OBJECT-ORIENTED MODEL FOR INTEGRATING CONSTRUCTION PRODUCT AND PROCESS INFORMATION

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ABSTRACT: Product and process models provide the necessary information framework for implementing computer systems for the architect/engineering/construction (A/E/C) industry. Although the focus of these models is slightly different, both are needed to provide a foundation for managing project information during the design and construction phases. Design information—"product" information based on building components—needs to be integrated with construction management tasks, the "process" information necessary to build the components. It is therefore important to provide an integrated information model to bridge the gap between product and process information for a construction project. An integrated information model not only encourages those involved in construction to use and add to design information, but also provides richer information representation, better efficiency and data consistency, and the flexibility to support life-cycle information management. The research presented in this paper was performed under the auspices of the collaborative engineering research program at the U.S. Army Corps of Engineers Construction Engineering Research Laboratories (USACERL), which is attempting to redefine existing design processes to make them more collaborative and to develop enabling technologies to support the new process. An important part of this research is the development of an integrated information model that allows agents to communicate/collaborate over the life cycle of the project. This paper presents an object-oriented model that integrates product and process information to support collaboration among design and construction agents, and two prototype construction agents for construction planning and monitoring project progress. The development of these two agents demonstrates the value of using integrated product and process models for managing facility information in the A/E/C industry.

INTRODUCTION

Information management, during facility design and construction, involves many individuals and organizations exchanging much information at different times and locations. With an annual expenditure in design and construction totaling \$4,500,000,000, the Army has proactively pursued innovative ways of managing this design and construction information.

Ideally, the information management strategy used during the design and construction phases would eliminate re-entering data, encourage design and construction integration, enable the collection of electronic as-built information, and provide facility operators/maintainers with the information structure necessary to successfully use and maintain a new facility.

Different computer applications typically support engineering and management tasks at each phase of the process. However, a coherent and integrated information management strategy is needed to better transfer facility information among the planning/design, construction, and operation/maintenance phases. Different product and process models, proposed to characterize or integrate facility information, provide guidelines to portray information flows and attributes that form the basis for implementing computer systems. Researchers are working on international information exchange and representation standards, so that facility information can be freely exchanged by different computer systems.

The present paper summarizes existing research in information modeling and project planning/control; current design and construction processes used by the Army; goals of the research program that are applying collaborative engineering to the current facility delivery process; an object-oriented model for integrating design and construction information; and two prototype agents based on the object-oriented model.

CURRENT RESEARCH

Information Modeling

Current information modeling for the architect/engineering/construction (A/E/C) industry includes product, process, and project models. A *product model* is a conceptual structure used to organize and communicate building product information among project participants. Gielingh (1988) developed the General A/E/C Reference Model, which specifies the structure of a product model, based on Product Definition Units, functional units, and their technical solutions. Bjork (1989) proposed the RATAS model, which organizes a building product model based on composition/decomposition relationships of building components. Researchers are working on STEP/PDES (NIPDE 1995), which attempts to standardize computer-interpretable representations and exchange of product data.

Process models represent important steps throughout a project's life cycle. Sanvido (1990) developed the integrated Building Process Model, a reference model for project processes. Key functions and information flows are identified by dividing the life cycle of a facility project into five processes (i.e., Manage, Plan, Design, Construct, and Operate facility) and their subprocesses. Fisher and Yin (1992) introduced the General Data-Flow Model based on data flow from a construction contractor's viewpoint.

Project models provide a framework for system integration of product, process, and organizational aspects for A/E/C

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Note. Discussion open until December 1, 1996. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on December 12, 1995. This paper is part of the *Journal of Computing in Civil Engineering*, Vol. 10, No. 3, July, 1996. ©ASCE, ISSN 0887-3801/96/0003-0204-0212/\$4.00 + \$.50 per page. Paper No. 12159.

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projects to provide richer semantics for project management. The Unified Approach Model (Bjork 1992), GenCOM (Froese 1992), BPM (Luiten 1992), and IRMA (Luiten et al. 1993) are among the project models for the A/E/C industry.

Project Planning and Control

Previous research into automating the planning process includes: Construction PLANEX (Zozoya-Gorostiza et al. 1989), OARPLAN (Darwiche et al. 1989), CASCH (Echeverry 1990), Integrating Construction Scheduling with Cost Estimating (Yau 1992), and Know-Plan (Ayman 1992). Other efforts to integrate construction cost and schedule for project control include Grobler (1988) and Rasdorf and Abudayyeh (1991). Other research (Liu et al. 1994; Ganeshan et al. 1994; and Chin et al. 1995) focused on controlling construction projects and managing as-built information during construction.

Summary

Current research in information modeling techniques, construction planning, and control is a good foundation for integrating design and construction information for construction projects. However, most modeling efforts are not developed to the level of detail considered useful for developing practical applications specifically in the domain of construction control.

Previous efforts in construction planning are fairly comprehensive; they consider issues related to construction technologies, crew allocations, and activity durations. OARPLAN and CASCH introduced the approach to sequencing activities, based on relationships between objects adopted in this effort. However, these approaches lack a flexible definition of "realistic" construction activities and consideration of spatial requirements associated with construction activities. An evaluation of OARPLAN in the context of construction planning for a "real-life" application (Winstanley et al. 1993) determined that the component-level plan was too complex to be useful. More realistic work packages were developed that aggregate component-level activities, based on the assignment of components to zones (Winstanley et al. 1993).

Managing construction progress has tended to focus on a particular viewpoint. A more flexible information system can be developed for construction management by using advanced object-oriented modeling techniques that integrate multiple viewpoints.

ARMY FACILITY DELIVERY PROCESS

The Army Corps of Engineers manages the design and construction of military facilities, civil work projects, and environmental remediation projects for the Army and other customers. Private architecture/engineering (A/E) firms designed approximately 75% of the facilities built for the Army in fiscal year (FY) 1995 at a cost of $319,000,000. Almost all of the $4,200,000,000 in Army construction in the United States will be accomplished by private sector firms during FY95. USACERL researchers have been working to improve both the facility delivery process and the quality of the constructed facility. Leverenz et al. (1983) analyzed the Military Construction Army (MCA) building delivery process to identify the MCA process steps, phases, participants, decision points, legal and technical requirements, and products. Similar investigations were conducted on two variations of the traditional two-step building delivery process: the Army Design/Build process (Napier and Freiburg 1990) and the Army Third Party Construction process (Napier and Stumpf 1993). Then USACERL

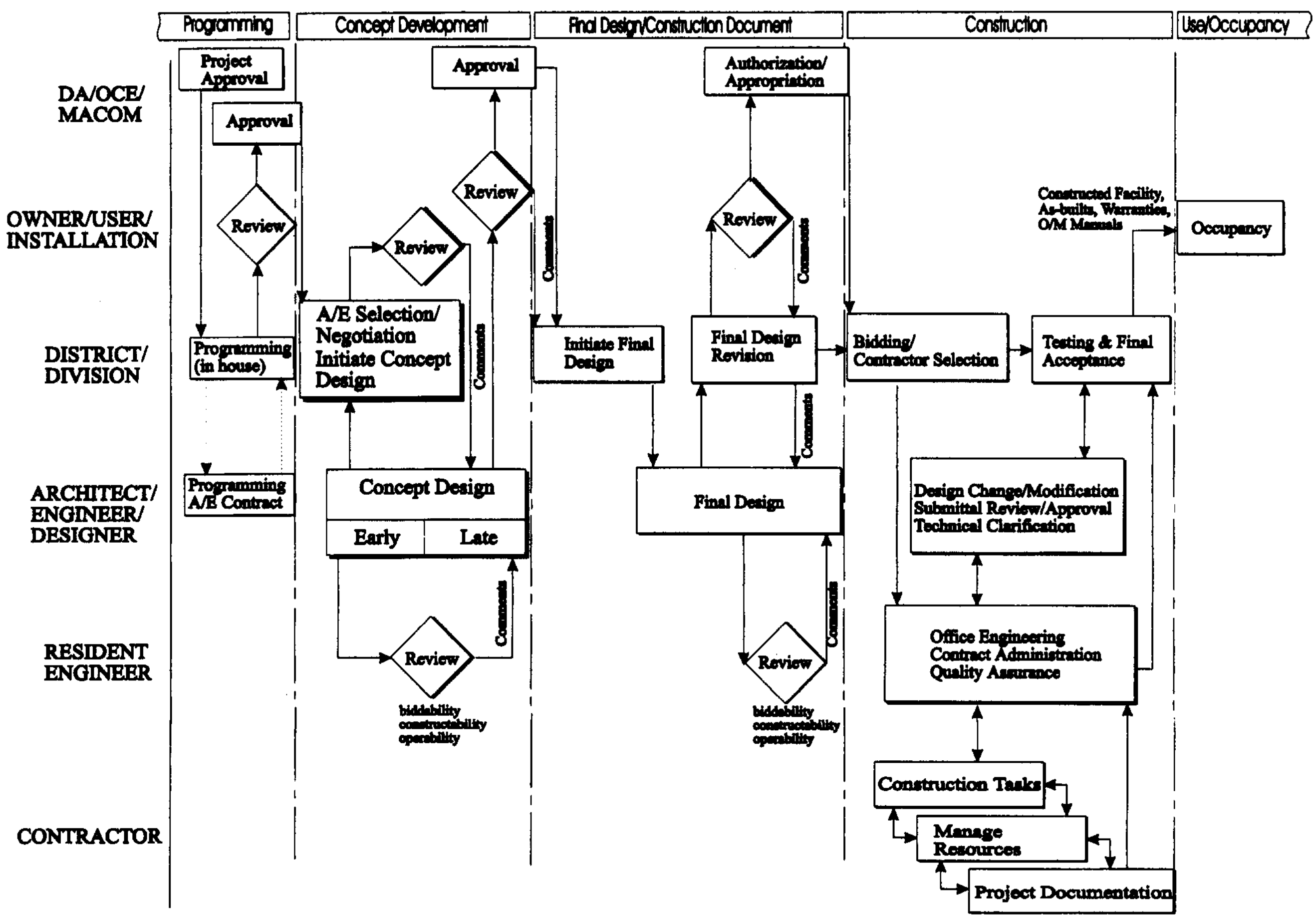

FIG. 1. Design/Construction Process of Military Construction Army

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TABLE 1. Participants, Responsibilities, and Products of Military Construction Army Process

Participants (1)	Responsibilities (2)	Products/documents (3)
Department of the Army (DA), Office of Chief engineer (OCE), Major Command MACOM	Functional and capability planning analysis, prioritize projects Request funding authorization from U.S. Congress Manage design and construction program Update design and construction requirement	Five year defense program Army stationing and installation plan Long-range construction program
Owner/user installation	Identify training and facility requirements Evaluate and select site Assess environmental impact Determine functional and technical requirements Design review and approval, user changes Construction coordination, acceptance	Installation master plan Real property requirements Environmental impact statement (if required) Detailed site plan Architectural program (functional/technical requirements) FORM 1391, cost estimate (scope and budget) ARMS (Automated Review Management System)
District or division	Request funding approvals for programming, design, and construction Develop architectural program (functional/technical requirements) or hire A/E firm Select A/E and negotiate (design) Coordinate design, review, and approval Bid and select contractor (construction) Expedite materials, manage public relations, close-out project (after construction) Manage public relations	Architectural program (functional/technical requirements) Design reviews/construction changes Design and construction contracts Project management plan, upward reports ARMS (Automated Review Management System)
Design agency (Corps or A/E firm)	Prepare design and engineering analysis Prepare concept and final design/changes Prepare construction documents, specifications, cost estimate, value engineering Review shop drawings Analyze life-cycle costs	Working drawings Specifications Design analysis Detailed cost estimate Design changes during construction ARMS (Automated Review Management System)
Resident engineer	Review and approve payment requests Negotiate change orders Assure contactor quality Review submittals, materials, shop drawings Assure customer satisfaction Review and analyze contractor's progress Prepare correspondence Monitor contractor's safety program Collect as-builts, warranties, O&M manuals Identify trends/lessons learned Site coordination Prepare A/E and contractor evaluations Review biddability, constructability, operability	Contract plans and specifications with modifications, construction progress reports, site layout, schedule approval, payment estimates, QA/QC plan, critical materials/status, actual/anticipated delays, record drawings, safety records, claims, funding status, QA/QC reports, significant deficiency action plan, submittal registers, shop drawings, accident prevention plan, environmental control plan, certified payrol register, affirmative action plan, A/E and contractor performance evaluation, project meeting minutes (prebid, preconstruction, construction quality control/assurance) ARMS (Automated Review Management System)
General contractor	Perform contract according to plans and specifications Manage site, labor, equipment, materials, time, and subcontractors Document construction progress, changes, quality, safety, and others	Preliminary schedule, cost estimate, site layout progress reports, payment request, QA/QC reports, schedule update, request for information, major resource schedule, samples/certification/test results, warranties/operational manuals, as-built drawing update (contract-specific), shop drawings, safety plan and records, daily manpower and minority

developed a detailed model of how participants collaborate during the design process (Case et al. 1995). Finally, the construction process was analyzed from the resident engineer's viewpoint to determine the type and format of design information that goes into the construction process; how resident engineers use the information during construction; what kind of as-built and project control information is collected during construction; and the type and format of the as-built information delivered to the facility's owner. Special attention was given the use of computer-aided design and drafting (CADD) technologies and information systems used by resident engineers during the construction phase (Stumpf et al. 1993). A study of as-built project information used (and desired) during facility management operations, and maintenance was also conducted (Liu et al. 1994).

Fig. 1 depicts the participants and major activities that occur during the MCA design and construction process. Table 1 shows responsibilities, requirements, and products at each phase of the process. The research described focuses on resident engineer's information-management needs during the design and construction process.

APPLYING COLLABORATIVE ENGINEERING TO FACILITY-DELIVERY PROCESS

A USACERL research program, "Architect's Associate," applies collaborative engineering to the facility-delivery process (Golish 1993). During the Architect's Associate effort, the Construction CADD Research project focused on obtaining and using electronic design information during the construction phase. The long-term goals for this project are the following:

1. Use intelligent 2D/3D CADD (tied to a database) design information as much as possible for biddability, constructability, and operability (BCO) reviews; cost estimating; scheduling; project control; quality assurance; and capturing as-built information.

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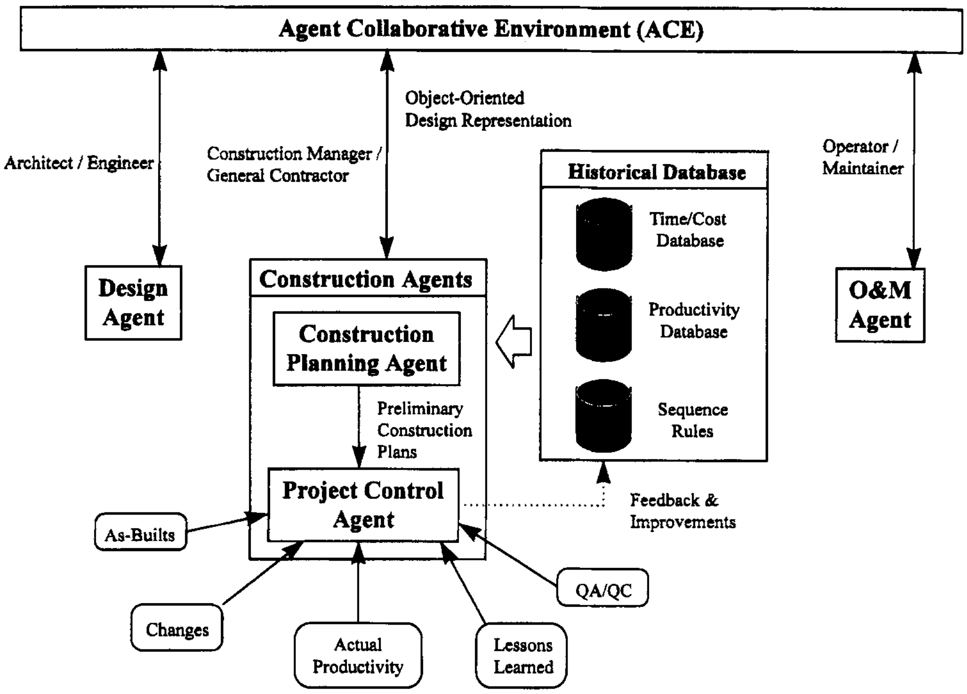

FIG. 2. Agent Collaborative Environment

2. Minimize redundant data input by starting with the design representation and adding changes/actual component information during construction.
3. Build an integrated information framework to allow use of intelligent CADD design information and addition of detailed building-component data, project-control information, and multimedia as-built information during construction.

Through an analysis of the MCA facility-delivery process and demonstrations of several prototype systems to resident engineers, construction planning (during the design phase) and construction project control were identified as resident engineer responsibilities that would benefit from an integrated framework of design and construction information.

This USACERL research focuses on two main technical areas: agent-based design tools and collaboration among agents in heterogeneous systems. An "agent" is an automated tool that helps the user perform specific tasks. The Agent Collaborative Environment (ACE) is a prototype system developed by USACERL to provide a platform for agent development, collaboration, and conflict identification (Case and Lu 1996).

The Construction Planning Agent (CPA) and the Construction Project Control Agent (CPCA) represent the construction viewpoint and collaborate with other agents being developed as part of the Collaborative Engineering project. Agents can communicate with each other in ACE because they share an object-oriented model that integrates product and process information for a design and construction project (Fig. 2). The CPCA extends the shared representation to include information specific to project control. The integrated object-oriented model presented in this paper forms the basis of this shared representation.

INTEGRATED CONSTRUCTION INFORMATION MODEL (ICIM)

Integrating product and process models is based on an object-oriented paradigm that defines relationships between design components and construction processes. Features of the object-oriented modeling approach include: data abstraction, encapsulation, inheritance, and relationships between objects. The ICIM in Fig. 3 shows construction planning, control objects, and their relationships based on Object Modeling Technique notation (Rumbaugh et al. 1991).

Component objects represent the physical aspect of a building, such as floor, column, beam, wall, and foundation. The building component hierarchy is based on the Uniformat classification (Uniformat 1992); however, it does not necessarily correspond one to one. Component classes may inherit from higher-level components and from material classes [based on SfB classification (Jones and Clegg 1976)], as shown in Fig. 4. *Component* objects can have other components for parts, as represented by the part-of relationship shown in Fig. 5. *Component* objects have an "is-version-of" relationship to track changes, such as as-planned, as-is, and as-built during construction. *Drawing* objects, in CADD files or models, are graphical representations of *Component* objects that have an "is-described-by" relationship with the *Component* object.

The *Activity* object represents construction process information. The many task-level activities in typical facility construction use the aggregation relationship ("is part of") to represent hammock activities. Precedence relationships among activities are represented by the "precede" relationship. The *Activity* class is further specialized following existing schemes such as the Activity Definition Index (Nomani et al. 1990) and Masterformat as starting points for the inheritance hierarchy. The top-level activity class includes attributes common to all activities, such as name, duration, early start, late finish, and so on. All other classes inherit from the *Activity* class, adding information necessary for the specific activity type. For example, the "Earthwork" class inherits attributes from the *Activity* class and defines additional attributes like soil type, soil moisture content, and so on. Further, the "Excavation" class inherits from "earthwork" and defines additional attributes like angle-of-repose, depth-of-excavation, bracing-required, dewatering-required, and so on. Instances of the *Activity* classes would be instantiated for a particular schedule. The *Construction Method* class is specialized into a hierarchy that organizes information about construction methods for activities like excavation and placing concrete.

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TABLE 2. Evaluation of Integrated Construction Information Model (ICIM)

Evaluation criteria (1)	Related objects (2)	Comments (3)
Adequacy of information types	Component, activity, cost, resource use	The scope of ICIM is construction planning and progress control.
Multiple abstraction	Component, activity, cost	Each object can support any hierarchical structure using part-of relationship. Combined information at any abstraction level can be generated using the relationships at the bottom level of ICIM.
Product and process integration	Component group	Component-group object represents the relationship between activity and component objects, based on construction work area.
Representation of time and cost integration	Resource use	In the planning phase, component and component-group objects are used to identify necessary activities. Required resources are assigned, and costs are identified based on these resources (activity-based costing). In the construction phase, the actual resource use is assigned from daily log, and costs are identified by cost account, which the resource use belongs to, or by resource type.
Geometric and topological representation of product model	Component	Component object includes topological and geometric shape information. This not only enables automatic activity generation and sequencing, but also makes it possible to partially detect geometric interferences between components, although it needs to include detailed process for construction method associated with activities.
Crew interference detection	N/A	This is not supported in ICIM. However, it is anticipated that it can be possible by refining the work-area concept and including organization model, which mainly represents contract and participating organizations.
Support of multiple points of view	Component, activity, cost, resource use, daily log	ICIM can support preliminary time and cost evaluation, construction progress control, budget control, resource management, and daily log report.
Information consistency and integrity	All relationships	Construction planning and control agents use object-oriented database and keep track of traverse and inverse relationship to guarantee consistency and integrity among objects.
Life-cycle support (information evolution and as-built information)	Is-version-of relationship in component, activity, schedule, resource use, and cost-account objects	ICIM supports design, construction, and facility operation and maintenance phases. By developing construction planning and control agents based on ICIM, information created during the design phase can be incorporated into the construction phase. "Is-version-of" relationship enables collection of as-built information and support of information evolution from as-planned to as-built information.
Extendability and flexibility	All objects	Taking advantage of object-oriented concepts, ICIM allows creation/derivation of new object types and knowledge.[a]

[a]Knowledge in ICIM is limited to automatic activity creation/sequencing and resource allocation/costing in the construction planning agent.

The *Schedule* class is an aggregation of *Activity* objects. Both classes have an "is-version-of" relationship that tracks changes during construction, which may cause changes to related activities. For example, if a duration is changed for an activity, changes to succeeding activities are required. *Daily Log* objects are used to describe the daily construction performance of activities. *Multimedia Document* objects contain daily log information in formats, such as documents, graphic image, video, and audio clips.

Construction Zone and *Component Group* classes enable design component aggregation either by location or by attribute similarity. This capability allows the user to control the level of detail in the construction schedule. Activities are generated for the installation of *Component Group* objects.

The *Resource Use* object represents resources used for a particular activity by associating the activity with *Resource* objects [adapted from the Unified Approach Model (Bjork 1992)]. The *Resource Use* object includes quantities and unit costs associated with resources used for the activity. An aggregation of *Resource Use* objects, *Cost Estimate* is used to estimate costs in planning stages. The *Resource Use* object also is associated with the *Cost Account* object to represent cost information for a specific resource, based on cost accounts established during construction. The *Cost Account* object has an "is-version-of" relationship to track changes to cost information during construction. Definitions for resources (labor, equipment, and crew) found in the MCACES (Micro-Computer Aided Cost Engineering Support System, MCACES GOLD 1992) unit-price database were used.

In Fig. 3, the *Project* object has aggregation relationships ("belongs to") with all project specific information objects, such as *Component*, *Activity*, *Resource Use*, *Daily Log*, *Cost Account*, *Drawing*, and *Multimedia*. The *Project* object represents general project information. The "is-version-of" relationship tracks changes to information at the project level to help capture changes from as-planned information to as-built information. The following sections describe two prototype systems developed on the basis of the integrated model.

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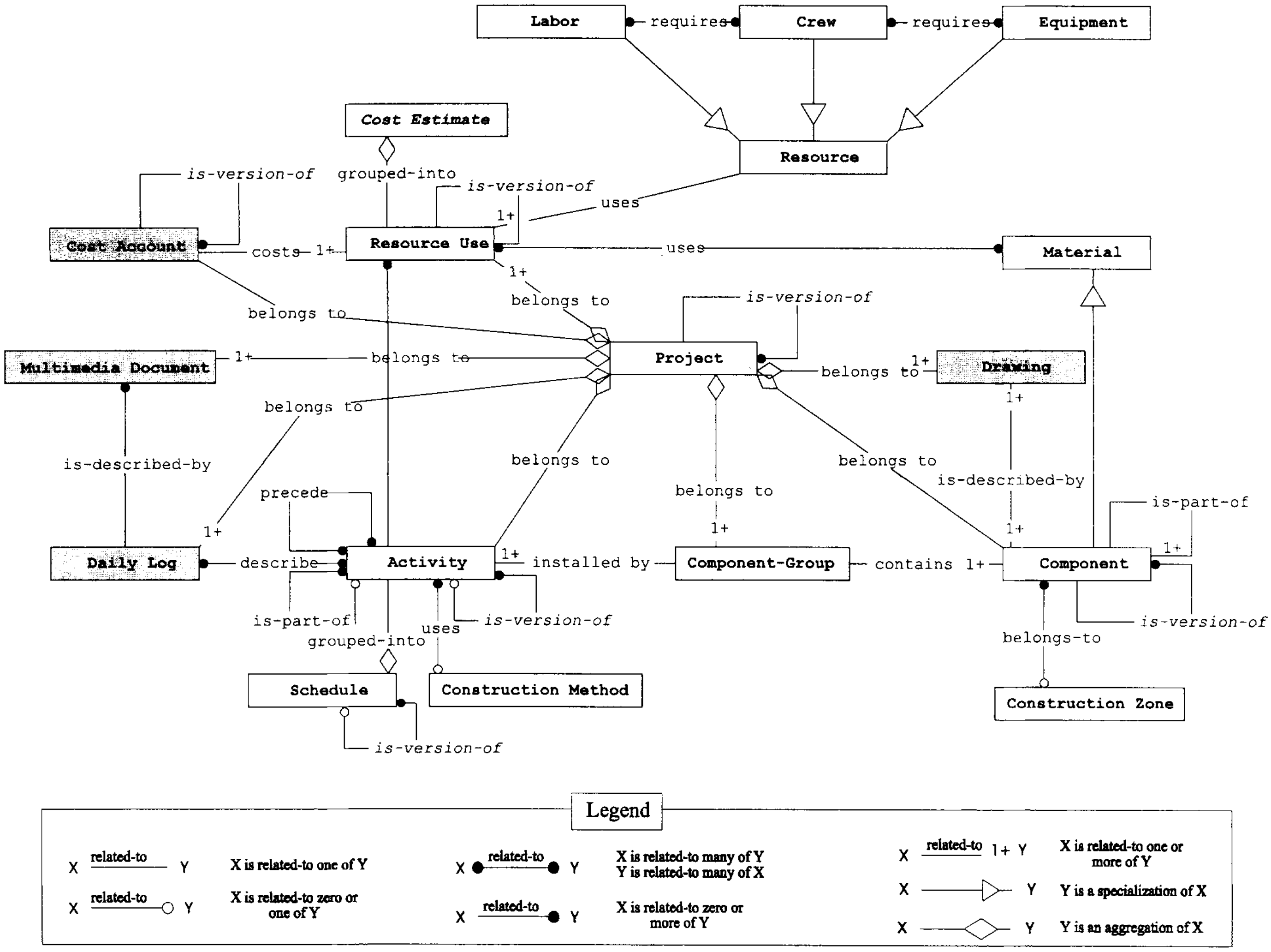

FIG. 3. Integrated Construction Information Model (ICIM)

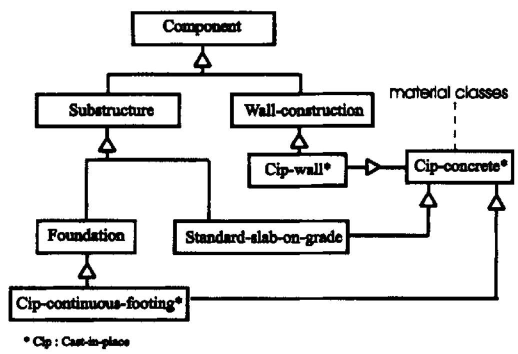

FIG. 4. Building Component Class

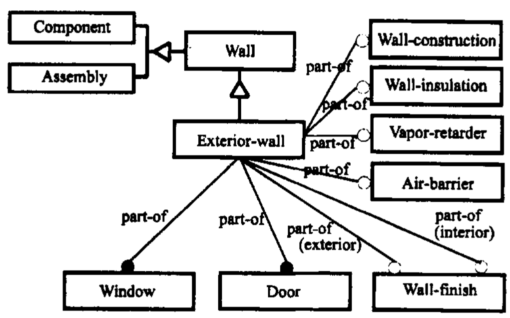

FIG. 5. Assembly

CONSTRUCTION PLANNING AGENT (CPA)

Construction planning determines these five interrelated issues: the overall construction strategy; the level of detail; construction activities; construction methods, resource requirements, and duration for activities; and activity sequence. For example, to determine the degree of site congestion, activities have to be scheduled. But the productivity of crews (and the duration of activities in the schedule) is affected by the degree of congestion on the site. Thus, construction planning is an iterative process where plans may be generated and evaluated several times.

The objective of the CPA is to support generation of a preliminary cost estimate and schedule for facility designs to assist facility designers in evaluating alternative designs from a construction time and cost perspective; animate the schedule to verify sequencing, identify constructability problems, and correct them before actual construction begins; provide a baseline schedule and cost estimate for the evaluation of contractor bids; and computer updated schedules and costs due to change orders and modifications.

The shaded areas in Fig. 6 indicate the scope of automation considered in this effort. The conceptual approach used for schedule generation is similar to the model-based planning approach used in OARPLAN. The goal is to build a complete construction planning environment with facilities for defining flexible work breakdown structures based on spatial zones, system or component parameters, finish constraints, or other deadlines; generating activities required for installation of building systems and components; choosing alternative con-

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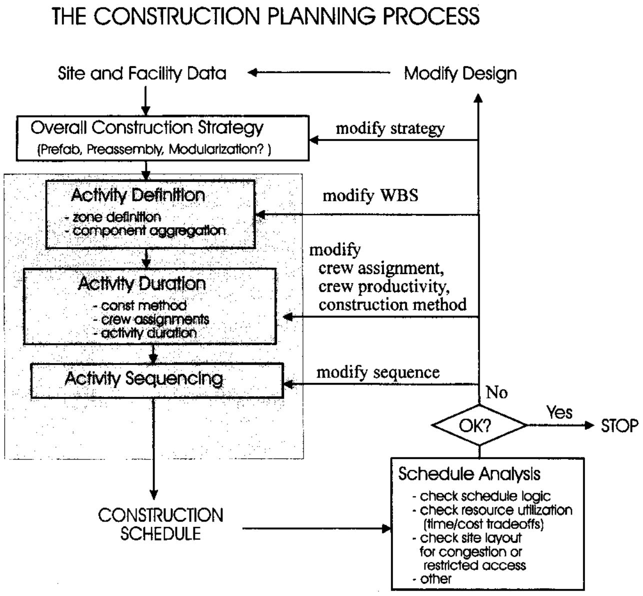

FIG. 6. Construction Planning Process

struction methods for construction activities; assigning appropriate resources; and animating the construction schedule.

The CPA uses the object-oriented model to organize knowledge needed for construction planning including: identifying activities required to install design components and assemblies; computing activity parameters and quantities of work; identifying construction methods; assigning crews based on historical project databases; and sequencing activities. The knowledge is represented as methods and rules associated with the classes in the object hierarchies, described earlier. The rules are grouped together by a type of knowledge or specific task (e.g., identifying activities or identifying construction methods) and the particular object class to which the knowledge is related. Such an organization of rules is necessary to maintain the knowledge-base, especially as it increases in size. It is also useful to reduce the amount of pattern-matching performed during execution of the program by activating only the relevant set of rules. The following sections elaborate on the knowledge representation for various construction planning tasks.

Identifying Construction Activities

The level of detail in a construction schedule is determined by its intended use. Three levels are often identified: organizational, project, and process levels. The *organizational* level involves only key project activities that need to be monitored for timely completion of the project. More detailed, the *project* level may identify activities like excavate foundations, pour concrete for foundations, and so on. The *process* level contains even more detail (e.g., field schedule), including activities such as excavate, load, and haul. In the present research, the detail is limited to project-level activities. Defining construction activities requires knowledge about project-level activities required to install each type of component, including supporting activities. Also, to generate a manageable schedule, the entire site is divided into construction "zones," and activities are generated for groups of components within these zones. Once the activities have been generated at the detailed level, it is possible to automatically generate work breakdown structures that summarize the detailed activities in various ways.

The activities needed to install various component types are generated by rules. The rules are organized by the type of material used and the type of component. Activities may also require supporting activities.

Computing Activity Parameters and Quantities of Work

Formulas and methods are required to compute activity parameters and quantities of work associated with each activity. In an excavation action, for example, the depth, width, and slope of excavation should be computed by the following rule: "If the soil moisture content is 'dry' or 'moist,' or if the soil is not firm but depth of excavation is less than 3.6 m (12 ft), then no bracing is required and the natural slope of the soil can be used." Similarly, rules are also used to compute the quantities of work associated with each activity. These rules use both attributes of design components and activity parameters to compute quantities.

Identifying Construction Methods

The choice of a construction method for an activity depends on factors, such as local site conditions, availability of labor and materials, and so on. For example, "If the depth of excavation is less than 3.6 m (12 ft), width is less than 1.8 m (6 ft) and soil is firm, use a wheel-trencher for excavation." Because the knowledge required to identify construction methods is hard to obtain and codify, method selection involves user interaction. Most rules now identify known construction methods for a particular activity type and allow the user to select the appropriate method for specific site conditions. An assumption is made that the activity generation process is independent of construction method selection. Construction methods can be specified at various levels of detail corresponding to the activities in the project.

Assigning Resources and Computing Activity Durations

The MCACES unit-price database contains standard crew, productivity, and unit-cost information for construction activities involved in the installation of common building components. The database was incorporated to compute activity durations according to assigned resources.

Sequencing Construction Activities

Activities in a schedule must usually be performed in a sequence determined by factors, such as the physical relationships among components in the design, and interactions between crews required to complete an activity. Different types of precedence relationships involve varying degrees of overlap among the activities.

The problem of determining an activity sequence may be considered in two parts: activity sequence involved in the installation of a single component type and activity sequence rising from the spatial and functional relationships between components. In the first case, the activity sequence does not change from project to project. In the second case, the activity sequence varies from project to project, based on the physical interrelationships between design components. Both OARPLAN and CASCH have identified many of these relationships and the associated sequencing rules.

This approach distinguishes between sequencing activities within a component group and sequencing activities belonging to different component groups. The knowledge for sequencing activities within a component group may be organized by the material type used to construct a building component or by general component categories. Sequencing of activities in different component groups is based on the "sequencing relationships" between the components identified in earlier work. For example, if component group 1 is supported by component group 2, then all activities associated with component group

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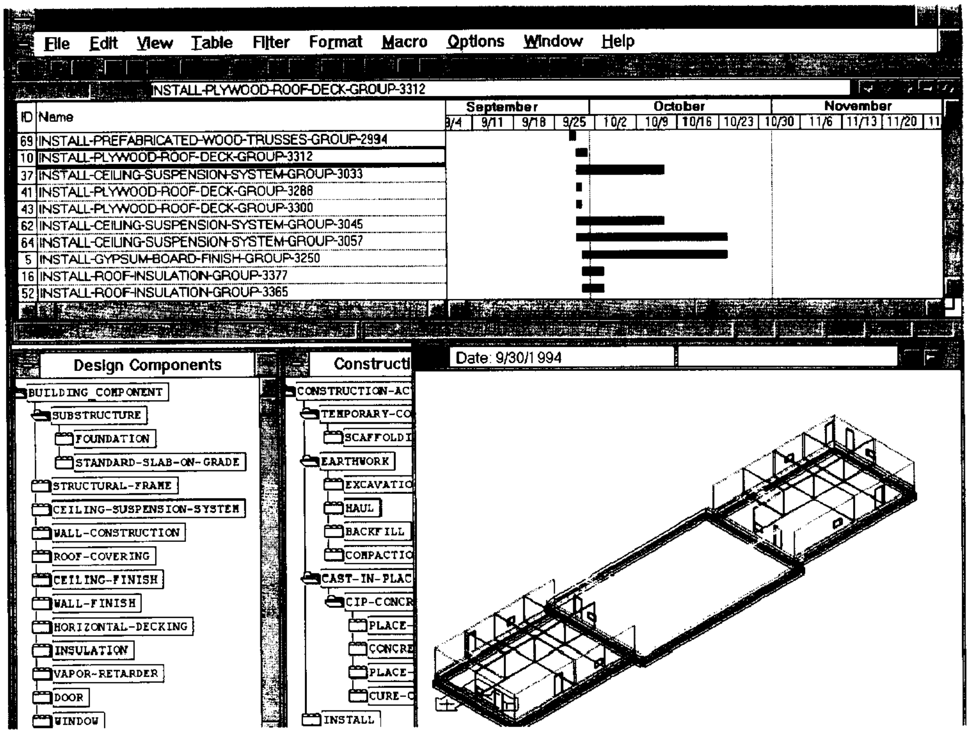

FIG. 7. Implementation of Construction Planning Agent

2 must precede all activities associated with component group 1.

Sometimes it is necessary to establish relationships between specific activities in component groups. For example, when a foundation wall is supported by a footing, backfill for the footings is done after the foundation-wall formwork is removed, or backfill for footings is done after the floor slab is cured if the basement wall supported by footing is braced. Presently, interactions between the crews involved in various activities are not considered. However, this type of knowledge can be accommodated.

Current Implementation of CPA

The CPA is implemented in the GoldWorks expert system-development environment. ACE provides a Dynamic Data Exchange (DDE) interface with AutoCAD that is used to display the building components in AutoCAD. A DDE interface with Microsoft Project is used to compute early and late start times using the critical path method. The prototype is also integrated with Microsoft Excel to present the cost information generated by the system in a convenient spreadsheet format for subsequent manipulation and printing. The GoldWorks open database-connectivity interface was used to access historical project information from MCACES files.

The schedule generation process currently receives the design from designer(s) agents; defines component groups; generates activities where activities required to install various components are identified, and parameters and quantities are also computed; identifies construction methods; compiles crew, productivity, and cost information; sequences activities; and sends the schedule to Microsoft Project.

Visualization (shown in Fig. 7) helps verify the validity of the generated schedule and also makes identification of any sequencing problems easy. Also, the user can visualize the construction progress at any selected date. The prototype system can handle only a subset of components and assemblies related to architectural systems. When it was demonstrated to schedulers and estimators both within the Corps of Engineers and in the private sector, the prototype system was well received.

CONSTRUCTION PROJECT CONTROL AGENT (CPCA)

Managing project information during construction is an important but difficult task. Good information management not only supports project execution, but also ensures that up-to-date as-built information is available for facility operations and maintenance (O&M) and future projects. Construction project information characteristics include: information about unexpected events during the construction process, presentation in diverse formats, a large volume of information, complicated interdependencies, ownership by many participants from different disciplines, and life-cycle impact.

Recognizing these characteristics, the relationships between design components and the construction process were defined, focusing on building components, construction methods and activities, resources, and cost, which are needed to successfully control a project. Based on the object-oriented information model, a prototype system (CPCA) was developed to support construction information management tasks performed by a resident engineer.

The version of CPCA described here manages progress information, updates activities in the schedule, and maintains a multimedia record of construction. An enhanced CPCA will include more construction information types such as submittals, change orders, and contracts.

Current Implementation of CPCA

The CPCA was implementing using C++ and ObjectStore. CPCA can import design components, component groups, and schedule information from the CPA. Once the information is imported, updates to construction activities can be made, and information on construction progress can be captured and stored.

By using various queries, CPCA supports multiple ways of viewing project database information, including the schedule, component, and resident engineer views.

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CONCLUSIONS

This paper has presented an object-oriented model that integrates product and process information to support collaboration among design and construction agents, and two prototype construction agents for construction planning and monitoring project progress. The concept of "component group" was introduced as an intermediate abstraction to relate activities to design components, thus integrating the product and process models. Table 2 provides an evaluation of the ICIM model with respect to criteria relevant to the construction planning and control domain. Demonstrations of the prototype have indicated that this corresponds to actual practice employed by construction planners.

Current research focuses on extending the model to include more construction information types, providing more flexible capabilities to define the work breakdown structure, and facilitating greater flexibility in modeling construction methods by incorporating a multilevel activity-generation process.

Future research includes: enhancement of the knowledge base for the design environment to include in-depth process knowledge, extension to support life-cycle information integration, capturing process knowledge and experience at all phases, and machine-learning and improvements to the knowledge base.

By integrating product and process models, a more powerful and semantically rich information framework can be created to enable the development of computer systems that support life-cycle information management. The two prototype systems described in this paper demonstrate the value of integrating the product and process models. The benefits of product/process integration lie in providing richer semantics, more data consistency, and life-cycle support for facility information. Ultimately, this information framework will provide better information integration, enhance the quality of information management, and improve the current practice of system integration in the A/E/C industry.

ACKNOWLEDGMENTS

This research was supported in part by an appointment to the Research Participation Program at USACERL administered by the Oak Ridge Institute for Science and Education, through an interagency agreement between the U.S. Department of Energy and USACERL.

We would like to thank Stephen McKuzes of Gilbane Construction Co. for discussing construction scheduling and providing feedback on our prototype. We also thank Mike McNett, Phyllis Jones, Chaba Kish, Liu Yang, and XiangQun Chen for their contributions during the development of the CPCA prototype.

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