive or negative outcomes. For example, the

CM model assumes that skill and dedication are essential attributes of workers. However, inexperience and general unwillingness to cooperate are also essential attributes of workers. Either may be active in any activity. Inaccuracy of human action is an essential attribute of human workers; all but the most highly skilled and most focused workers have a possibility of doing work that sometimes is, to some degree, inaccurate. Another example is the difficulty of performing accurate work repeatedly. All human workers have this essential attribute.

- Generic Hazards are the most generic causes of specific risks of an activity that involves use of a resource to perform a specific action. Generic hazards can be caused by essential attributes that are active in a particular situation.
- Risk factors are specific situations concerning supporting activities that, if unchecked, may lead to project problems. Carefully developed procedures or explicit management attention sometimes can prevent risk factors from causing problems.
- Problems are situations concerning construction activities that delay project progress.

The CM model activates essential attributes when an a resource attempts to work against some inevitable physical or organizational force. For example, a framing steel column, even one that is long and heavy, will not fall if it is not erected. To erect a steel column is an action against the law of gravity. To erect a long and heavy steel column with a careless worker is dangerous.

If workers must place many similar framing steel pieces in exactly correct positions, the "difficulty of performing accurate work repeatedly" essential attribute will cause a generic hazard to the success of a framing activity and thus to the overall construction project. The latent hazard becomes an actual risk factor that may lead to a problem if specific management effort does not provide adequate worker training, strong motivation, and careful measurement and review of work accuracy.

Workers' essential attributes compete with each other to determine whether generic hazards emerge. For example, many workers are both motivated to do good work and are easily distracted from doing quality work quickly. Thus, when a worker is careful, there is little risk and no problem if the work is very simple and the site conditions uncomplicated. There may be a problem when a careless worker does delicate work or a careful worker must work in bad weather or work while tired.

The problem cascade shows the potential ways that management activity may be able to block the cascade of effects from hazards to problems. The CM system simulates the sequence of activity completion. The manageability analysis shows each place in the activity schedule there is an opportunity to exert management control force to reduce the likelihood of hazards becoming problems. Those times when the need for management attention is greatest are the times when the project is most likely go to out of control: without management attention, generic hazards quickly become real problems.

Our experience has shown that "changes in site situations" have the largest impact on the control force available to managers. Management must manage change on construction sites. These changes include the changes of activities from one to another, departure and arrival of work teams, shift in work places, and changes in organization, design, plan, weather, etc. Changes of site situation cause increased management load and thereby increase the possibility that risks will lead to problems. Therefore, if we could plan a construction project so that it has small changes in all factors over the entire project duration, the project might go well without problems. Factory operations are generally more stable than construction. To make construction sites more like factories would be an effective way to reduce problems. However, construction projects always have changes because progress implies that activities are constantly starting and finishing.

As an example, Figure 5 shows the problem cascade for one potential problem for an activity that involves placement of framing steel. Resources and actions have essential attributes (note that the site is a resource in most activities); resources have generic hazards and risk factors; activities have problems.

3.2 Problem Simulation

Simulation, the fifth step in the CM step as shown in Figure 2, involves considering each activity in the construction schedule, identifying risk factors that may be present with the activity, and describing the causes and possible effects of those risks.

The CM system simulates possible activity behavior to identify the problems that activities can encounter and to identify the associated need for management effort to minimize problem likelihood and severity. The simulator uses heuristics to identify problems that might occur with each activity. Heuristics consider the following issues:

- Essential attributes of resources and activities; the CM simulator checks all essential attributes of all resources in all activities that work in a planned project at each diagnosis time. The simulator activates the essential attribute of an activity if an essential activity and its enabling physical action are both present in the activity.
- Size of each activity component [problem likelihood increases with more repetitions or more physical size of objects being manipulated].
- Worker skill [problem likelihood increases with decreasing worker skill.]
- Familiarity of workers with other workers who will be sharing a job site [problem likelihood increases with decreasing worker familiarity.]
- Problem difficulty [amount of management attention required to address a problem varies with activity size, worker skill and problem difficulty.]

The user runs the simulation interactively, like a computer game. The user asks the computer to simulate problems during some period, e.g., one day or one week. The system identifies potential problems with activities being performed during that period. The user selects activities to receive discretionary problem-management attention. If available management influence exceeds the management effort required for the problems of the selected activities, the system removes the problems associated with the selected activities. Activities simulated in future time periods will then have fewer problems when the user chooses to give attention to problems of their preceding support activities.

Figure 7 shows the user interface of the CM system after it analyzed two time periods in the simple test case schedule and as the user selected to activities to receive management attention.

- Window [1] shows a dialog box that contains a scrollable list [1.1] of all project activities performed in the most recent period. Each activity has a set of potential problems. To the right of each activity name, the system shows a number (in parentheses) that represents the estimated total management effort to manage the problems associated with the activity. For example, the first activity requires 35 management units to attend to its potential problems, and the second activity in the dialog box requires 161 units to attend to its potential problems. In Figure 10, the height of each problem column indicates the level of management difficulty for the associated activity. In this example, the user chose to devote management attention to the first and fifth activities. The window also shows [1.2] the total management influence available during the selected period, after management attention to routine tasks -- 135 attention units in this case, a number calculated based on the number of available project managers, their productivity rate per time, and the duration of the period. Remaining management influence [1.3] is the difference between maximum available influence and the amount of influence required to attend to the problems of the selected activity. The vertical histogram [1.4] shows that, after the user chose some activities to manage carefully, the remaining available influence is about half of the total available.
- Window [2] shows a text report that describes each problem and its associated problem cascade.
- Window [3] shows an iconic description of all the potential problems with activities during two periods. The boxes in this window are color coded according to their potential severity. The user can select any of the boxes and see a problem summary in Window [4] and a graphical view of the problem cascade as shown in Window [5].
- Window [4] shows a problem summary for a selected activity.
- Window [5] shows a the problem cascade for the problem shown in window [4]. Section 3.2 and Figure 9 discuss the problem cascade in more detail.

3.3 Manageability Analysis

As the result of manageability analysis, Figure 8 shows a complete Gantt chart for the simple case example (bottom window), maximum available management influence during each period between vertical time lines in the Gantt chart (middle window), and problems during each period (top window). The Gantt chart identifies activities with problems by assigning them a different color and, as shown in Figure 8, slightly larger bar height, during the periods in which the system infers that problems may be active.

Total management capacity during any period, as shown in Figure 10, varies directly with the number of available managers, their skill and their roles in a management organization. Management influence varies inversely with increasing number of workers scheduled to work and difficulty of the planned activities.

3.4 Case Example

Figure 8 shows the result of manageability analysis. The lower window in Figure 8 shows a Gantt chart for a portion of this project. The upper window of the figure shows potential management problems with each period of the proposed schedule. Each box represents a problem. Each vertical column of boxes shows the problems with the activities within a period set off by two adjacent vertical bars in the Gantt chart. Icons are color coded by severity of their associated problems. As shown in Figure 7, the user can select any individual problem box with the mouse and obtain an explanation of the associated problem. The center window of Figure 8 shows a summary of the available management influence on this project by time period. In this test case scenario, they have no predicted available management influence for the second period of the project schedule (Time 0 isn't applicable), since the project is just starting. The third period has some available management influence, since the number of activities is small, and only one activity starts and one other ends. During this period and then during the middle of the project, the project has no management slack. Thus, any problems that occur during these periods of low manageability are likely to have serious impact on project completion time, cost, quality or safety.

Generally in Figure 8, low manageability periods occur during or just after periods of low management influence. Low management influence in a given time span appears to cause later low manageability. Furthermore, Figure 8 shows that the number of problems increases after periods of low management influence and decreases after periods of high management influence. We infer that the project status at any time depends on a balance between the severity of the problems and the influence of management.

3.5 Evaluation

A test project for the evaluation of the diagnosis theory developed in this research project involved construction of an administration facility for the Port of Los Angeles. For this example, the project organization included the following major participants:

- Client
- Designers
- Design consultant
- Property owner
- Construction management assistant to the owner
- General contractor
- Subcontractors to the general contractor

We modeled each of these organizational participants as an instance of a generic resource, and each had specific skills, functions and coordination requirements. We modeled the activities and resources for this project at a high level. As organized, the system analysis showed that there was no available manageability until the very end of the project schedule: management was so busy managing regular work that there was no slack available to manage unanticipated problems until the very end of the project. More specifically, the CM system predicted that decision-making would be slow both at the project start and later in the project.

The various project participants lacked well-developed practice in communicating with each other, causing slow decision-making. In the actual project, delay of decision-making in the design phase was one of the biggest problems that occurred in early in the project. Slow decision making caused other problems, such as delay of supply-framing steel.

As a "what-if" experiment, we changed the project organization to include only a client, general contractor with complete design and coordination responsibility, and subcontractors. We modeled these organizational entities as resources that were slightly more efficient than in the original organization because they shared working styles and procedures. Project managers are still busy on this revised project, but they have slightly increased predicted available management influence both at the project beginning and end. In this situation, the CM system predicted that decision-making would be more responsive from the project start because the various project participants had well-developed practice in communicating with each other. This revised project still has little management slack, but it has slightly more and thus slightly better capacity to respond effectively to problems that otherwise could have serious impact on project completion time, cost, quality or safety.

4 Discussion

The CM system uses an object hierarchy to represent a symbolic building model. The user manually identifies symbolic features (e.g., walls, columns, beams) in the 3D CAD model and some feature relationships (e.g., *Supports*). Feature dimensions and the user-identified relationships are sent from the CAD model to the symbolic model. In simulation results, low management influence in a given time span appears to cause later low manageability. Furthermore, simulation results show that the number of problems increases after periods of low management influence and decreases after periods of high management influence. We infer that the project status at any time depends on a balance between the severity of the problems and the influence of management.

Table 1 summarizes the principal components of the knowledge representation used in the symbolic model. The CAD application sends messages to the symbolic model and reports names and attributes of specific building elements found in the drawing. The model application creates instances of those building elements, as shown in Figure 3. As discussed in Section 2.3, the CM system infers activities needed to construct the building elements. The planner creates each activity as an "instance" of one of a set of generic activity types, e.g., place reinforcement, remove scaffolding, arrange for a building inspection.

This project used AutoCAD as a 3D CAD modeling package and Kappa as a symbolic Object-Oriented modeling tool.

The AutoCAD and Kappa applications use interprocess communication to transfer data between each other. Direct transfer is much faster than use of file data transfer. We built AutoCAD routines to recognize features in the graphic model and to send those features to the Kappa application. Messages from AutoCAD report the features found in the graphic model and some dimensions of those features. A Kappa module interprets the feature data received from AutoCAD, finds a "class object" that each feature description relates to, creates appropriate "instance" objects to describe the features of the graphic form, and assigns symbolic feature attribute values based on the parameter values received from AutoCAD.

The current research suggests a number of extensions. The definitions of essential attributes and risk factors are now based only on our personal experiences and judgment, and they could be refined. The CM model does not now include potential learning effects. For example, the model takes worker skill and familiarity of workers with other workers as constant. Clearly they can change, both through the normal activity of a project and as the result of management effort. Although our data collection and modeling were short and informal for the industry test case reported in Section 3.5, we conclude that the simulation results were consistent with observation and suggest the potential of the system. Thus, extensive validation is required to test the theory and model more fully.

A long-term benefit of this research would be development of theory and implementing tools that help project managers to review a plan and schedule and help them to identify construction-phase risk factors. If such a manageability analysis gives them an early notice of the possible presence of risks, the forewarned project mangers can then attempt to modify methods, plans or schedules or to watch for and attempt to manage the predicted problems.

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Master planning and scheduling

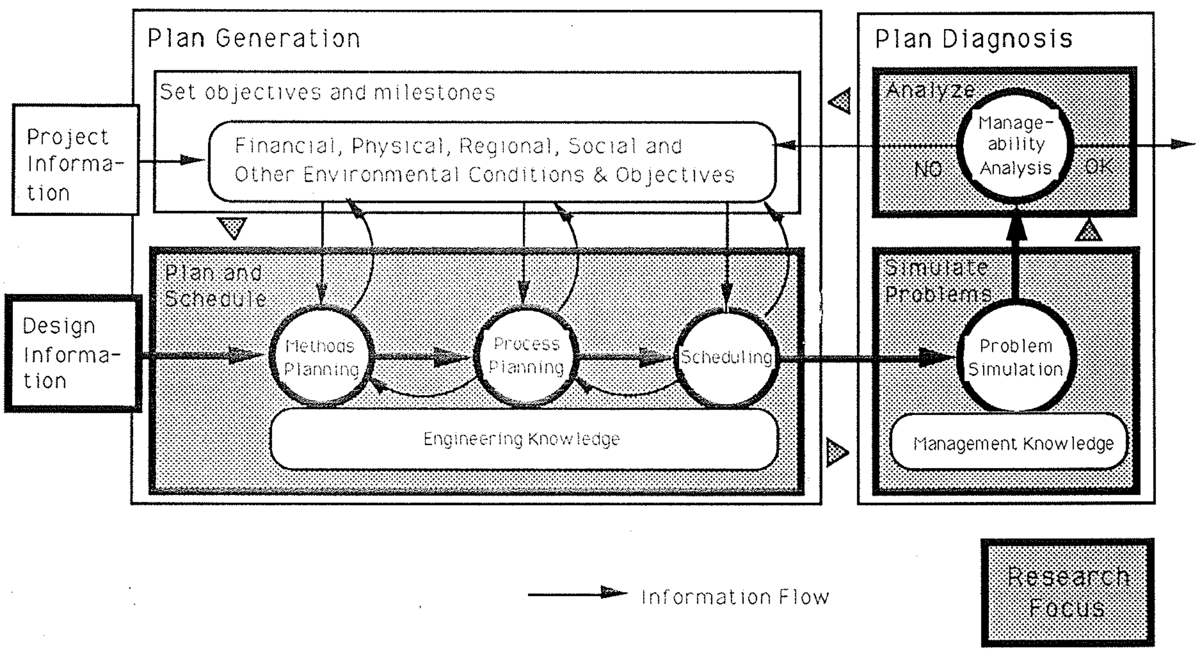


Figure 1: Master planning and scheduling process

Human project managers routinely perform master planning. They try to assess project manageability, but because they are busy and do this work informally, they often cannot recognize problems with a master plan and schedule until during the construction phase.

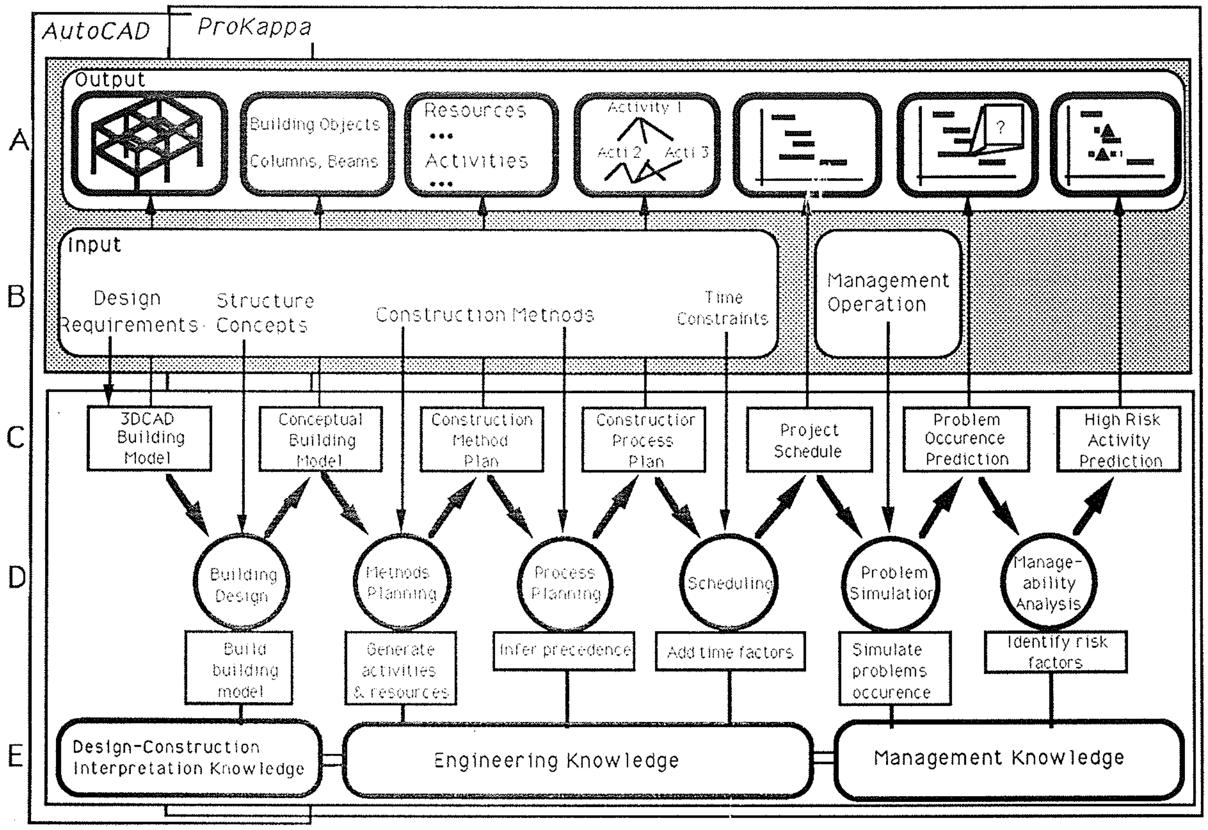
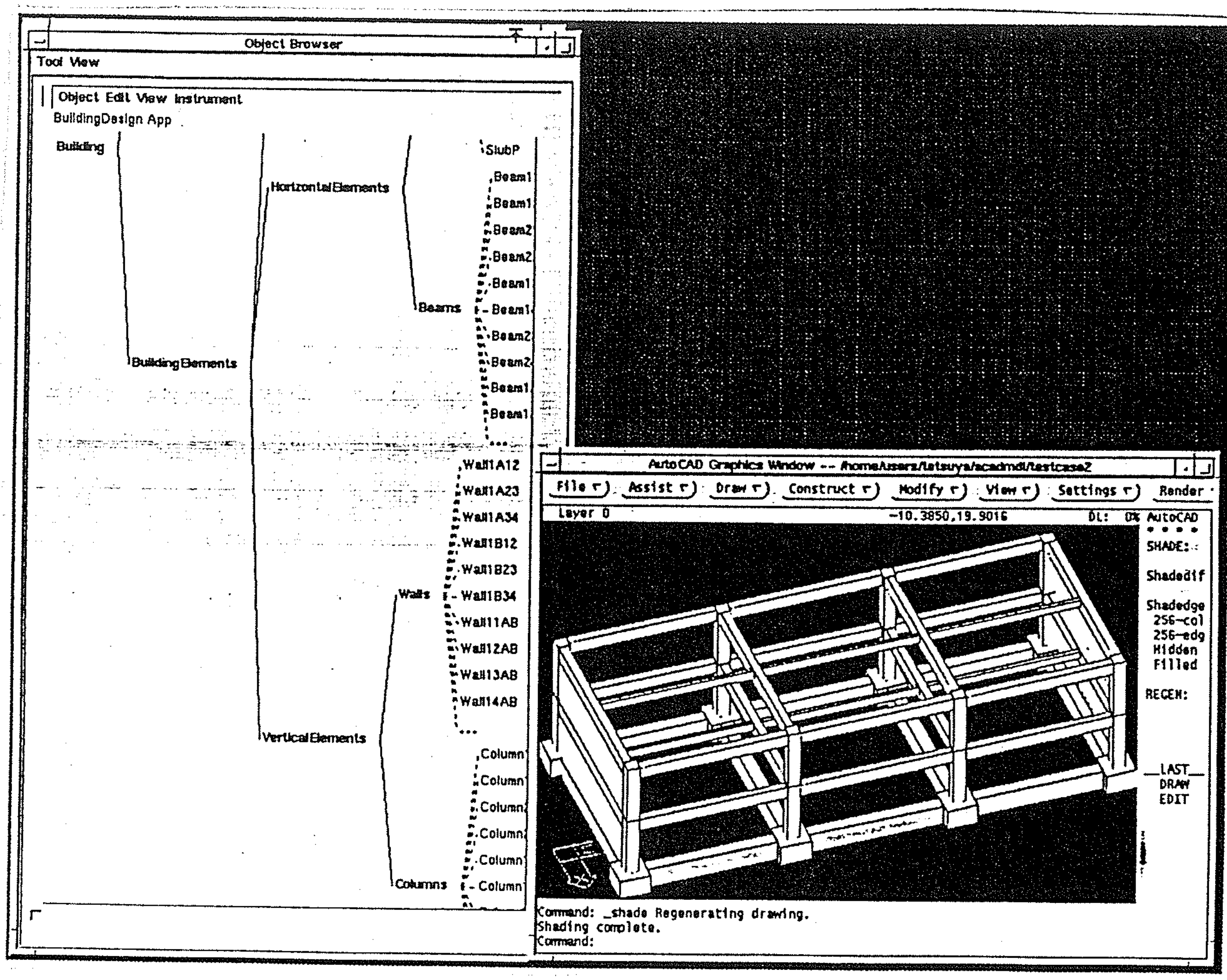


Figure 2: CM System information flow

As shown in the D level of this figure, the CM System implements a series of six steps in construction management planning: build a symbolic model; generate activities and resources, etc. Each step has inputs and outputs as shown in the C level. Users provide the inputs shown in the B level. The various systems provide output shown in the A level. The six applications use knowledge as shown in the E level of the figure.



<u>Figure 3: Test case</u>

The CAD drawing (right side of figure) shows columns, beams, and some of the walls in a simple apartment building. The CAD system uses a small number of graphic primitives. The user manually classifies each graphic primitive (e.g., a particular extruded rectangle) as a component to be constructed (e.g., particular column or beam), and the user identifies engineering relationships among graphic objects, e.g., *SupportedBy*. The components to be constructed, building feature classifications, relationships and dimensions are sent to the symbolic model (left side of figure) where they are recorded as individual beams, columns, etc.

Process Planning

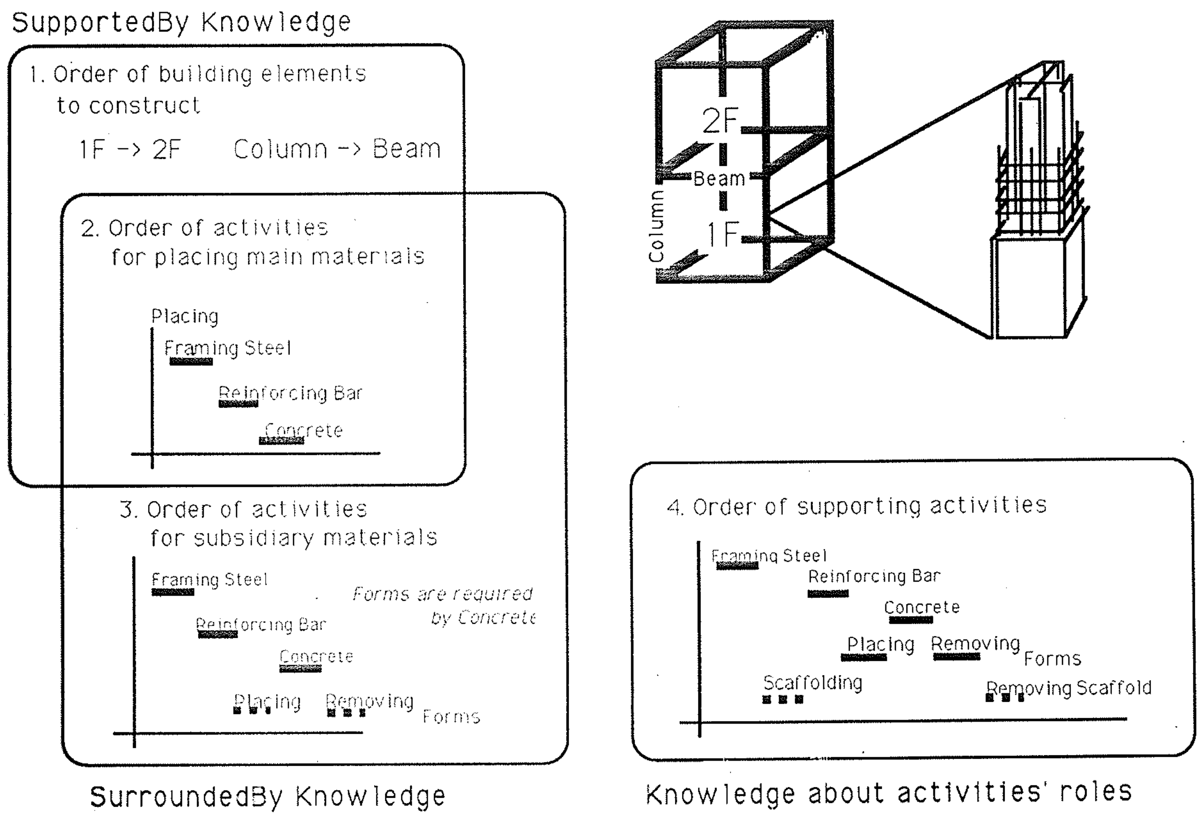


Figure 4: Inferring activity precedence

Activities are made up of an Object-Action-Resource triple. The process planner identifies activities needed to construct objects identified in the CAD model, and it infers activity precedence based on *SupportedBy* or *SurroundedBy* relationships among the objects in a set of activities (Steps 1, 2-4 respectively.) The Gantt chart on the right of this figure shows activities to construct the first floor columns.

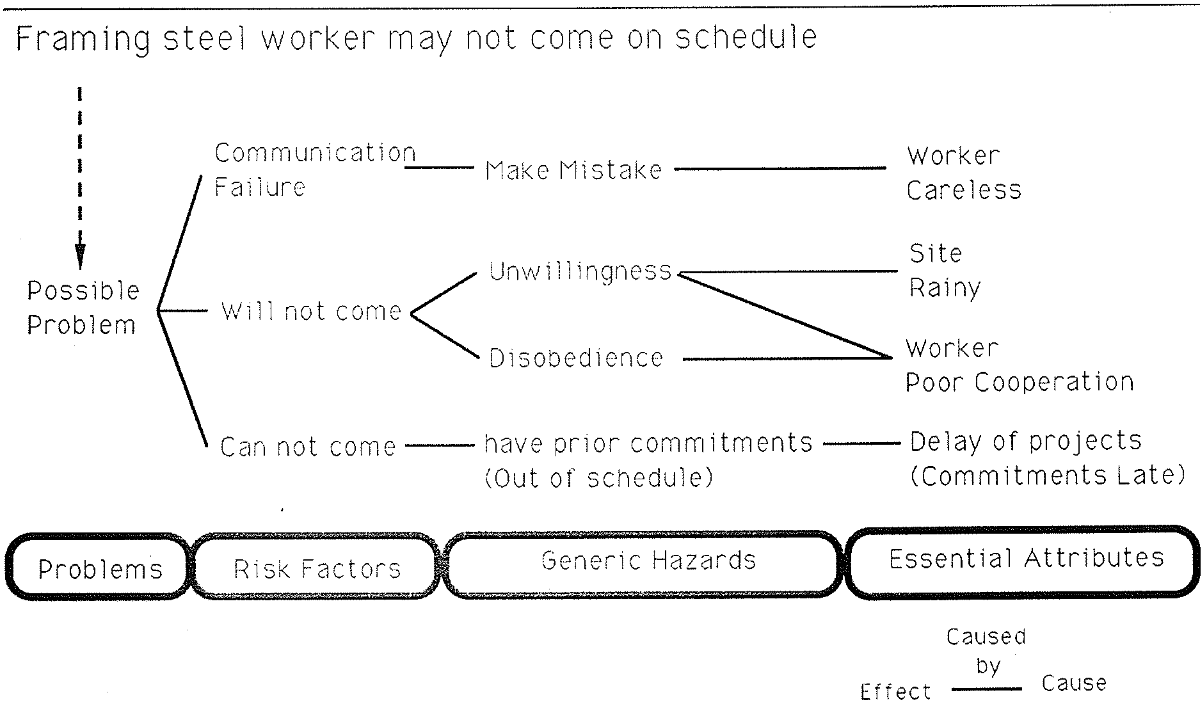


Figure 5: Inferring activity problem potential

Activities may have problems if enabled by a cascade of causes.

Mistake of cutting and bending of steel reinforcement
Incorrect usage of steel reinforcement or framing steel
Incorrect placement of reinforcement or framing steel
Inappropriate placing electric connection box in a column
Incorrectly welding joint of steel reinforcement
material falling of when held by a crane
Collapse of forms by wind
Deformation of forms by concrete
Imperfectly filling concrete in a form
Project delay caused by lack of labor
Project delay caused by lack of material
Project delay by difficulty of work
Injury of worker when removing forms
Inadequate concrete quality
Cold joint
Lack of solidity of concrete
Shortage of concrete

Figure 6: Examples of Risks in Construction Projects

The CM system explicitly represents a large number of construction risks, including those shown in this partial list of risks that accompany framing work.

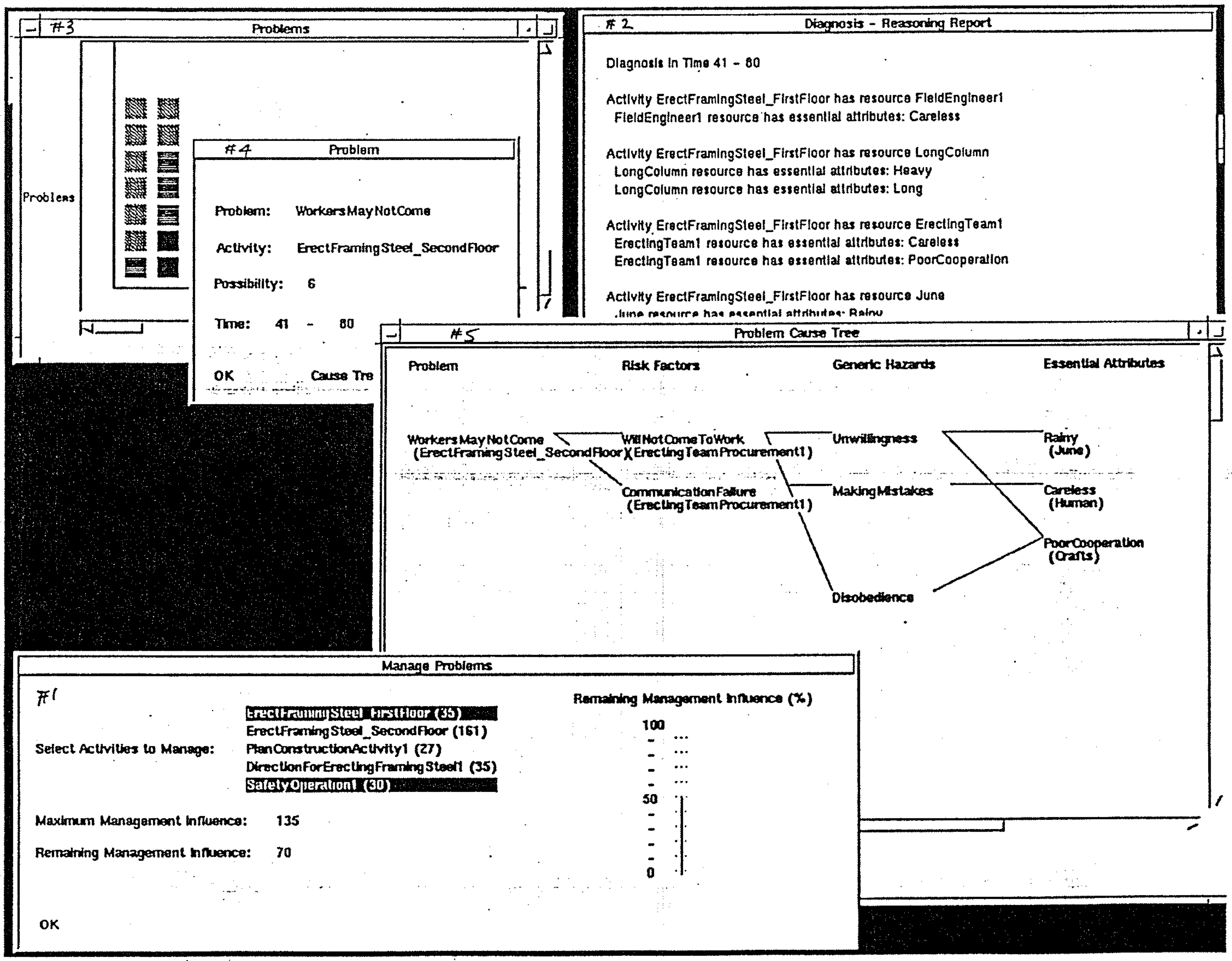


Figure 7: Example CM System detailed output

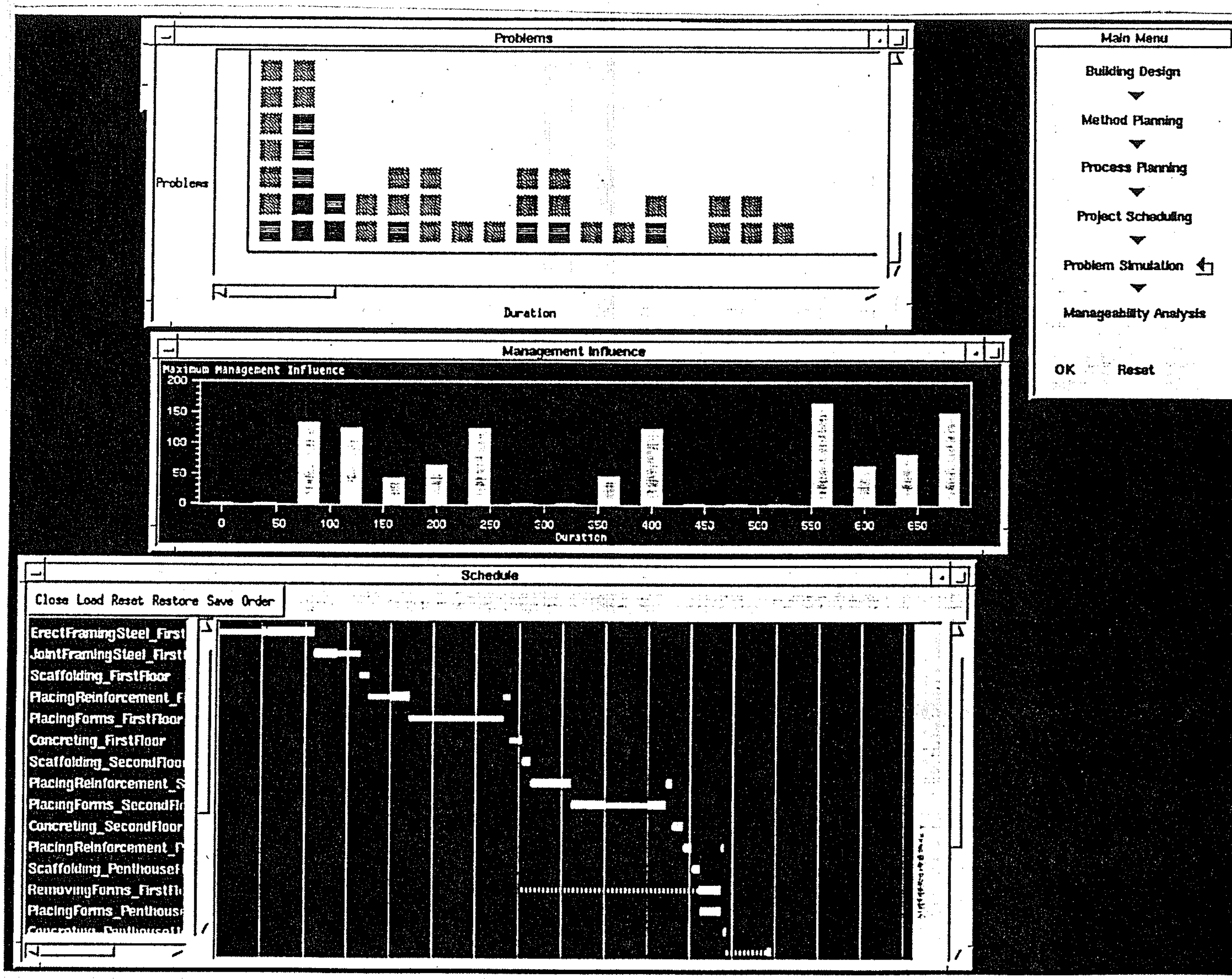


Figure 8: Example CM System output summary

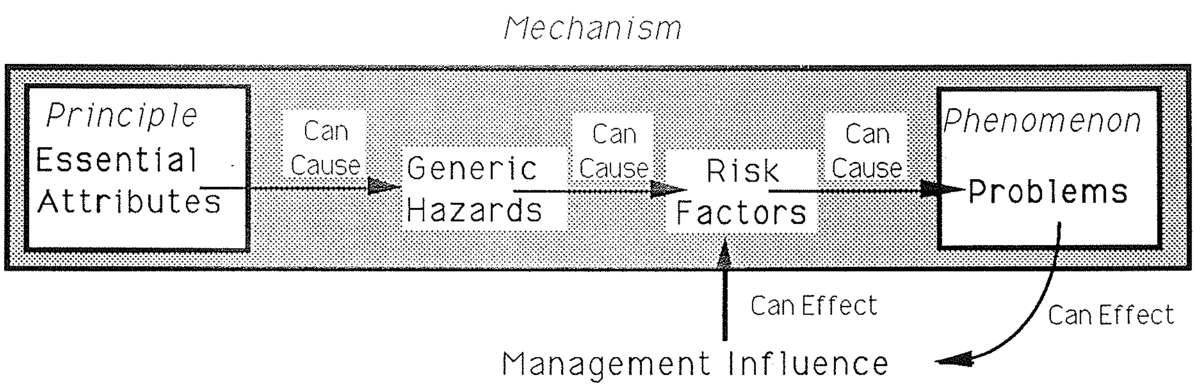


Figure 9: Activity problem cascade

Through a cascade of effects, essential attributes of the behavior of activities and resources can cause problems in activities. Problems adversely affect activity duration, quality or safety and thus, potentially, adversely affect project outcome.

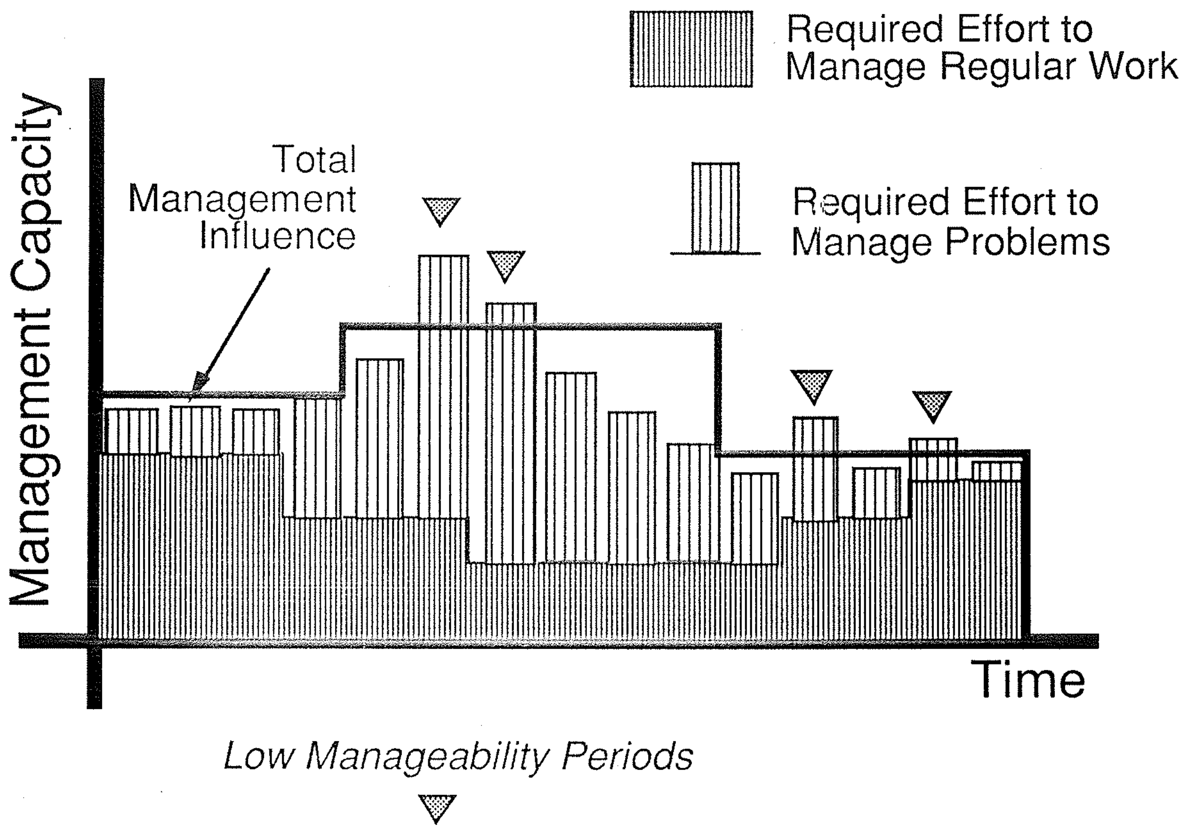


Figure 10: Manageability analysis

The CM system assesses manageability periodically during a project schedule. Total management influence at any project period depends on the amount of management staff available during that period. Managers use their influence to manage routine activities and, as necessary and possible, to manage problems. When demand for management attention exceeds total available management influence, a project is in a period of low manageability.

- Construction Activities, e.g.,
  Erect framing steel work
  Placing form work
  Concrete work
- Supply Resource Activities, e.g.,
  Supply labor
  Supply materials
  Supply equipment
- Maintain Site Facility Activities, e.g.,
  Maintain moving equipment
  Maintain passive facilities: site offices, enclosure walls, etc.
  Maintain energy supply facility
- Plan, Schedule, Operation Activities, e.g.,
  Identify design requirement
  Construction planning and scheduling
  Site direction and operation
- External Coordination Activities, e.g.,
  Coordinate law requirement
  Negotiate with neighbors

Table 1: Activities represented in the CM model.

The functions of the CM system are to plan and schedule these types of activities as they are required to construct a given building and then to analyze the manageability of the plan and schedule that are built using these planned activities.

Relationships	Activities	Construction Methods	Resources	Functions	Principles	Problems	Generic Hazards	Risk Factors	Essential Attributes
	Classes of Activities								
Failed Activities						Activities			
Activities						Activities		Activities	
Risk Factors	Risk Factors								
Management Difficulty	(hatched)								
CausedBy							Essential Attributes	Generic Hazards	
Causes							Risk Factors		Generic Hazards
Cooperating Factors							Generic Hazards		
Size	(hatched)								
Essential Attributes			Essential Attributes						
Essential Conditions	Principles	Principles							
Function	Functions					Functions			
Function Failure								Functions	
Magnitude						(hatched)			
Materials		Resources							
Principle									Principles
Resources	Resources								Resources
Status							2 (hatched)	3 (hatched)	1 (hatched)

Table 2. Relationships among entities in the CM system.

The top row of the table lists the important generic concepts of the CM system. The left column lists the important relationships of the system. Hatched table cells indicate values calculated by the system as it operates; numbers indicate the sequence in which the system assigns these values. Entries in table cells indicate classes of values for attributes of specific instances of concepts. For example, the risk factors of some activity must be an instance of the class of Risk Factors.