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USING SIMULATION AND VISUALIZATION TECHNOLOGIES TO STRENGTHEN THE DESIGN / CONSTRUCTION INTERFACE

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ABSTRACT

The design and construction of a building, heavy civil or industrial project requires input from a wide range of members of the project team. Throughout the different phases of the facility development process, different members of the project team need to interact with each other, with one party generating information that needs to be used by the other party for their own tasks. The interface between the design team and the construction team is particularly important, especially since the quality of construction for the facility many times is a function of the quality of the information generated during the planning and design phases, and especially of the degree of construction input to the design process. This paper describes a new methodology for simulating construction operations, which strengthens the design/construction interface. This methodology provides a way of running interactive and real-time simulation of construction operations in a virtual environment that brings the user closer to the real world than ever before. Within this environment, a user can identify problems visually during the planning or design phases of a project, and solve them prior to actual construction of the facility.

1 INTRODUCTION

Transforming an idea into reality, whether a building, a heavy civil or an industrial project, requires input from a wide range of members of the project team. This team is normally composed of different organizations, each with a wide range of administrative units, with their own organizational culture, individual project objectives, and technical approaches to the project. The owner team includes members from the project development, project management, operations and maintenance suborganizations. The design team includes representatives from all the technical design disciplines involved in the project. Finally, the construction team, which includes general and/or prime contractors, subcontractors, and vendors and suppliers. The traditional approach in building construction projects precludes effective integration of all these parties within the project team

At different stages of the facility development process, individuals from these organizations need to communicate with each other; exchange technical and management data and information (e.g., plans and specifications, change requests and orders, as–built drawings); analyze and comment on this information to resolve issues and make decisions; and, when necessary, negotiate to reach agreements among all parties. In many projects these are complex tasks, which are made even more difficult by the problems created by the differences between the intrinsic nature of design (with its primarily visual and graphic interface), and of the intrinsic nature of construction operations (with their complex interaction among human, material, equipment and technological resources).

The quality of the total project team decision–making and implementation process is a direct result of the availability, accessibility and reliability of information, combined with an ability to visualize what other parties communicate. The design/construction interface is especially important since the quality of construction facility many times is a function of the quality of the information generated during the planning and design phases, and especially of the degree of construction input to the design process. Consequently, design/construction integration, i.e., the effective linking of construction knowledge and experience to the planning and design phases of a project, has been identified by both researchers and practitioners as one potential means of enhancing project performance.

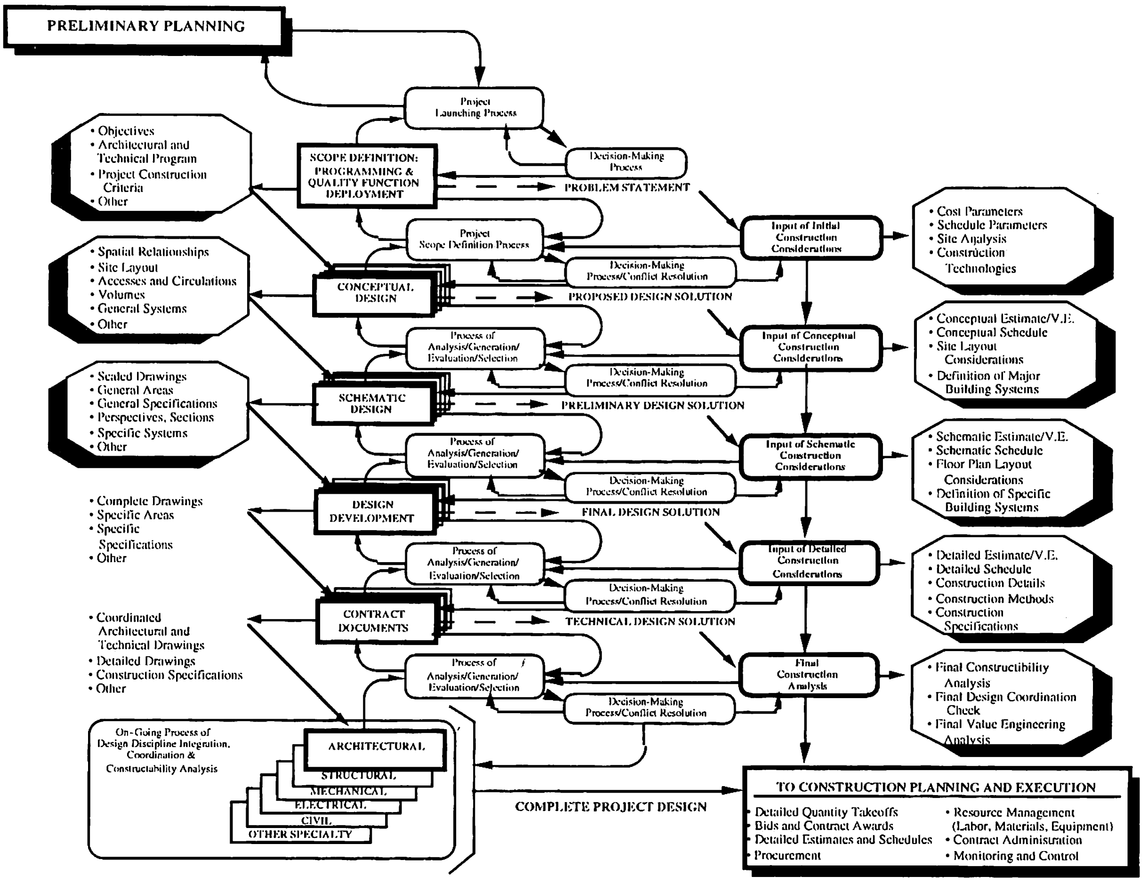

Figure 1: The Design/Construction Interface During Design

2. CHALLENGES

Each member of the project team plays a key role in the project: the owner team sets the project's objectives, which drive design and construction, with both disciplines being subordinate to the owner's goals and needs; the design team, including architectural, structural, mechanical, electrical and other designers, controls most of the planning phase; the construction team controls the execution of the project. However, it is very common for the construction team not to be involved at all in the planning phase but still to assume the responsibility for carrying a project successfully to completion when the design arrives for execution. This lack of an integrated approach often causes adversarial relations between project participants, increases the opportunity for things to go wrong, and often misses important opportunities for improved project performance.

A second obstacle for a stronger design/construction interface is that each phase of the overall process (planning, design, construction, startup, and operation) contains a complex system of relations, interdependencies, and data exchange between its principal activities. For example, as shown in Figure 1, the total design of a facility is a synthesis of a complex process that begins with scope definition or programming, and concludes with a coordinated set of architectural, structural, mechanical, electrical, and other specialty designs that ideally meet the budget, schedule, and quality objectives established by the owner; the aesthetic, functional, and systems performance solutions developed by the architects and engineers; constructibility issues identified by the construction team; and the constraints and limitations established by codes, norms, and regulatory agencies. In reality, this is not a seamless process, particularly because designers and constructors visualize the project from different points of view. For example, while the designers look at a facility from the perspective of the components of the final product, the constructors look at it as the process and issues (e.g., cost, schedule, methods) that stem from the assembly of these components.

A third obstacle for a stronger design/construction interface is many times poor coordination. The planning, design and construction phases of a single project are typically carried out by different parties: planners (developers, estimators, schedulers, space programmers, users), designers (architects, landscape architects, interior designers), engineers (civil, structural, mechanical, electrical, and other specialists), general contractors and specialty subcontractors, often working for different public or private organizations. Ideally, the complete set of design documents generates all the information required for construction planning and execution: plans and details, quantity take-offs, construction specifications. This information initially forms the basis for detailed cost and schedule estimates, bids and procurement activities, and plans to determine labor, material and equipment required for all construction operations, and once construction begins, it provides the reference parameters for monitoring and control. Once again, the differences in the perspectives on the project between the designers and the constructors may lead to problems of interpretation, thus making it difficult to agree on issues and decisions, and/or to coordinate any changes among all the design professionals involved in the process.

Although there has been consensus that computer applications offer the largest potential to overcome many of these obstacles, computer use in the facility development process has tended to reinforce rather than reduce fragmentation of the overall process. Pioneers in the use of computers become "islands of automation" due to an absence of standards, the incompatibility of the different systems used, and a lack of structure for communication and flow of design information and data. Existing computer applications perform a variety of specific, but isolated, tasks such as accounting, estimating, scheduling, structural analyses, or data management. In addition, there are few design and production integrated computer-based tools for the construction industry that address all stages of the facility development process: planning, analysis, design, construction and operation, or assist in the visualization of the final facility from both a product and an assembly process perspectives. Even the introduction of computer–aided engineering (CAE) and computer–aided design (CAD) systems, which have the potential to achieve this, have fallen below the levels of expectation and added fragmentation, rather than integration, to the design and construction processes. Furthermore, these tools are used primarily by designers rather than constructors.

3. USING SIMULATION

Many industries in the U.S. are currently using or beginning to use CAD modeling and animation systems in the design of products to help correct problems before actual construction begins.. However, conventional CAD and animation systems usually fail to account for the actual time and the behavioral and geometrical constraints of the people, materials, and equipment used during the implementation phase. Furthermore, such systems lack the capabilities to effectively support the communication between all the parties involved in design in a real–time basis.

Constructors are also beginning to gain a new understanding of the use of simulation as a planning, optimization and communication tool (Vanegas et al., 1993, Vanegas et. al., 1994). Because of the complexity of interaction among units in the construction environment, simulation techniques offer the only general methodology that can model construction operations. However, even though simple deterministic simulation models have been developed for earth moving operations, it is difficult to use this approach to model other construction operations because of their complexity (Halpin and Riggs, 1992).

Simulation languages can define models of static systems in a simple and logical way, however they fail to provide the flexibility necessary to model the more complex models in which resource distribution is a variable factor. It has been suggested that the site characteristics that play an important role in the equipment selection, as well as the site characteristics which have a major importance on the behavior of construction resources be included in the simulation model. An important site characteristic is the site topography, which plays an important role in equipment selection and location as well as the behavior of construction resources. Unfortunately, there are no simulation languages and very few packages that allow designers to incorporate the site topography into the simulation model (Opdenbosch, 1994).

In a real construction project, planners have to decide which equipment to use for various operations. This decision affects the fate of the entire project (Halpin and Riggs, 1992). The ability to choose construction equipment is lost when a construction simulation model is determined without allowing users to test different alternatives. The important specifications and characteristics of construction equipment vanish when these machines are modeled with distributed random numbers to represent the duration of the tasks they perform. The geometry, specifications, and dynamics of machines, which play an important role in the outcome of construction operations, should be supported by simulation languages and packages so construction planners and designers get a more realistic feedback from the simulation analysis (Opdenbosch, 1994).

There is a need to develop a technique that is specially designed to simulate construction processes. The current techniques are slight variations of methods used in manufacturing simulation(Cleveland et al.,1988). These techniques do not fulfill the requirements imposed by the uniqueness and complexity of construction processes(Paulson, 1978). Construction site operations take place in a complex 3-D dynamic environment that is extremely difficult to represent in 2-D. Since the environment plays an important role in the execution of construction operations, it is crucial that all the relevant components of the environment are presented to the user (Opdenbosch, 1994). An approach that could integrate all the important aspects of construction planning and design would enable the user to make designs cost effective and to make construction techniques more efficient.

4. VIRTUAL SIMULATION OF CONSTRUCTION OPERATIONS

Opdenbosch (1994) introduced a new methodology for simulating construction operations. This methodology applies a combination of techniques from different areas to solve the problem of simulating construction operations in an interactive and dynamic virtual environment. A virtual environment application, implemented using IV++, serves as the platform for designing and testing the new simulation methodology.

This simulation technique was designed from the beginning to work in a virtual world, instead of being designed as a virtual application that would interact with an existing simulation method. The latter approach has been used previously to produce systems that can display simulation output using computer graphics. However, these systems lack the ability to allow the users to interact with the system through the graphical environment (Kirkpatrick and Bell, 1989). This old approach, which has been successfully applied to manufacturing simulation, fails to provide enough insight when it is applied in the construction domain. In addition, it also underestimates the power of both computer graphics and user interaction.

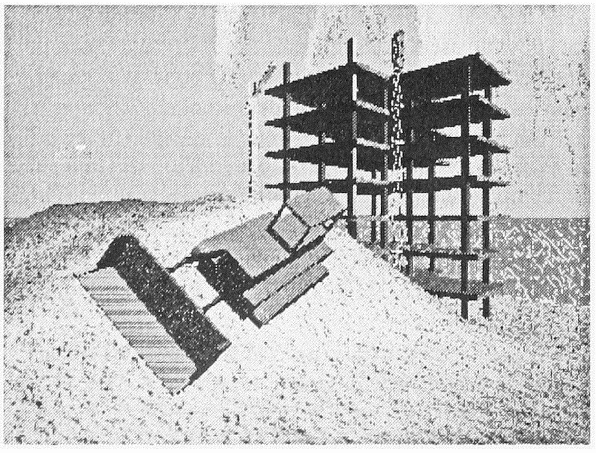

Figure 2: Screen Shot of a Virtual Bulldozer Working within the IV++ Virtual World of a High-Rise

The new methodology provides a way of running interactive and real-time simulation of construction operations in a virtual environment that brings the user closer to the real world than ever before. The user can identify problems visually and solve them in the same practical way they would be solved in real life. The addition of virtual reality to the user interface puts the system on the cutting edge of technology in terms of computer graphics and user interaction. Figure 2 shows an example of a virtual machine working in a virtual world.

One important component of this methodology is a new technique called Computer Aided Design and Assembly (CADA), also developed by Opdenbosch (1994). CADA was conceived to simplify the process of defining simulation goals by using CAD. It takes advantage of the fact that, during the design stages of construction projects, designers are already involved with CAD. Thus, with minimum extra effort, it is possible to incorporate additional information into the CAD model of a building project so it can generate assembly goals when the model is placed in the simulation environment. Because of the nature of the CAD model, CADA goals take into account the geometric component involved in construction projects. By taking into account the geometric component of a building project, the new simulation technique allows the designers to see how the actual design of a building affects its construction process. The use and inclusion of geometric objects to design the simulation model is one of the characteristics that sets this technique apart from current simulation methods. Section 5 discusses CADA in more detail.

The interactive simulation environment developed by Opdenbosch was designed to support virtual construction equipment. This virtual equipment is capable of performing the tasks needed to complete the assembly goals that are contained within the building model created using CADA. The initial system prototype did not have an interface between the building model and the virtual equipment. Rather, specific assembly instructions, contained within the building model, told the machines what to do. This method proved to limit the flexibility of the entire system because changes in the environment could interfere with the completion of an assembly goal. In addition, it is always difficult during the design process to know what kind of resources are going to be available at the construction site.

The solution to overcome this difficulty was to design a General Problem Solving (GPS) planning interface between the building model and the virtual equipment. The planner, as it was later called, processes the goals contained within the building model, rather than the original assembly instructions. Then the planner figures out a way to achieve these goals by using the resources that are available at the time.

During the simulation cycle, the user can make the equipment selection and observe the results. The planning algorithm constantly checks the state of the system and decides which machines will perform the tasks. The construction equipment can also be removed from the environment if the user decides that a particular machine is not adequate for the job. In addition, it is possible to stop the autonomous mode of a virtual machine and control it manually. The user can switch the view point to a camera inside the machine that is being controlled and perform a task manually. All the interaction that takes place during the simulation cycle requires no alteration of the code and, therefore, the users fully concentrate on the analysis of results instead of determining the commands and changing the logic of the program.

The autonomus behavior of the virtual machines has been achieved by using a reactive control algorithm that enables the machines to adapt to the unexpected changes in the environment. Once a machine has received a mission from the planner, it will try to complete the given goal by evaluating the state of the system and adapting to it on every cycle. The adopted reactive strategy uses repulsion and attraction fields which create a resultant force on the adaptive machine and causes movement. The combination of repulsion and attraction fields can result in complex behavior, which could be difficult to obtain by using other methods. The only requirement for reactive control is access to information about the system state at all times. This requirement can be satisfied very easily because it is used in a virtual world. Figure 3 shows an example of a virtual crane moving a steel beam from a truck to its final destination using this approach.

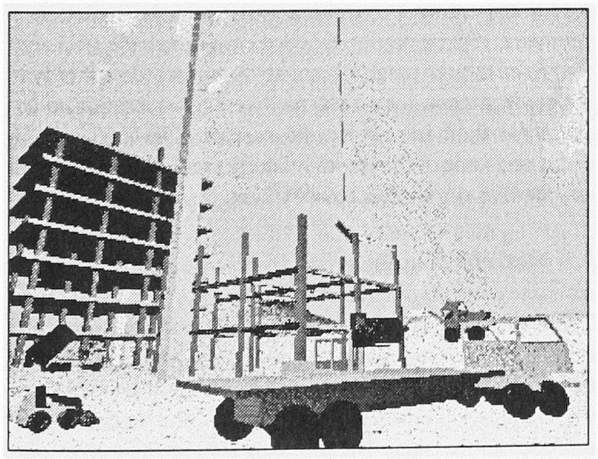

Figure 3: Example of the Use of the Reactive Control Algorithm for Autonomous Behavior

Even though the focus of this research effort concentrated on the user's needs, careful consideration was given to the fact that the virtual simulation environment needs to be updated and maintained. The environment developed using IV++ is not only a stand alone application, but also a collection of libraries that can provide future developers the necessary tools to define new virtual machines, new components, and even adapt the system for use in other areas.

5. COMPUTER AIDED DESIGN AND ASSEMBLY (CADA)

Computer Aided Design and Assembly (CADA) is the technique used to define a Building Object (BO). The BO is used in the interactive environment IV++ to represent the goal of the project. As the environment processes the assembly sequences contained in the building object definition file, the individual goals are extracted and transferred to the planner. The planner then distributes the tasks to the equipment according to their capability and availability.

The idea to use CAD to generate simulation input originated by Nevis and Zabilski (1991). They describe how the CAD model of a building was created in the same order as the actual building. The construction simulation, in this particular case, was done by the CAD operators. However, it seemed possible that the assembly sequence could be captured and used later to generate the input needed for non-user driven simulation. The lack of a practical way to generate that kind of information was one of the main concerns of this study, and motivated the search for a possible solution. The technique described by Nevis and Zabilski was adapted to meet the requirements of the new simulation approach, and tested with encouraging results. Designing BO's with CADA required little effort beyond the work done with CAD. Also, since CAD is one of the main components of building design, it was decided to incorporate CADA as a major component of the new adaptive simulation technique. This section describes the elements that define a BO, as well as, the procedure to create such objects.

5.1 Building Objects

A BO is in essence a list of primitive objects or components arranged in a hierarchical and sequential fashion. The sequences are determined by the order in which building components are scheduled to appear in the environment. The hierarchy is determined by the dependency that exists between components. In construction operations, a process does not take place until the necessary prerequisites have been completed. The third floor of a building, for example, will not be constructed until the second floor is ready to support it. The operations, associated with primitive objects, that take place in the same hierarchical level will take place when the resources become available. The order in which these operations takes place is determined by the priority associated with the object in question. If no priorities are given to objects within a hierarchical level, the planner will assign them the same priority and process them in parallel. After all operations within a level are completed, the next level of operations is initiated. Figure 4 illustrates the hierarchical distribution of building components as it would be defined in CAD.

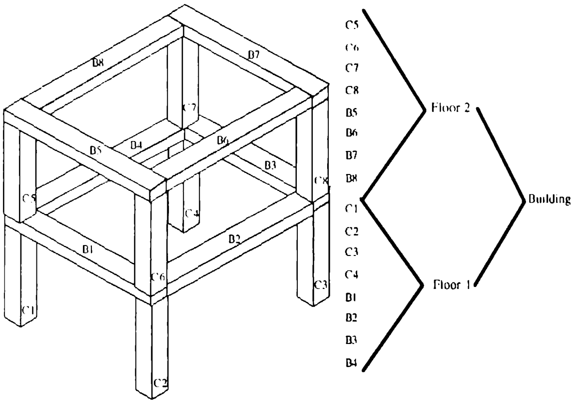

Figure 4: Hierarchical Distribution of Building Components

There are three types of data associated with CADA:

- The first type is the geometric information associated with building primitives. This type of information is completely supported by CAD.
- The second type is the hierarchical information that establishes the relationship between building components. Most CAD applications have the capability of dealing with this type of data also because most of them offer the tools needed to group objects together.
- The last type of data associated with CADA is the priority information that is used to ensure that the preconditions of a procedure are fulfilled. This information type can be represented using CAD attributes such as color, line thickness, line type, etc.

The procedure involved in constructing a BO from the model shown in Figure 4 requires the use of the grouping tools of the CAD package to specify hierarchical dependency and the use of CAD attributes to specify priorities. The objects that belong to floor 1 need to be grouped together with a name that associates them to that floor. The same procedure needs to be followed with the objects that belong to floor 2. Floors 1 and 2 are subsequently grouped together to form the BO.

When this file is read by the interactive environment, the geometry files associated with each primitive type are linked to the primitive to form the final building object representation. The primitives are used to describe the relevant characteristics of the parts that form the building. They are the most basic component of the BO. The next section illustrates the main features of building primitives and explains how they interact with the planner and the adaptive machines.

5.2 Building Primitives

The Building Primitives (BP) are the fundamental unit in a BO. In the interactive environment IV++, the BP's are responsible for requesting actions from the planner when they are introduced to it. A primitive descriptor is in essence a data file which contains the basic information needed in the environment to manipulate and interact with it. The standard data file of a BP contains the following data:

- geometry
- action
- materials
- initial location
- initial orientation
- add coordinates
- color

If these current fields do not suffice, developers can add new ones. It is also possible to remove the geometry component from the description file and place it in the BO definition file. By doing this one can have different geometric shapes with the same primitive characteristics. One example is horizontal beams with different lengths. The beams may be different geometrically, but it is advantageous for them to have the same primitive characteristics. The limitation of using this approach is the loss of accuracy in the primitive definition. There are some fields in the BP descriptor that are closely related to a primitive's geometry. Additional information about a BP may be linked to a geometric representation that does not match the BP itself.

Even though materials are not represented explicitly in the environment, they have received consideration to account for their impact on the system. The next section discusses some of the issues related to material handling in an adaptive simulation environment.

5.3 Material Handling

There are two sources of information in the primitive definition file that allow the interactive environment to handle materials. The first source is the action type listed in the BP descriptor file. The second is the material type included in the same BP file. A machine capable of performing the action specified in the BP descriptor has the knowledge to handle the material associated with the primitive.

At the current stage of development, IV++ runs in an unlimited resource mode. This means that it is capable of tracking the amount of materials used, but it does not handle situations where materials may become temporarily unavailable. The potential for simulating this type of model is available and could enable a user to explore this important component of construction simulation. One suggestion is to treat material sources as physical entities that can exist in the environment and interact with the construction equipment. The amount of materials available can be determined by the random variables generated with selected distribution functions contained within the material source definition. The user could inspect how much is available, find out when the next shipment is going to arrive and request additional shipments. During the interactive cycle the user could add, delete, and replace material source objects.

6 SUMMARY AND CONCLUSIONS

This paper described a new methodology for simulating construction operations, which strengthens the design/construction interface. This methodology enables both designers and constructors to run interactive and real-time simulation of construction operations in a virtual environment, thus bringing the user closer to the real world than ever before during the design phase.

This environment also enables users to identify problems visually during the planning or design phases of a project, and solve them prior to actual construction of the facility

Simulating the construction of a building using this methodology consists of five steps:

- First, the building must be designed using Computer Aided Design and Assembly (CADA).
- Second, the simulation is run with all the relevant elements in the environment (terrain, cameras, lights, and the building in question).
- Next, the virtual equipment is chosen.
- Then the assembly process is started.
- Finally, machines are changed, added, and deleted, cameras are switched, and the user turns to Virtual Reality.

After the interaction with the building model, the user can choose to go back to CADA, make changes to the building design, and repeat the entire process. There is no computer programming involved in the user sequence and the only knowledge required is CAD.

This approach can be effectively used to strengthen the design/construction interface by providing a tool for both designers and constructors to more easily visualize, during the design phase:

- a facility from a product perspective:
  - how all physical components of the product integrate into a whole, and conversely, how a whole product breaks down into all of its physical components; and
  - the product's measureable physical attributes at different scales, e.g.: shapes, connections, dimensions and tolerances.
- a facility from a process perspective:
  - all the necessary resources for a given method, e.g., labor, material and equipment resources, including their measureable attributes;
  - how resources relate and interact with each other, and also evolve over time; and
  - how all of the construction tasks, activities and/or processes integrate into a whole product, and conversely, how a whole product breaks down into all of the tasks, activities and/or processes.

Finally, further research in CADA could lead to a system specially conceived to do building design and assembly with direct access to a primitive data base. Another interesting alternative would be to place CADA inside the virtual simulation environment. An application of this kind could become the host for all the activities associated with the design process, making it a comprehensive design-simulation-implementation system.

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