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The Application of Model-Based Planning Technology to Full-Scale Construction Projects

by

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Summary: TECHNICAL REPORT #66

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Abstract

Model-based representation and reasoning has been shown to have great potential in the planning and management of industrial projects, but little evidence is available on their use in significant, full-scale projects This report describes an effort to model and to use such technology at the design-to-construction interface of an $11 million structural steel facility. Although the central knowledge-rich project model and the reasoning mechanism behind the system's ability to create a logically correct plan is vital to the power of the OARPLAN system, the availability of commercial design and presentation facilities was found to be essential to its viability in industry. This document reports research into the problems encountered in both the production of an adequate computational model of construction, and the use of the resulting highly complex project networks. A project planning environment was developed, incorporating the Primavera™ project management system and an extension of AutoCad™, known as CIFECAD.

Subject

The work described in this report was carried out over a period of twelve months with a clear aim of applying the OARPLAN project planing system to a full-scale construction project. The system had been used previously on reduced-scale projects, and the development effort involved research into problems associated with the scaling up process. In the research, two NASA buildings were modeled under OARPLAN; the first being in the design phase, and therefore providing the research team with the kind of design decisions typical in any real-life construction project. The second test case was chosen because it had already been designed and constructed, and could therefore provide the team with a complete comparative case. This report documents our efforts in modeling and planning full-scale construction projects, and discusses important research, carried out along the way, which addresses some significant problems encountered in the scaling-up process.

Objectives/Benefits

The research has been instrumental in demonstrating the viability and importance of the model-based planning philosophy in the construction industry. By concentrating on two separate, but similar style buildings at Moffett Field, California, it has been possible to produce exemplar material for future ventures of this kind. The problems associated with the scaling-up process are mainly due to the complexity resulting from the application of planning knowledge to real-life project models. However, this report describes our efforts in dealing with, and overcoming some of those problems. The integration of software able to provide a 'traditional', flexible and powerful interface to industrial users is considered crucial to the acceptance and future widespread use of the technology.

Methodology

Much initial effort was spent in the knowledge elicitation process. The project team analyzed the drawings and specification for the first NASA building; the Shop/Office Complex, and created several versions of the generic object, action and resource hierarchies that make up the OARPLAN general model. During the iterative process of analysis/model/test/evaluation cycle, many modifications and developments of the model were made. The team made an early decision to use the 'standard' drawings and specifications as a vehicle for analysis and modeling, and this paved the way for a full component-level description of both buildings in terms of each component and its associated components. Early OARPLAN research had identified inter-component relationships appropriate to project planning, and these were used as the basis for our product description. A grid reference system was devised, based on the CSI MASTERFORMAT, and this was used as a spatial reference scheme that OARPLAN could use. CIFECAD would be used in future modeling ventures, and much was gained in the elicitation process that would be useful in future developments and integration of the CIFECAD system.

The second of the two NASA buildings, the Human Performance Research Laboratory (HPRL), provided the 'main' test case for comparative evaluation. Once an adequate model had been produced, and a full description of the facility had been input to OARPLAN, the resulting project-specific model was planned using OARPLAN's knowledge-based reasoning mechanism. Activity aggregation was performed according to physical zoning principles suggested by our domain expert (Mike Chacon) and the zoned plan was then transferred to the Primavera project management system. CPM and Bar Chart output was produced and subsequently evaluated by the project team. The report demonstrates this process by isolating one zone; Zone 4, and showing details on the planning and presentation of that zone.

Results

The research demonstrates that a system such as OARPLAN can be scaled up from a research vehicle able to plan simplified and 'hand-engineered' projects, to a fully functioning project planning and management system able to support the facility engineering and construction process. The problems associated with full-scale projects cannot be underestimated, but our research has faced them, and applied some considerable effort in overcoming some of the major barriers. The evaluation undertaken as part of this research has shown that, not only can the technology be successfully applied to real-life engineering projects, but that it can bring with it the added value of efficiency. The domain expert employed on the project could see very many extensions and potential new uses as the project evolved.

A paper, based on this report, has been submitted to the Journal of Computing in Civil Engineering.

Research Status

This particular project is now completed. However, the results have indicated the need to develop intelligent aggregation functionality, resource allocation, duration determination and the incorporation of building methods knowledge. Some assumptions were made in this research, and although our assumptions were made on the basis of a realistic assessment of the situation at hand, more work is required to endow the OARPLAN system with the power to reason with the multitude of project variables encountered in industry. The research has demonstrated that functionality can be increased by adding new modules, such as an estimating system, or a module capable of reasoning about constructibility and safety. The current system requires the output of such reasoning, which is presently provided as predefined values, but there is very little to stand in the way of further integration.

The Application of Model-Based Planning Technology to Full-Scale Construction Projects

Graham Winstanley[1], Michael A. Chacon[2] and Raymond E. Levitt[3]

Abstract

Construction planning and scheduling is a complex process involving the design process, activity sequencing, resource allocation and timing. The problems are compounded by the multi-disciplinary nature of the AEC industry and a multitude of factors which are capable of interfering with any predetermined schedule. This paper addresses the problems inherent in the detailed design-to-construction process and describes an integrated system which incorporates the technology of CAD and that of computer-based scheduling software, but has at its heart the detailed model of a specific project as an instantiation of a large general model. The OARPLAN system uses a method of representation based on the definition of a project activity as the intersection of its constituents action, object and resource, and this provides the basis for a powerful engineering modeling and reasoning methodology. The applicability and scalability of the system is demonstrated by its use in the planning of a substantial NASA building, and some of the problems encountered in the process are discussed.

1. Background: Model-Based Planning

In current US practice, design documents specify different subsystems of a facility to be built at varying levels of detail. The building facade might be specified in great detail including the precise dimensions, the exact color of stone to be used, and all waterproofing details; at the same time, the building's plumbing system might be specified in terms of hot water, cold water and drainage services to be provided at varying locations; and the heating, ventilating and air conditioning (HVAC) system might be specified only in terms of performance requirements for minimum and maximum temperatures, humidity levels and air change rates. The set of specifications is presented to the contractor in paper form as a set of plans and written specifications, which may reference industry or governmental codes and standards (see Section 3.1). From this set of documents, a contractor is expected to prepare a construction plan, schedule and cost estimate in order to price out its costs and submit a bid for providing construction services.

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Since most architects and engineers have only limited capability for predicting the construction time and cost implications of their design choices, the first realistic cost and time feedback that they get on their designs is often at the bid opening—and the news is seldom good! (except perhaps during economic slumps, when bids may be lower than expected).

Designers are increasingly using CAD systems to generate the paper drawings that they issue to contractors. However, they are sometimes reluctant to share their CAD files due to fears—real or imagined—about potential legal liabilities resulting therefrom. One way to provide the designers with earlier feedback about the time and cost implications of their design is to develop knowledge-based planning and estimating systems that can reason about architectural and engineering CAD descriptions of a facility to generate this feedback automatically.

In order to address this problem, the *Center for Integrated Facility Engineering (CIFE)* at Stanford University initiated a research program to develop a class of automated planning and scheduling systems that could reason about slightly annotated CAD descriptions of facilities to produce construction plans and cost estimates. A system specially developed within CIFE, known as CIFECAD [Ito 1989] has been used to provide a greater level of detail on individual construction designs than conventional CAD systems. Built as an extension of AUTOCAD™, it provides for a description of a facility, not merely as an ordered collection of dimensioned geometric shapes, but also as an interrelated set of components which together describe the whole building. As a result of the inherent 3-dimensional design process within CIFECAD, a textual description is available to systems such as OARPLAN, which includes the following type of information (using concrete beams as an example):

- Unique identifier, level (floor) within the building and X,Y,Z coordinates
- Center-to-center length, span length and material
- Top width, bottom width, depth, strength and percent reinforcement
- Supporting objects

From this information, it is possible for OARPLAN to extract information relevant for modeling and subsequent planning.

OARPLAN [Darwiche 1989], described in this paper, is one of a family of knowledge-based construction systems that have been developed at CIFE, and belongs to a class of automated planning systems which employ a knowledge-rich domain model in their problem-solving strategy. The model is centered around a generic project description, based on the concepts of product breakdown structure, and similar data structures able to express actions and resources. The system uses declarative knowledge of action/object pairs to identify activities within the plan, and object relationships for activity sequencing. This approach differs from the STRIPS-style 'classical', or state-based planners [Fikes 1971], which are based on preconditions and effects of operators (in this case, activities). The central concept used in these early systems was that an operator, or activity, could only be applied if its stated preconditions can be satisfied, and that the application of the activity would have an explicit set of effects, which may or may not satisfy the preconditions of other activities, etc. In such systems, the planner carries out a state-space search—forwards, backwards, or in both directions—and attempts to generate a sequence of actions that will incrementally change the world from its initial state into the goal state. This form of activity representation provides a general approach to planing and can thus be applied to any planning problem, but it exploits little domain knowledge about a given planning problem. Consequently, planning systems based on this representation of activities must search extensively, even when provided with heuristics to guide the search, must often backtrack to resolve interferences, and are capable of solving only simplistic problems to date. Problems of plan interaction and interference resulted in the planner's inability to find optimal solutions, or any at all. Sophisticated solutions to these problems have been proposed [Sacerdoti 1973 and 1975, Tate 1976, Wilkins 1983, Chapman 1987], but in all these cases the planning systems lack fundamental knowledge of engineered systems, and are unable to reason causally about the inclusion of activities in a plan, and their subsequent sequencing. An excellent review of planners of this type is provided in [Tate 1985].

We believed that it should be possible to develop some “principles” of planning for construction so that we could model the problem using much more knowledge about the domain than would be possible using Strips operators.

SIPE [Wilkins 1988], a planner in the STRIPS-style, considered the problem of resources which may be required by more than one activity. It identified such conflicts as arguments existing in two operators, but unlike OARPLAN, the system was not equipped with fundamental knowledge about each object, or the relationships between them. Significant modifications have been made to the original system in SIPEC [Kartam 1990], to incorporate fundamental knowledge of the relationships between objects in a plan . This work also demonstrated the viability of a computational link between a commercial CAD system and an AI planner [Ito 1989].

PIPPA [Marshall 1987, Winstanley 1990] was one of the first model-based planning systems to be developed and evaluated in an industrial context, although the definition of an activity as the intersection of objects, actions and resources, was derived in part from the MOLGEN concept of object and action abstraction [Stefik 1981a, 1981b]. The PIPPA system was designed to cater for the configuration problems found in the design-to-implementation of large scale, high-technology engineering products. It is based around what the authors refer to as a central 'information base', which incorporates a generic description of the product and the processes required to produce it. The information base also contains a specific model of a project as it is dynamically planned and directed by the system during run-time. Each element in the component breakdown structure, action hierarchy and resource description holds information and fundamental knowledge, which can be applied as required through the invocation of rules [Winstanley 1989]. This implementation strategy results in an object-oriented system behavior, where each component, action, resource and therefore activity is responsible largely for its own existence within the ensuing specific model and manufacturing plan.

[Levitt 1985] had developed model-based systems for project schedule revision, and [Kunz 1986] reported on a system for project objective setting. Thus there was some evidence that this approach to planning might bear fruit. After careful analysis of the construction planning problem, we identified several relationships—e.g., *supported by*, *enclosed by*— among the components of a facility that determine their order of installation, and used these as our principles of construction planning. We demonstrate in this paper that our model-based planning approach can produce realistic construction plans for full-scale facilities by reasoning about CAD facility descriptions with stored construction knowledge.

The current implementation of the system is on the KEE™ 3.1 platform, on top of Sun Common Lisp 4.0™. Previous versions have been implemented as a blackboard system, using BB1 [Hayes-Roth 1987, Darwiche 1989], and on a Macintosh computer in Allegro Common Lisp™.

2. OARPLAN: a model-based planning system

OARPLAN has been used to provide an integrated design/construction environment, in which detailed designs are available from the computer-aided design phase, to be used in the production of construction plans. The core concept of this system is a generic model of the domain, existing within the system as component, action and resource hierarchies. Planning knowledge is used in the form of rules, which are applied to establish precedence between construction activities on the basis of inter-component relationships. The application of the OARPLAN methodology on simplified problems in the construction domain has been reported previously [Darwiche 1989], but recently the system has been extended, enhanced and applied in the planning stage of full-scale facilities. Two major construction examples were used in the experiment; an industrial shop/office complex and a performance testing laboratory. Both of these were structural steel facilities, and both belong to NASA (National Aeronautics and Space Administration); located in Mountain View, California. Table 1 serves to describe them in terms of their size and complexity.

Test Case Data		
ATTRIBUTE	**BUILDING 1** *Shop/Office Complex*	**BUILDING 2** *Human Performance Lab*
Project value	$13 million	$11 million
Type of construction	Structural steel	Structural steel
Number of floors	2	3
Number of individual components	500 (partially-modeled)	1400
Total area of building	80,000 square feet	57,000 square feet
Status	Undergoing design	Completed

Table 1. The attributes of test cases (Building 1 and 2)

Computer-aided design systems are able to provide descriptions of designs in terms of the project's individual components. Relationships between these components, and groups (or classes) of components, are used in construction to properly sequence and consequently to schedule project activities. By representing objects at the most detailed level, along with information on their specifications, position and relationship to other objects within the design [Ito 1989], it is possible to build a computer-based model of the product. Figure 8 in Section 3.2.1 of this paper shows part of the generic object hierarchy in the current implementation of OARPLAN. Section 3 also contains a discussion on conventions adopted in the building of generic models.

The OARPLAN methodology states that an activity within a project is a specific action on a specific object using a specific resource (or resources). Activities can share objects and actions with other activities, but in order to produce a plan as an ordered sequence of activities, it is necessary for the system to be equipped with both action and resource models. The action model is constructed in a similar fashion to the component hierarchy, having ACTIONS as its root. The actions *construct*, *install* and *order* are classed as EXISTENCE_ACTIONS and similarly the actions *dispose*, *erect*, *excavate*, *place*, *pour*, *reinforce*, *remove* and *weld* are represented within the class MODIFICATION_ACTIONS. The hierarchy is further elaborated until 'primitive-level' actions, which are defined as those actions which would be carried out on a component at the lowest level in the object hierarchy, are represented. Figure 1 is a schematic view of of the three hierarchies making up OARPLAN's generic project model, and demonstrates how the system represents its plan as a sequence of activities, each of which is associated (by links created dynamically) with an object, an action, and one or more resources. Notice from Figure 1 how activity nodes can share attributes with other activities. In the figure, activity_23 shares the resource laborer with activity_31.

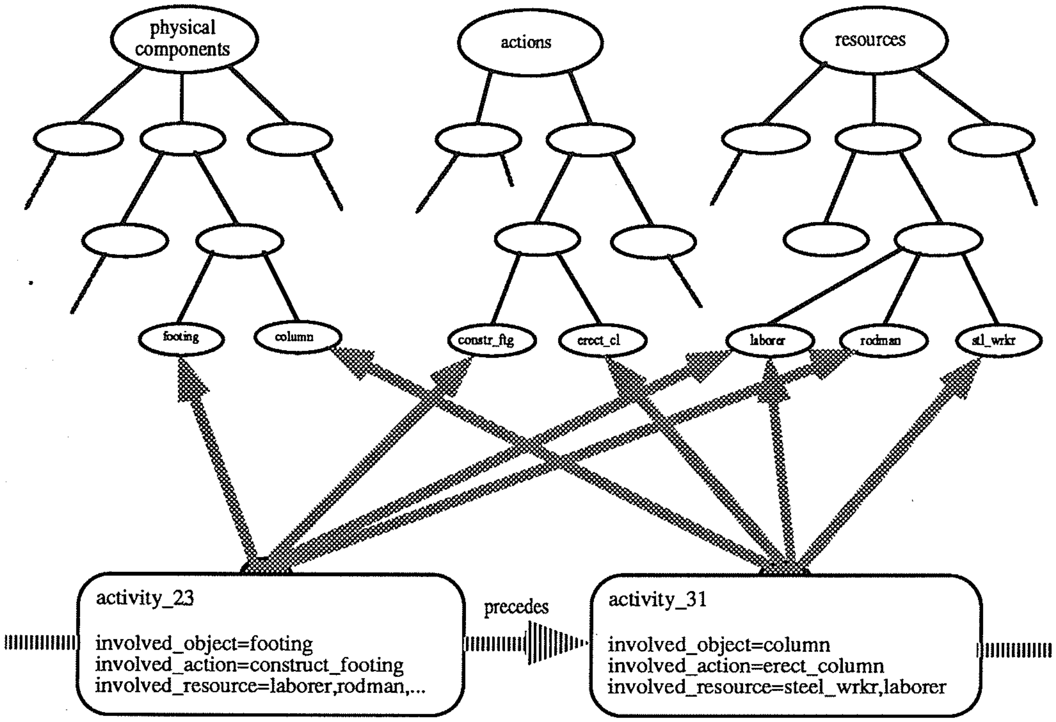


Figure 1. The OARPLAN generic model is comprised of an object, action and resource hierarchy. Each activity in the plan represents the intersection of those three concepts

By careful design of the action and object hierarchies, it is possible to describe activities at many levels. For example, at one level, it is possible to create an activity for the reinforcement of all the spans in a building by linking the object Spans (or rather the object *class* spans) with the action Reinforce. However, this activity can be represented by a number of lower-level ones. For example, by linking the action Reinforce_beam with the object Beam, and by linking the action Reinforce_column with the object Column, etc., a whole sequence of lower-level activities are created. Resources are represented in yet another hierarchy under the standard classes of Equipment, Labor and Materials. Resources are also defined as consumable or non-consumable, and specific resources are attached to the action hierarchy, so that for example, the action *construct_column* would (or might) require the human resources *Carpenter, Rodman and Laborer and Finisher*

2.1 The OARPLAN Process

In order to produce an ordered sequence of activities, the OARPLAN system must carry out the following fundamental processes:

1. Input the details of a construction design. This necessarily includes each individual component within that design, described in terms of its component class (Beams, Columns, etc.), a unique identifier (BM123, C123, etc.), its relationship to any other components (Supported_by, Connected_to, etc.) and a list of components which are related in that fashion. Figure 2 shows a small, but representative, section of a typical input file.

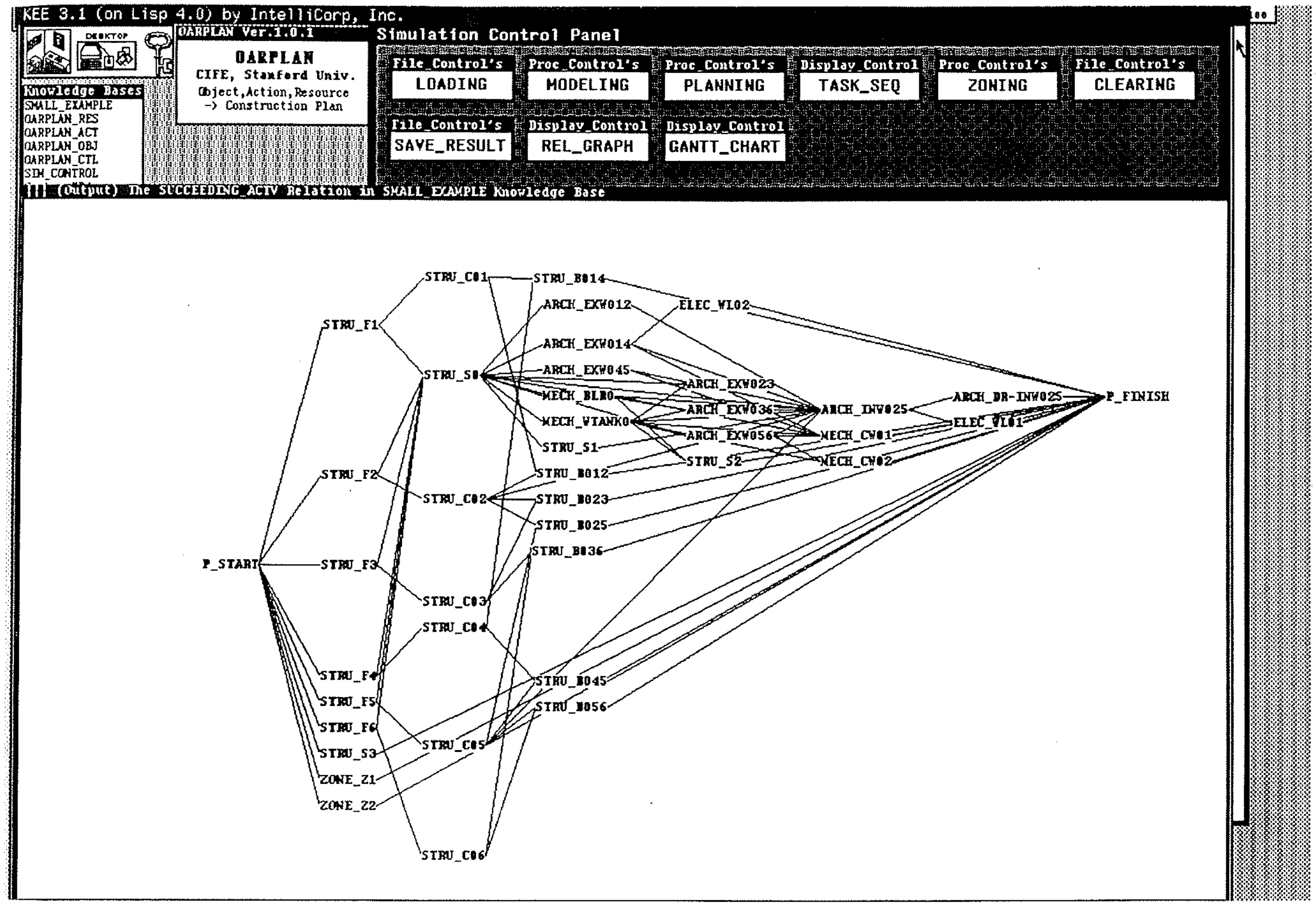
2. Produce a specific model for the building as an instantiation of at least part of the generic OARPLAN model. Once this process is complete, the specific model exists as an unordered set of activities; their constituents being instantiations of generic objects, actions and resources. It is possible to browse the model and interrogate constraints and construction implications by viewing the cluster of related information now associated with each component.

3. Planning. In the current OARPLAN system, a plan is defined as a sequence of activities, ordered by precedence relationships. These relationships are established on the basis of domain-specific knowledge applied to the model, using the inter-component relationships defined in the input file. Activity classification occurs at this time (compound or simple activities), and activity elaboration may optionally be performed. Figure 3 is a KEE screen display of a plan, based on the input file of Figure 2. The file represents a very small project of 38 activities in all, but shows the graphical plan presentation as a network of activities in a precedence network. Figure 3 also serves to illustrate the OARPLAN system functionality, with active 'buttons' and interactive display windows on a typical KEE™ desktop.

4. Plan output. This is available as a graphical display on a KEE™ window (as in Figure 3), or as an activity listing. The graphical display is useful in gaining an immediate appreciation of plan sequence and potential plan concurrency, but the usefulness of this form of display is limited by the size of the plan and the physical limitations of the computer screen.

```
(SLABS S0 SUPPORTED_BY (F1 F2 F3 F4 F5 F6))
(COLUMNS C01 SUPPORTED_BY (F1))
(COLUMNS C02 SUPPORTED_BY (F2))
(BEAMS B012 SUPPORTED_BY (C01 C02))
(BEAMS B023 SUPPORTED_BY (C02 C03))
(EXT_WALLS EXW012 SUPPORTED_BY (S0))
(EXT_WALLS EXW023 SUPPORTED_BY (S0))
(INT_WALLS INW025 SUPPORTED_BY (S0 C02 C05))
(DOORS DR-INW025 SUPPORTED_BY (INW025))
(WATER_TANKS WTANK0 SUPPORTED_BY (S0))
(BOILERS BLR0 SUPPORTED_BY (S0))
(WALL_LAMPS WL01 CONNECTED_TO (INW025))
(WALL_LAMPS WL02 CONNECTED_TO (EXW014))
(PIPING CW01 CONNECTED_TO (BLR0 EXW014 EXW045 EXW056 WTANK0))
(WATER_HEATERS HW01 CONNECTED_TO (BLR0 EXW014))
(INT_WALLS INW025 WEATHER_PROTECTED_BY (S1 EXW012 EXW023 EXW045 EXW056 EXW014 EXW036))
(SLABS S0 COVERED_BY (S1))
(WATER_TANKS WTANK0 COVERED_BY (S2 INW025 EXW023 EXW036 EXW056))
(BOILERS BLR0 COVERED_BY (S2 INW025))
```

Figure 2. A very small sample of a typical input file to the OARPLAN system, the file format being:
Component class -- identifier-- relationship -- a list (possibly empty) of related components



(Output) The SUCCEEDING_ACTV Relation in SMALL_EXAMPLE Knowledge Base

Figure 3. The project plan produced by first creating a model of the project and then invoking OARPLAN's Planning system on the input file of Figure 2. Annotation on the graph has the following meaning:
STRU = Structural ARCH = Architectural MECH = Mechanical ELEC = Electrical

Planning knowledge exists in the form of rules, which are used to infer precedence between activities once the specific model has been produced. Currently, planning rules exist to establish precedence using the component relations: Supported_by, Enclosed_by, Connected_to, Covered_by, Weather_protected_by and Damaged_by. The general form of these rules is:

```
if      activity_1 and activity_2 are in the plan
        and   activity_1 is linked to object_1
        and   activity_2 is linked to object_2
        and   object_ 1 is related to object_2 by the dependency relationship P
then    activity_2 is the predecessor_of activity_1
```

The application of these planning rules produces a logically correct sequence of activities (assuming correct input file representation). Other relationships currently under investigation include:

Absorbed_by
Changed_by
Controlled_by
Created_by
Decreased_by
Filtered_by
Generated_by
Insulated_by
Prevented_by
Reduced_by
Protected_by
Reflected_by
Rejected_by
Separated_by
Shielded_by
Transmitted_by

The process of design to planning is illustrated in Figure 4, which shows that an initial component-level description provides the necessary data for modeling. The actual process of modeling is crucial, and results in activity creation and instantiation of relevant parts of the three abstraction hierarchies. The central definition within OARPLAN of each activity being the intersection of an object, action and resource(s) is realized in this phase, and a report file is generated. Once modeling has taken place, subsequent steps in the planning procedure operate on activities, but now each individual activity has direct access to a knowledge-rich description of all the relevant attributes required in establishing a viable construction plan. Activity elaboration is also possible, through the application of elaboration rules. One example of this is the activity *place concrete*. Elaboration rules will recognize the antecedents *object-concrete* and *action-place* and produce ordered sub-activities which include the action-object pairs *pour concrete, finish concrete and cure concrete* (and possibly the activities related to *formworks*, etc.). Elaboration rules can be general, i.e. elaborate the most abstract action-object pair *construct building* into successively more detailed sub-actions and sub-objects through the existing abstraction hierarchies, or they can operate at the most detailed level available from CAD - *construct* (concrete) *column* is a good example of this. The column is described in CAD (CIFECAD) in terms of its dimensions, material, material volume, associated components, etc., but the actions required to actually produce that column on site can only be established through generic information and knowledge represented within the model and the planning system itself. The database query language and distributed database system is known as KADBASE [Howard 1988], which has been designed to facilitate communication between query systems (including knowledge-based systems) and databases of various kinds. At the heart of this system is a central controling and interpretation module which handles both syntactic and semantic translations. With such a facility, it is possible for a reasoning system such as OARPLAN to make queries to CIFECAD of the form "what are the components associated with BEAM_40....". Figure 4 illustrates the feedback connection of information (in the form of high-level queries, and information responses) from the elaboration step in the process to the CAD system.

Elaboration of this sort, based on a reasoning capability about the nature of the generic model and knowledge about the domain itself can lead to some interesting possibilities. The sub-actions, sub-objects and the resources required for optimum completion of a particular construction project are dependant on the building methods chosen, the type/size/structure of the building, the location of the building, the time of year construction will take place, and many other more tacit considerations. Taking these into account, elaboration takes on the feel of a configuration process in which an initially abstract model is successively extended and refined on the basis of sometimes conflicting constraints. Elaboration is facilitated in the OARPLAN system by the object_class and action_class attributes associated with each object and action. These are defined as either *compound*, which means that sub-elements exist, or *simple*, in the case of a lowest-level represented concept. Activity class rules are invoked on each initial activity generated during modeling, and through interrogation of each associated action and object, assigns the correct attribute. Elaboration rules are then used to refine the specific model by adding the more detailed sub-activities.

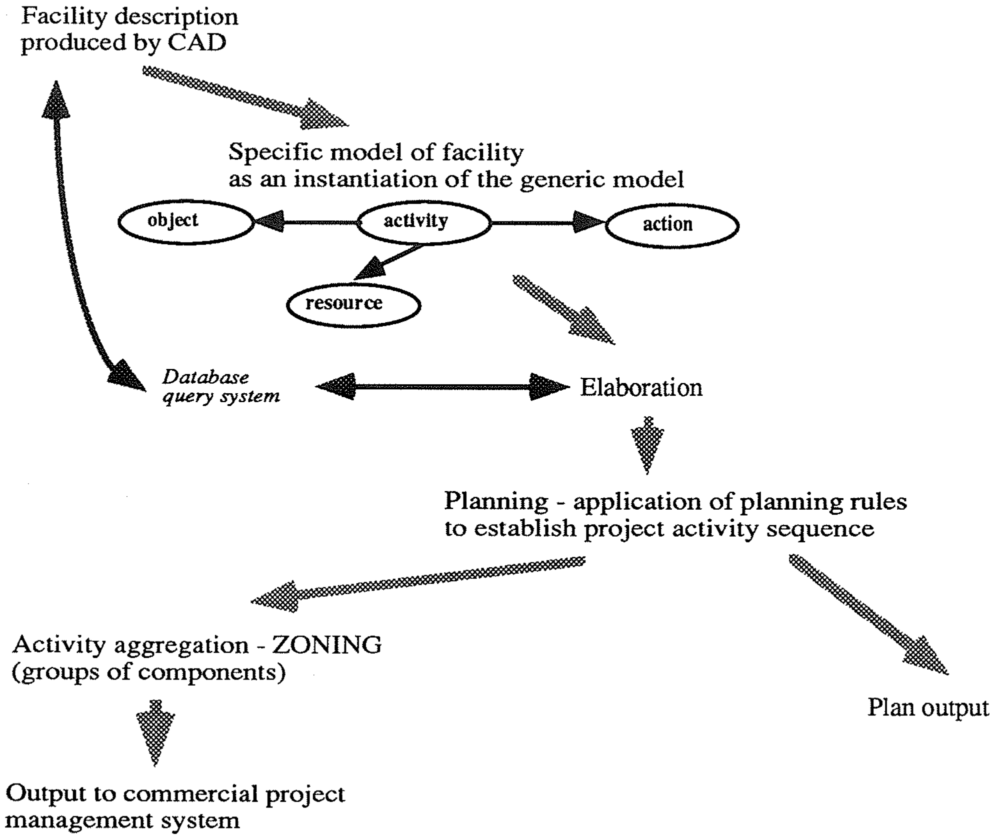


Figure 4. The OARPLAN process from CAD to standard plan output

2.2 Complexity reduction through Zoning

Problems associated with model-based planning on a real project are mainly the result of complexity in the plan produced. Although the sequence of activities may be subject to verification, the sheer size of the plan produced at the component level granularity causes problems by virtue of the resulting network complexity. Precedence relationships can be displayed to great effect graphically, but with such very large networks, a clear graphical presentation is important. Textual output and the use of commercial project planning software can alleviate plan presentation difficulties, but the sheer size and complexity of component-level precedence networks remains a problem. Component-level precedences are useful mainly at the level of daily or weekly crew planning by a foreman. However, it is possible to aggregate activities into realistic work 'packages', each with their own set of activities, actions, objects and resources, and capable of being scheduled as such. This approach, which we have termed 'zoning', allows for bottom-up aggregation to any level; that level being specified by the designer and represented directly within the CAD output file. This is similar to the strategy adopted in the PLANEX system [Zozoya 1989], but the OARPLAN implementation is not limited to the 'mechanical' structuring of the product breakdown structure, but rather is dependent on the more flexible grouping of 'virtual components' by the designer, or inferred by the system itself. Figure 5 shows part of the foundation layout of the industrial shop/office complex, with zone boundaries defined. In the normal course of planning using the OARPLAN system, each of the individual components (column_footings, grade_beams and slabs) would be associated together by one of several relationships. Using zone boundaries, it is possible quite literally to partition the problem into smaller clusters of components. It is not necessary, or desirable, to replace or modify any of the relationships exiting between components in two or more zones, but it is possible to provide an extra piece of information on each zone and the components which exist within the pre-drawn zone boundary. That extra piece of information being the relationships existing only within each zone.

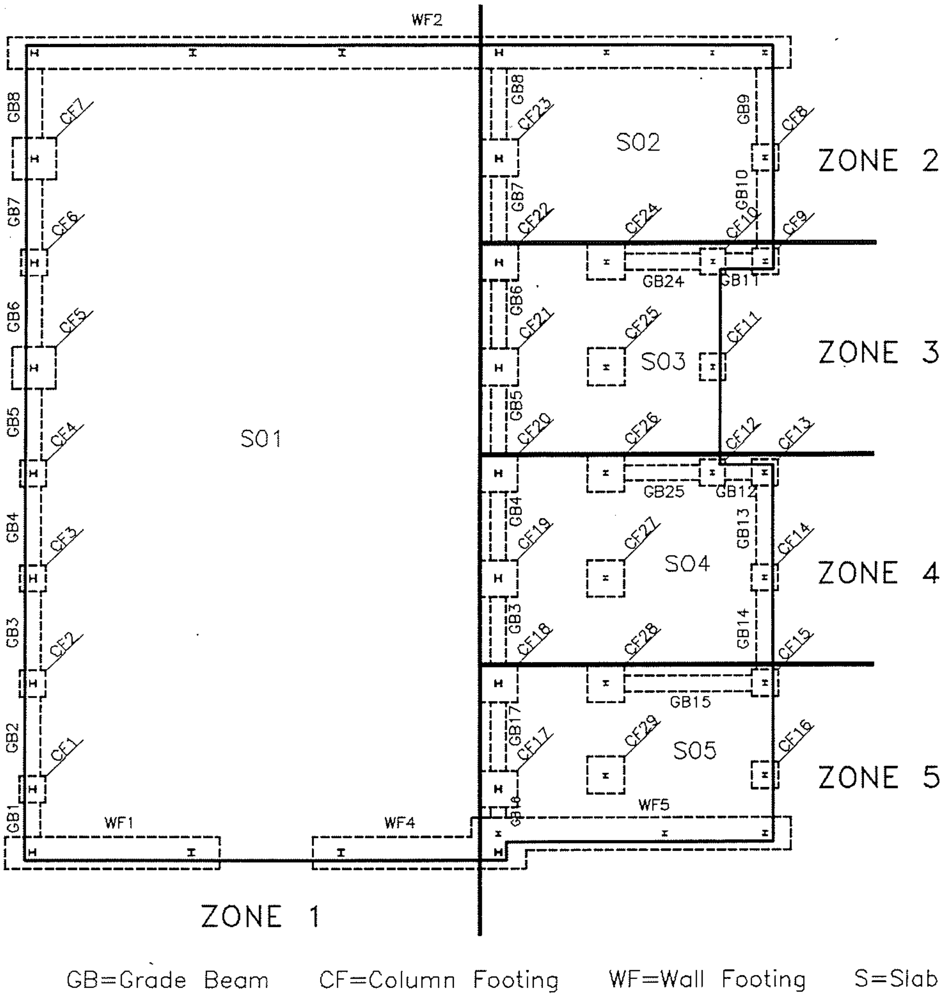


Figure 5. A layout of part of the NASA Shop/Office Complex foundations, with zones.

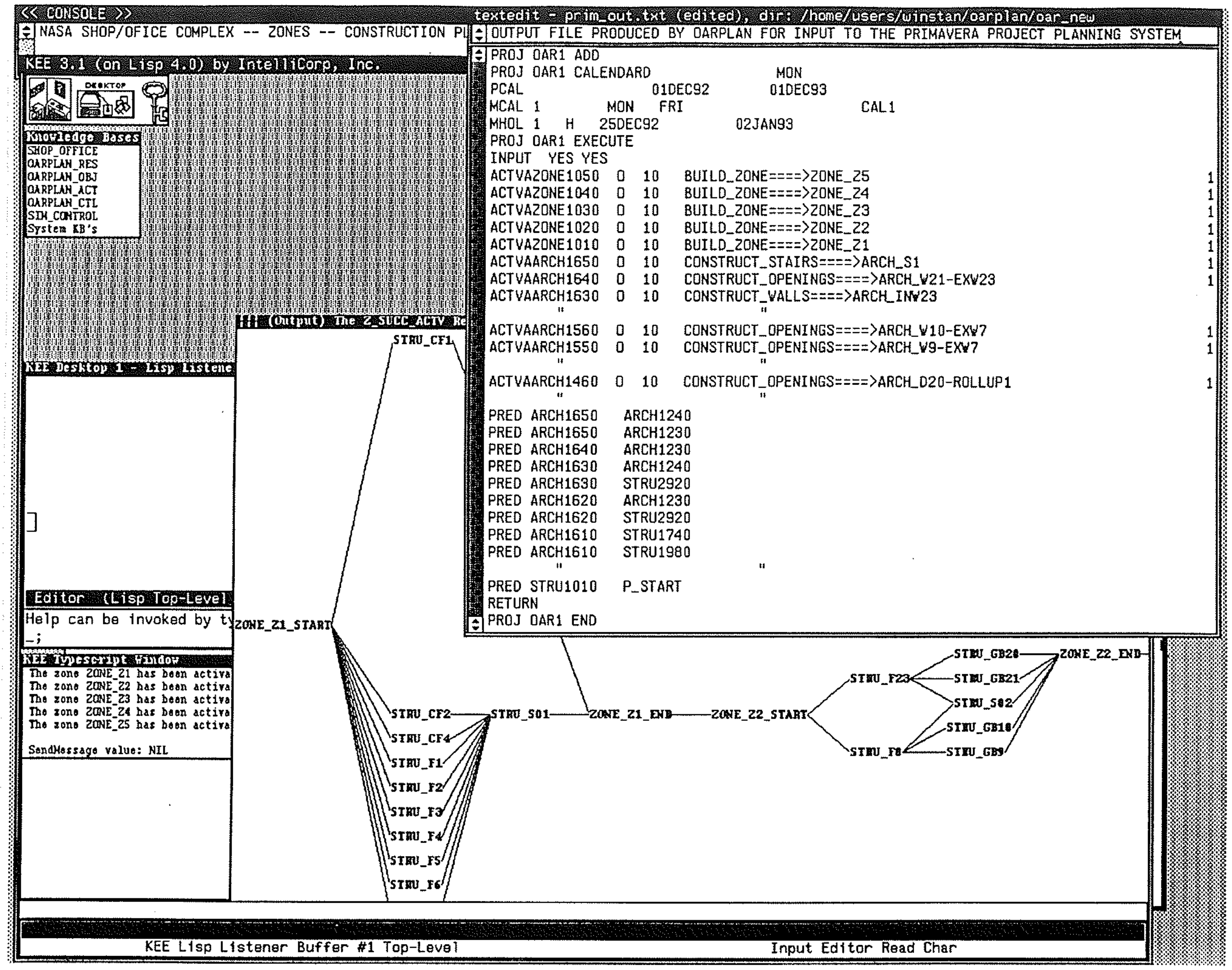
From Figure 5, the following input file is produced:

```
GRADE_BEAMS GB1 SUPPORTED_BY (CF1 F1))
(GRADE_BEAMS GB2 SUPPORTED_BY (F1 F2))
(GRADE_BEAMS GB3 SUPPORTED_BY (F2 F3))
          |                    |
(SLABS S01 SUPPORTED_BY (CF4 CF3 F1 F2 F3 F4 F5 F6 F7 F17 F18 F19 F20 F21    F22 F23 CF2))
(SLABS S02 SUPPORTED_BY (F20 F21 F22 F23 F8 F9 F10 F24 CF2))
          |                    |
(COLUMNS ........
(BEAMS  ..........
          |                    |
(ZONES ZONE_1 INCLUDES (CF1 F1 F2 F3 F4 F5 F6 F7 CF4 CF2 S01))
(ZONES ZONE_2 INCLUDES (F23 CF2 F8 GB20 GB21 GB9 GB10 S02))
(ZONES ZONE_3 INCLUDES (F21 F22 F24 F10 F9 F11 F25 GB18 GB19 GB22 GB11 S03))
(ZONES ZONE_4 INCLUDES (F19 F20 F26 F39 F12 F13 F14 GB16 GB17 GB23 GB12 GB13 GB14 S04))
(ZONES ZONE_5 INCLUDES (CF3 F17 F18 F28 F15 F16 F29 GB15 GB24 S05))
```

Once the modeling phase has been completed on this building, a number of activities are created, each with an attached object, activity and resource, as well as 'place holders' for activity durations, etc. The planning phase produces a large precedence network of activities, and the zoning phase results in activity aggregation using the explicit 'includes' relation. Using relatively simple zone sequencing heuristics, and by interrogating only those activities existing as 'zone activities', it is possible to produce a precedence graph of zone activities and the precedence relationship between those zones.

2.2.1 The implementation strategy for zones and its implications

The core representational concept of object-action-resource in OARPLAN provides a simple, and yet powerful, means to build engineering models and provide reasoning in their application. In order to fully exploit this methodology and to provide for multiple-levels of aggregation, i.e. zones within zones, zones themselves are represented as objects with actions and resources. A zone activity is therefore created as a zone action upon a zone object using a zone resource. Actions and resources are merely collections of included attributes, but in the case of zones, each zone activity has responsibility within the system for the creation of start and end units, and for the actual aggregation (or collection) of appropriate activities from the previous (un-zoned) plan. Figure 6 is a KEE screenshot displaying a partial graph of the foundation construction plan for Figure 5. In this figure, it is possible to see each zone's start and end unit, the precedence relationship between individual foundation components within the zones, and the over-simplistic relationships imposed, for illustration purposes, between the zones.



```
Help can be invoked by ty
-;
```

```
The zone ZONE_Z1 has been activa
The zone ZONE_Z2 has been activa
The zone ZONE_Z3 has been activa
The zone ZONE_Z4 has been activa
The zone ZONE_Z5 has been activa

SendMessage value: NIL
```

```
OUTPUT FILE PRODUCED BY OARPLAN FOR INPUT TO THE PRIMAVERA PROJECT PLANNING SYSTEM
PROJ OAR1 ADD
PROJ OAR1 CALENDARD                 MON
PCAL                01DEC92       01DEC93
MCAL 1        MON   FRI                          CAL1
MHOL 1   H   25DEC92          02JAN93
PROJ OAR1 EXECUTE
INPUT  YES YES
ACTVAZONE1050  0  10   BUILD_ZONE====>ZONE_Z5                                           1
ACTVAZONE1040  0  10   BUILD_ZONE====>ZONE_Z4                                           1
ACTVAZONE1030  0  10   BUILD_ZONE====>ZONE_Z3                                           1
ACTVAZONE1020  0  10   BUILD_ZONE====>ZONE_Z2                                           1
ACTVAZONE1010  0  10   BUILD_ZONE====>ZONE_Z1                                           1
ACTVAARCH1650  0  10   CONSTRUCT_STAIRS====>ARCH_S1                                     1
ACTVAARCH1640  0  10   CONSTRUCT_OPENINGS====>ARCH_W21-EXW23                            1
ACTVAARCH1630  0  10   CONSTRUCT_WALLS====>ARCH_INW23
        "                       "
ACTVAARCH1560  0  10   CONSTRUCT_OPENINGS====>ARCH_W10-EXW7                             1
ACTVAARCH1550  0  10   CONSTRUCT_OPENINGS====>ARCH_W9-EXW7                              1
        "                       "
ACTVAARCH1460  0  10   CONSTRUCT_OPENINGS====>ARCH_D20-ROLLUP1                          1
        "                       "
PRED ARCH1650   ARCH1240
PRED ARCH1650   ARCH1230
PRED ARCH1640   ARCH1230
PRED ARCH1630   ARCH1240
PRED ARCH1630   STRU2920
PRED ARCH1620   ARCH1230
PRED ARCH1620   STRU2920
PRED ARCH1610   STRU1740
PRED ARCH1610   STRU1980
        "                       "
PRED STRU1010   P_START
RETURN
PROJ OAR1 END
```

Figure 6. An OARPLAN display of part of the zoned activities of Figure 5. The inset window shows a small part of the output text file, produced as an option after planning has taken place (see section 2.3). The output file shows intra and inter-zone precedences

By exploiting the system's inherent bottom-up approach to planning, in which component-level relationships are established and stored, it is possible to use these low-level precedences to provide accurate constraints on aggregated zone activities. For example, once durations have been attached, and by making use of precedence relationships which exist in the overall plan (but not shown on the zone activity plot), it is possible to constrain the level of concurrency between individual zone activities to that permitted by precedences external to the 'zone boundaries'. OARPLAN is therefore capable of not only producing a plan through elaboration, which includes sufficient detail to cater for estimation and control, but is also capable of abstraction through aggregation. The zoning strategy used has the effect of applying extra constraints on each activity, thereby facilitating intelligent zone planning and dynamic redefinition of zone boundaries.

2.3 Activity Duration

Future versions of OARPLAN will be linked with an automated estimating system. In the present study, the RS Means™ [1987] estimating guide was used as the basis for calculating activity durations. The guide calculates the average cost and productivity for most all types of construction, from all major US cities. Crew breakdowns are provided as well as geographical adjustment factors to account for price differences within the US. RS Means is one of the most used cost estimating references in the construction industry.

The process employed to arrive at activity durations was as follows:

1. The activity was referenced in RS Means by component,
2. productivity rate of units (square feet, cubic yard, etc.) per crew hour was recorded,
3. the number of units for the subject activity was calculated,
4. activity units was divided into the productivity rate,
5. the resulting figure represented the number of crew hours required to accomplish the activity.

The assignment of durations to planned activities, and the process of activity aggregation resulted in the realization of schedules capable of objective evaluation by potential users.

2.4 Integration With a Scheduling System

Early in the study, it was discovered that, in order for a realistic user-assessment to take place, it would be necessary to present OARPLAN's results in a form acceptable and generally understandable to the user. Not only was a comprehensive plan output deemed a priority, but the ability to manipulate, query, improve and schedule was considered necessary for any real-life application. Our strategy here was to integrate into our system, an industry standard commercial software package - Primavera™ for these purposes. OARPLAN is now capable of producing a batch file, which can be read by the Primavera system. The inset text window in Figure 6 displays part of a typical file produced by OARPLAN, and Figure 11 represents a typical subsequent output from Primavera. Once OARPLAN has completed its planning phase, information is available in the specific model (some from the generic model through inheritance) to provide the following information:

- The project title
- Project start, finish and data dates
- Information on the working week and non-work periods
- Activity code definitions and activity codes
- Resource definitions (resource dictionary)
- Activity records (containing a unique identifier, activity title, and calendar ID)
- Precedence relationships between the activities defined in the activity records

The activity title field is created as the concatenation of an activity's action and object, e.g. CONSTRUCT_COL_FTGS====>STRU_FT_1F. The unique identifier in the activity records is created by concatenating a numeric identifier attached to each activity , with the type of activity, e.g. STRU, ARCH, etc. Both of these values are created by OARPLAN during the modeling phase. Most of the other fields are completed by the user at the time of file creation (apart from resources, which are discussed in section 3). A form-based front-end will be added to the system in the future to facilitate the input of project-specific data, such as holidays, total project duration, title, etc. This kind of interface will also be useful in eliciting details which could be used during specific model instantiation, for example building methods, building type, location, etc.

3. A Case Study: The Human Performance Laboratory

As a robust test of the system, an existing substantial construction facility design was selected. The facility is the 'Human Performance Research Laboratory (HPRL), located at AMES Research Center in Mountain View, California. The $11-million HPRL facility supports NASA's research of human performance and capabilities in space. It is a steel-frame and concrete building composed of a two-story portion attached to a high bay structure. The two-story portion houses computer rooms, disciplinary laboratories, technical support work areas and offices, and a mechanical and receiving area, which total approximately 57,000 square feet of floor area. The 80 foot clear high bay is provided for space station mockup support and shop areas. Figure 7 shows the plan configuration and perspective of the HPRL.

3.1 The Design-to-Construction Process

The HPRL followed the standard design-to-construction process, which is common for the majority of public works construction projects. Architectural/Engineering (A/E) services were contracted by NASA and construction bids were solicited, with the lowest qualified bidder being awarded the construction contract. The government established a project budget prior to awarding any contracts, which covered the cost of A/E services, construction costs, inspections and NASA's costs to administer the project. The project budget typically is not modified after approval, but additional features of the project may be added or deleted, depending on the A/E's estimates for the cost of construction and the award amount for the construction contract.

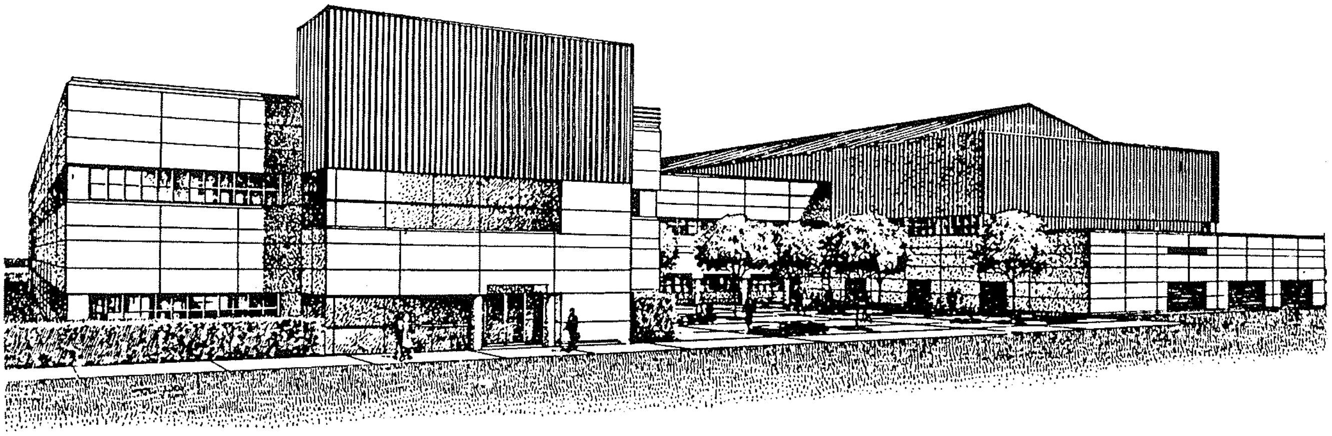


Figure 7. The NASA Human Performance Research Laboratory at Moffett Field, California

This process is filled with pitfalls. In the case of government projects, the A/E must adjust their design approach. Functionality is the primary goal, with aesthetics relegated to the lowest priority - if prioritized at all. NASA's facilities are research and support service oriented and can be aptly described as utilitarian in nature. Government and non-government owner's alike face challenges throughout the process; clearly the owner, A/E and contractor are motivated by different factors. Considering that the owner relies on the A/E to forecast construction costs and schedule, the nature of the contract documents and the award of the construction contract to the lowest qualified bidder, it is clear to see that the link between design and construction is critical. The HPRL was an ideal case study for OARPLAN. The design is relatively unsophisticated, the structure is of substantial size and contains a large number of physical components. In addition to this, the building already exists, i.e. has been subjected to the design-to-construct process, and therefore provides a good example for comparative testing.

3.2 The testing procedure

The drawings and specifications for the HPRL were subjected to a 'reverse engineering' process, which not only resulted in an adequate description of the facility, but also provided the necessary vehicle for knowledge elicitation. This information was then processed by the OARPLAN system and tabular reports and network graphics were produced. The system was constantly reviewed and modified with each iteration of input file generation during the knowledge elicitation and model-building phase of the study, and many subsequent reports and graphics were available for on-going evaluation. The basis for modifications to the OARPLAN system was:

application:	will the information and format of the information generated be useful to practitioners (construction contractors, managers, etc.)? and;
innovation:	how can the design-to-construct process be improved and/or maximized by OARPLAN?

Two representation schemas were developed to cater for the reverse engineering and model-building processes: the generic model and the 3-dimensional grid reference system

3.2.1 The Generic Model

The modeling methodology of OARPLAN demands that the three concepts of object, action and resource are represented. In our implementation, all three attributes of a project activity are modeled as abstraction hierarchies, with each node in the hierarchies being frames into which generic information is placed. That information includes descriptive and associational material. The physical_components hierarchy represents a generic model of, in this case, a facility. It holds information on possible building configurations, and by virtue of its association with similar hierarchical structures for actions and resources, sufficient information can be accessed in the inferential process of construction planning. In our study, we developed a physical_components' hierarchy, specifically tailored toward structural steel building types. During the early stages, the shop/office complex was used as the primary test case and served as the developmental foundation for the hierarchy. After initial validation, the HPRL became the subject test case and served as a basis for expansion of the hierarchy into its current state.

Development of the physical_components was initially based on the CSI MASTERFORMAT, which is published by the Construction Specifications Institute and is widely used in the US to organize specifications in a standard format. It is well known in the construction industry and was instrumental in assuring potential gaps and overlap in the physical_components hierarchy were avoided.

The hierarchy is organized according to a building's major components: 'Architectural, Structural, Electrical and Mechanical'. These major components and each subsequent class of component were successively elaborated into classes and sub-classes, until individual components of the building were represented at the leaf nodes, i.e. grade_beam, column, slab. The hierarchy breakdown is similar to the Work Breakdown Structure (WBS) used by many estimators and schedulers today. The structural components portion of the hierarchy is shown in Figure 8.

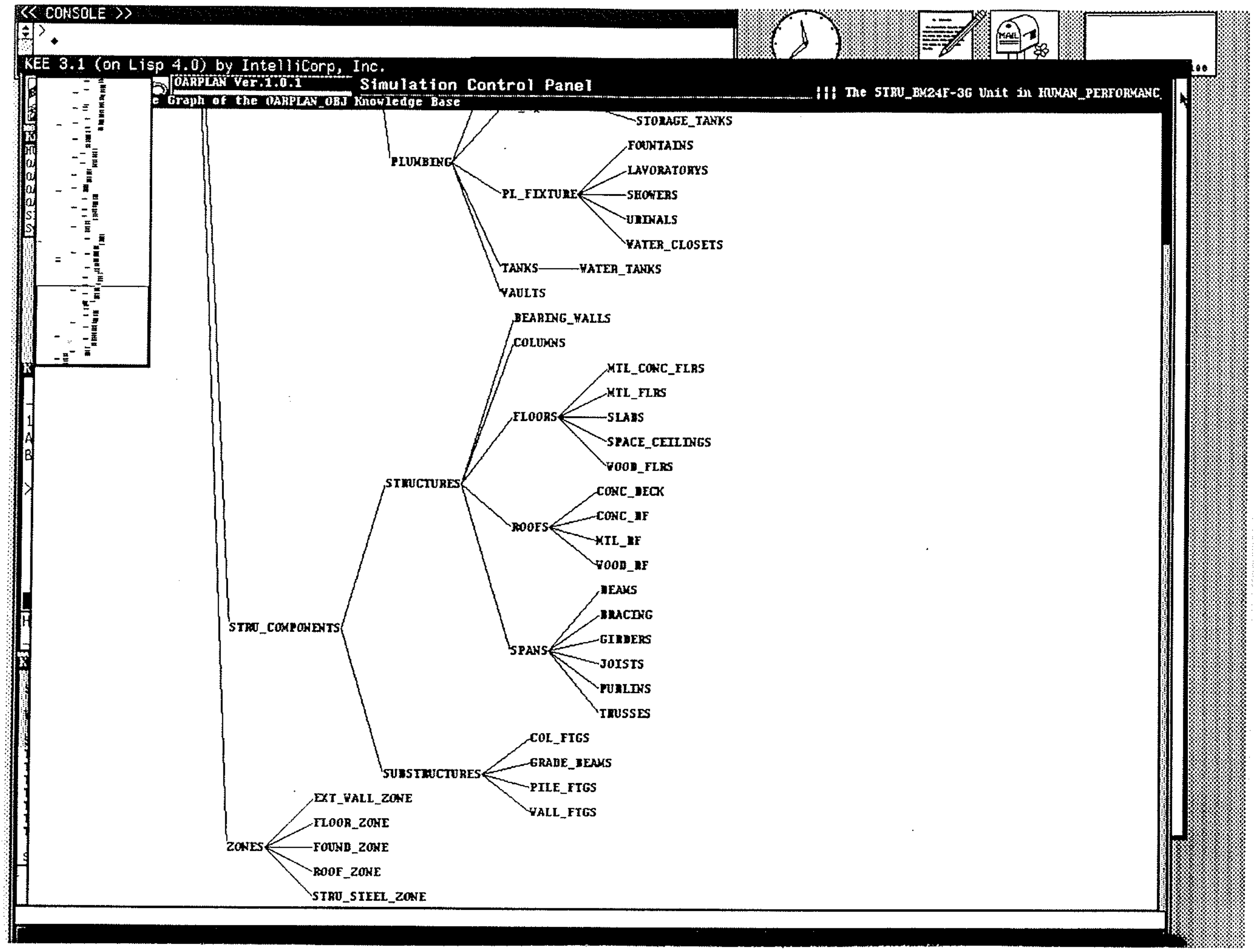


Figure 8. Part of the physical_components hierarchy in OARPLAN, showing mainly the structural components sub-hierarchy

The resource hierarchy was segregated into its natural division of labor, material and equipment. Labor resources (or trades) are based on the labor market and union agreement jurisdictions. When establishing material and equipment resources, consideration was given to the fact that a variety of construction methods and means are available to the contractor. All resources required to construct the HPRL were known (the building exists), however flexibility was built into the hierarchy to display its universal application. Economics is the predominant consideration when the contractor is selecting a construction method, and this typically equates to the contractor employing standard methods of construction to accomplish the project. In the case of the HPRL, 'standard' methods were used, specifically to construct the foundation and erect the structure. Labor, material and equipment resources were developed in particular for each structural component of the 'Physical_Components' hierarchy. Flexibility in the resource hierarchy was maintained specifically by allowing for varied site conditions. For example, the trades 'Carpenter' and 'Finisher' are associated with 'grade_beams', which may or may not require the action 'form_beam' and/or 'finish_beam', depending on the soil conditions and elevation of the 'grade_beam'. In either condition (or both), the appropriate trades are available in the generic model.

3.2.2 Grid Reference System

The grid reference system is required to uniquely identify individual components within the building. Such an arrangement is vital in any system capable of spatial reasoning. OARPLAN is capable of representing and reasoning about the interrelationships which exist between components making up a building, and 3-dimensional virtual components through zoning. In response to this need a Grid Referencing System (GRS), based on the existing grid system created by the A/E during the design and delineated on the working drawings, was developed. The two-axis grid system is used on most large projects by the A/E and typically reflects the structural system, with grid intersections coinciding with vertical structural supports. An example of the A/E developed grids used by the GRS is shown in Figure 9.

Logically, the grid system must be labeled numerically in one direction and alphabetically in the transverse direction. It is preferable that the grids be labeled consecutively. This would allow the user to quickly locate components based on their GRS label; an example would be the component 'BM21JK', which is taken from the input file of the HPRL and indicates the following: '2'nd floor 'BM' (beam), located along grid '1', and extending from grids 'J' to 'K'.

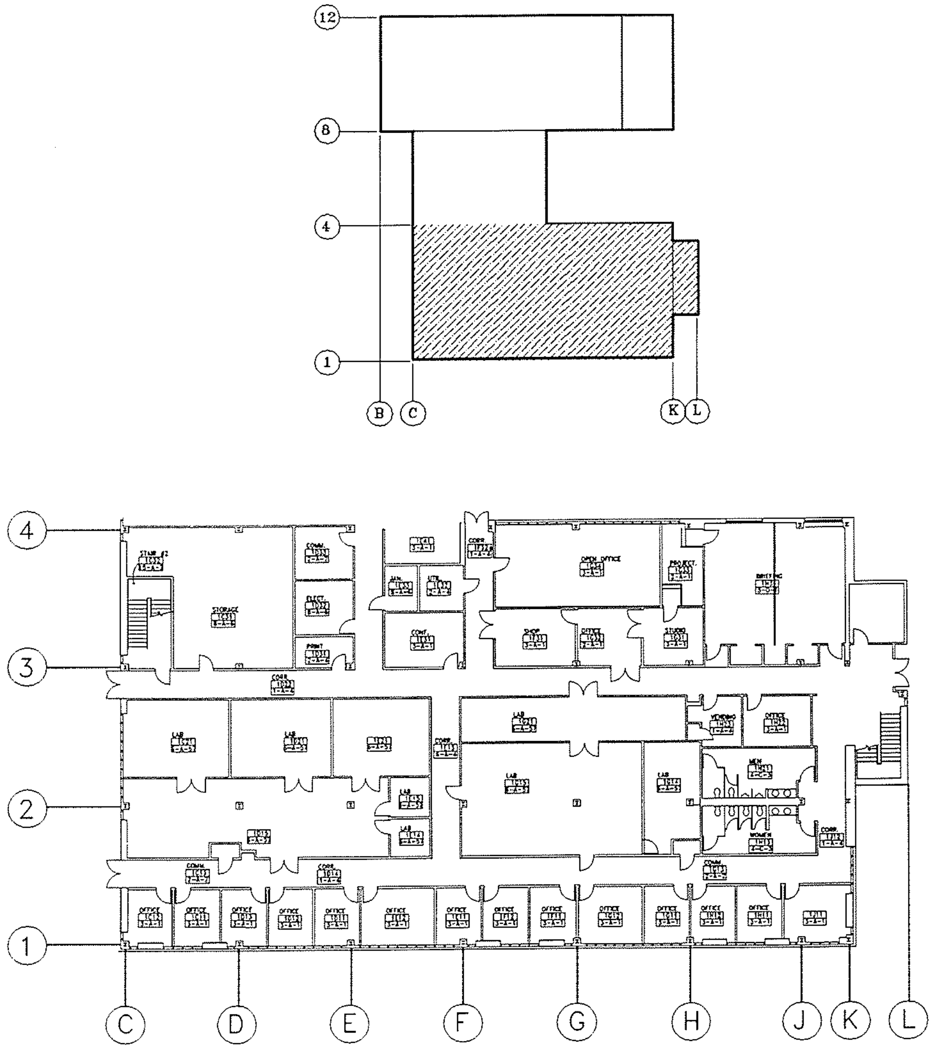


Figure 9. An overall layout and detailed drawing for the HPRL

3.3 Results of Application

The process illustrated in Figure 4 was applied to the HPRL. The plan produced by OARPLAN was used as the primary (batch) input to Primavera for scheduling and display purposes, both as a total (unzoned) plan and as planned and aggregated activities. For illustrative purposes, and in the interests of clarity, we have concentrated in this section on one relatively small, but representative, zone within that plan - Zone4.

Zone4 represents an area of work in which average-size crews of each trade would be able to perform the work required, without stacking or overcrowding of trades. Factors such as cycling trades from one area to the next were also considered in the determination of crew sizes. In keeping with common construction practice, Zone4 was also determined by the logical segregation of an area as specified by the drawing grid lines.

Figure 10 shows the sub-plan produced by OARPLAN for Zone4, including its self-defined start and end nodes created during the zoning process. Figure 11 is the same plan presented as a bar chart and produced by the Primavera™ system.

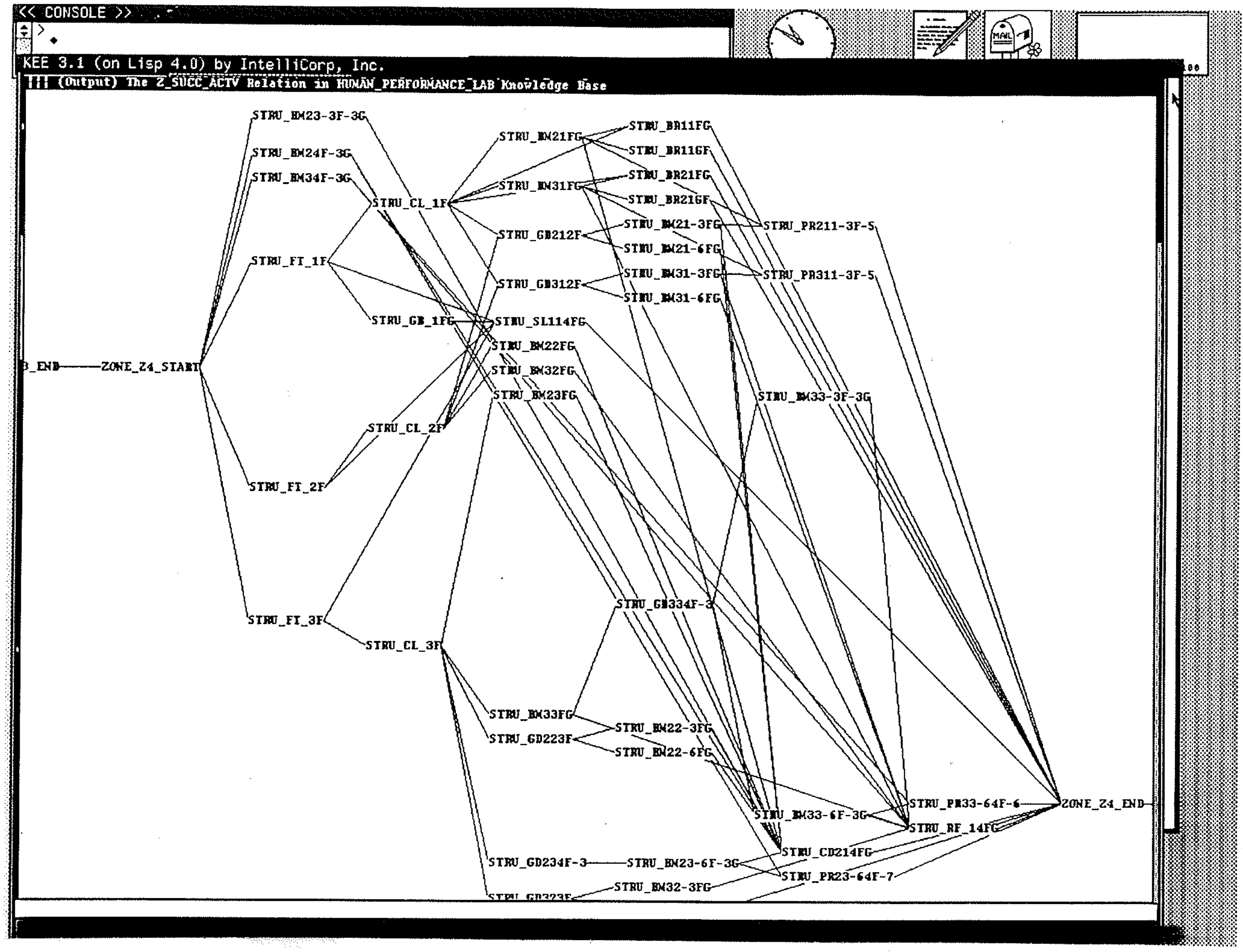


Figure 10. The plan produced by OARPLAN for Zone4 and presented as a precedence network

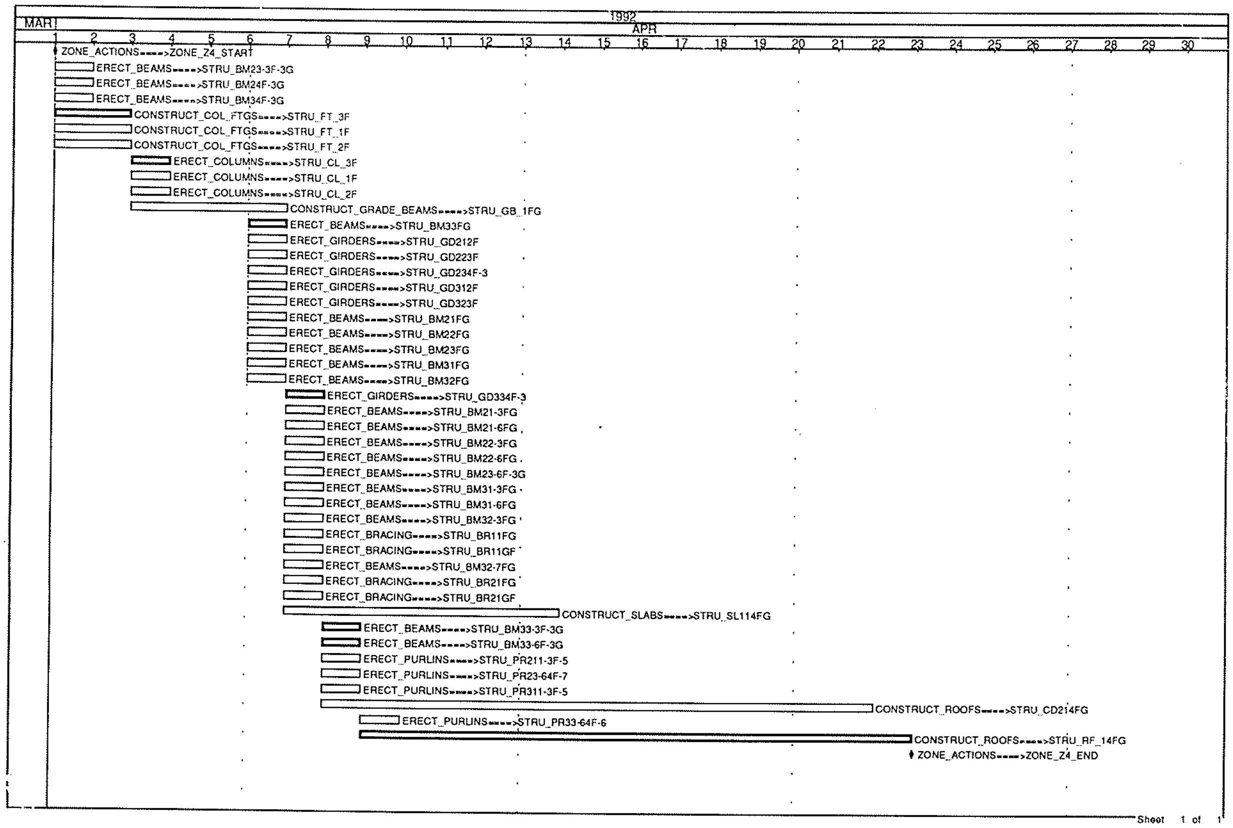


Figure 11. A bar chart presentation of the plan shown in Figure 10

4.0 A Practitioner's Evaluation[4]

Throughout the design-to-construction process the project team (Owner/Developer, A/E and Contractor) estimates, plans and records information related to the cost and duration of the project. The following are just a few questions and situations that may require estimates and schedules to be revised or modified:

- The cost of a significant piece of equipment
- The overall estimated construction duration
- Scheduled activities for the next two weeks, and for the remainder of the project
- The impact of delaying material delivery or unexpected labor shortages

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[4] Mike Chacon, the second author, is employed as a Construction Manager at NASA, Moffett Field. As a domain expert on the project, he provided a continual evaluation of the system and its results, and was crucial in guiding the development of the structural steel facility general model on which much of the work was based

The existing process of estimating and scheduling projects has been in practice for years. The A/E produces an estimate and schedule from the drawings and specifications at various stages of the design phase. In turn, the Owner uses this information to forecast costs and time requirements. Subsequently, contractors bid the project, based on the completed plans and specifications. The low bidder is awarded the contract, prepares a schedule and begins work. The description is extremely simplistic, but leads to the point that - the A/E's and Contractor's estimate and schedule are rarely reconciled. The use of OARPLAN provides the platform to facilitate reconciliation with little difficulty.

The Owner constantly requires schedule (actual and projected) updates and feedback throughout the life of the project. The more common information sought is: How much time is required to construct the project? and, Can the time be reduced? or, When will the structure be complete? and, When will the building be closed (roof and walls be constructed and substantially complete)? OARPLAN's capability to provide automatic feedback, allows the A/E to respond to these types of questions. Contractors can benefit fully from an integrated system incorporating OARPLAN, by utilizing its design-to-scheduling capabilities. The system can assist in the creation of construction plans, preparation of bids, and more, but most importantly will be the opportunity for the Contractor to view the assumptions made by the A/E for the amount of resources required during the design process. Significant differences between the A/E's estimate for construction and duration and the Contractor's bid and schedule can be highlighted in the early stages of the project and resolved with minimal effort and impact.

Additional system capabilities will be the consideration of safety, site conditions, available resources, contractual constraints and 'seasonality', to name a few, in the creation of estimates and schedules.

5.0 Conclusions

Our work has demonstrated the suitability of the OAR representation applied to the modeling of realistic-scaled construction facilities. The representation provides the means, not only to build and maintain large generic component and process hierarchies, but also to perform reasoning about plans and actions. Simple example buildings can be scaled up to real projects, but the resulting complexity of the plan (not the model) can lead to problems in validation. A plan serves to facilitate a schedule, and activity zoning provides a convenient and intuitive means to compartmentalize the problem and manage complexity. Zoning can be physical or functional, and by virtue of our implementation, can be both, i.e a complete floor of a building can be assigned to a zone as a virtual component, or functional zoning can be achieved by assigning convenient areas of work assigned on a trades basis. At present the OARPLAN system relies on physical zones, established by the designer and included in the CAD input file. However, problems may occur during scheduling, when inter-zone constraints are taken into account. Future work will include research into the use of knowledge-based critics as used in the GHOST system [Navinchandra 1988], which could provide the means to refine and dynamically shape the zones on the basis of scheduling knowledge.

The temporal component of the model can be determined by taxonomic references, such as the RS MEANS™ data base, or company-specific data on anticipated crew sizes and known productivity. Quantities (ft^2, ft^3, etc.) can be automatically extracted from the CAD model in order to provide parameter values required for estimating purposes, and from those, realistic schedules can be produced.

The future holds the promise of expressively-rich domain models, resulting in the ability to produce plans either in a top-down fashion, in which many heuristics must be employed in producing schedules, or as a bottom-up process, in which aggregation must occur for realistic schedules to result. Our system is able to apply both techniques in an initially bottom-up fashion in response to the detail available from CAD, and then by zoning on the basis of a number of principles. Since the system's primary data input is from a CAD system, the models produced at this level of detail not only provide the means for reasoned aggregation, but also provide the foundation for two-way integration with the planning/scheduling and CAD systems.

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