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CAD for process innovation in the construction industry

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Abstract. This paper presents the concepts of *Process Innovation* and *Concurrent Engineering* in view of their use within Integrated CAD Systems. It follows by proposing process models that support an effective implementation. The work is practically founded on the authors' experience in performing the initial steps of implementation of some of such integrated systems for the construction industry.

Key words: integrated CAD systems; process innovation; concurrent engineering.

1. Introduction

At the early stages of construction processes, contractors present to designers, clients and managers their understanding of the design under consideration and, accordingly, the way envisaged to carry out the corresponding construction. This process suffers from communication faults, contains misunderstandings, partial understanding, leads to changes in supply orders, may arise future judicial questions and increases the fragmentation of the construction industry (Reinschmidt, *et al.* 1991).

On the other hand, throughout the construction process, contractors are constantly required to update the construction planning, to recalculate quantities, to update cost forecast, to reconsider supply orders and to produce progress reports for invoicing purposes. These tasks render the management job difficult to be accomplished and produce delays, ill-specified orders, rework and incorrect progress evaluation.

Moreover, contractors are facing today a global competitiveness crisis and suffering from a continuous scaling of overheads. As a negative result, several large companies are compelled to extinguish entire working groups and give away technological capacity.

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A possible path to address many of these issues and promote productivity and competitiveness under such constraints is the adherence to new information technologies, and the adoption of new computational ways of supporting more powerful individual tools and better integration levels.

In this paper the authors claim that all the questions raised above would benefit from being analysed in the light of Process Innovation and Concurrent Engineering. Moreover, such systematic approach should lead to an effective implementation of Integrated CAD Systems that blend the design and planning processes with executive processes, such as fabrication, assembly, purchase and cost control (Fig. 1). This integrated approach to CAD systems should alleviate communication problems, reduce the industry's fragmentation and drastically improve productivity, quality and competitiveness.

This work presents the concepts of Process Innovation and Concurrent Engineering followed by a proposal of models for some of the most important construction sub-processes that support an effective implementation of Integrated CAD Systems. These models are: 3D Models, Design Process Models, Planning Models and Integration Models. The work closes by presenting examples of partially integrated systems for the construction industry based on the proposed approach.

2. Process innovation

Several researchers and consultants pointed out that the massive investments in Information Technology (IT) made by the majority of the companies in the 80's had very little impact on productivity (Roach 1991, Loveman 1988, Bowen 1986). The new concepts of Process Innovation have revealed that the main reason explaining such poor results was related to the lack of understanding that companies must be reorganized in terms of processes instead of activities or functions (Davenport 1993). Indeed, automation of traditional activities can be a waste of time and money if the processes to which they belong are not evaluated and innovated. Before the introduction of IT in a construction company, one should evaluate its productive processes, innovate them and eventually destroy old paradigms. In this context, the implementation of Integrated CAD systems requires the execution of a Process Innovation plan. In fact, Process Innovation and Information Technology have a symbiotic relationship - one does not exist without the other.

Process analysis revealed that most of the companies are far from being flexible, efficient, creative and dedicated to the clients. The world where the companies live today has changed

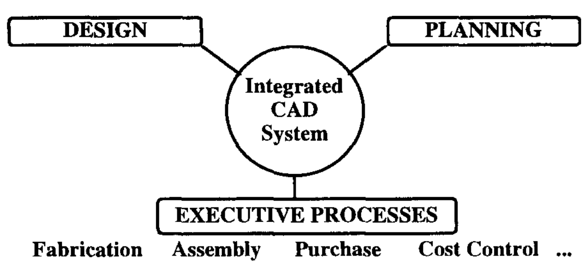

Fig. 1 Integrated CAD system.

beyond their capacity of self-adjustment. The renewal of the competitive capacity is not a matter of working harder, but that of learning how to work in a different manner.

As pointed by Hammer and Champy (1993), the historical reasons for the current lack of efficiency of some companies may be found in the concept of work division proposed 200 years ago by Adam Smith and on the organizational model of the period 50-60. Nowadays, most companies still follow Adam Smith's principle of work division. The degree of workers' specialization and the fragmentation of work are proportional to the size of the company. The essence of today's bureaucracy is still that of programming people to obey rules and standards.

The ideas by Henry Ford transformed tasks to be done by workers into simple ones, but turned the work of coordinating people into a very complex job. The organizational model in the years of great economic growth in the 50s and 60s was based on complex planning strategies where the targets were set up in terms of budgets and specific results expected from each manager. A consequence of this model was the creation of large teams of managers, inspectors, schedulers and auditors. As pointed by Hammer and Champy (1993), that model was perfect for that period of great demand where the main concern of executives was to increase capacity. In that model, the pyramidal structure was adequate, in the sense that it was sufficient to keep adding workers in the low layers and filling the managerial layers above. The training programs were simple because the tasks were simple ones. The picture was that of a complex managerial structure and a great distance between management and customers.

Construction companies live today in a different scenario. The crisis of global competitiveness does no longer belong to a traditional cycle of prosperity-recession-prosperity. According to Hammer and Champy (1993), neither the growth of the market, the demands of the clients, the product life cycle, the technological changes nor the nature of competition are still constant and foreseeable. As these authors have pointed out, in the current scenario, customers took over control, competition has increased and changes became unpredictable, fast, ubiquitous and tenacious.

The concept of Process Innovation as a way of breaking with obsolete paradigms, a method of adapting companies to the current scenario and a tool to obtain significant jumps in productivity and quality, became a worldwide obsession after Davenport's (1993) and Hammer and Champy's (1993) contributions. The basic principle of this new systematic approach is to force the company to organize itself in terms of processes instead of work division. In this context, process is defined as a collection of activities with an output that has a value attached to the client.

3. Innovation in the construction industry

At present, most construction companies exhibit the following characteristics in need of changed: (i) no one has the responsibility for a complete process; (ii) focus is on the internal affairs (of each section) neglecting the outside world and the clients; (iii) the processes are fragmented; (iv) the increase of overheads is sky-high and more than proportional to the increase in productivity. Process innovation should change this situation through a radical redesign of the way companies carry out their business. Hammer and Champy (1993) coined the term reengineering to denote process innovation and had the idea of explaining this concept by outlining what it is not suppose to be, that is:

(1) It is not automation; i.e., automation alone does more efficiently the same wrong things;

(2) It is not downsizing; i.e., downisizing alone means to make less with less resources - reengineering immodestly aims "to do more with less";

(3) It is not reorganizing; i.e., new structures on the top of old processes do not eliminate the causes of the problems;

(4) It is not a bureaucracy review; i.e., bureaucracy is the glue that keeps traditional organization working and its straightforward removal would cause chaos - the solution is to review the processes and to avoid fragmentation;

(5) It is not a quality improvement program; i.e., reengineering aims to create new processes, instead of improving old ones.

Unfortunately more than 50% of the companies fail in the effort of reengineering their processes. The success depends on the correct elaboration of the overall planning, the awareness of the common mistakes, the correct approach to Information Technology and the adequate human resource policies. Furthermore, Process Innovation should be carried out closely aligned to the concept of competing for the future, otherwise companies will at most catch up the competitors and will fail to excel them (Hamel and Prahalad 1994).

4. Concurrent engineering

One of the main streams for innovation in the industry today is the possibility of using Concurrent Engineering, also called Simultaneous Engineering or Collaborative Engineering. Concurrent Engineering means a change in the flow of processes from serial to parallel and is based on a cross-functional organization within the design teams and between these teams and the other sectors-mainly the manufacturing and sales/marketing ones. The authors claim that the concept of Concurrent Engineering also embraces the concept of industrialization-oriented design, where the design phase of the product development cycle is concentrated on the processes by whose the product should be manufactured. Indeed, if an artefact can be made easily, its cost will be lower and, quite certainly, its quality will be better (Gomory and Schmitt 1988).

Most of the problems in the construction industry have their roots in the lack of integration between designers and contractors. In this particular, the authors claim that any practice of Concurrent Engineering requires a central computational model as illustrated in Fig. 2.

Some researchers (Jo et alii 1993, Naveiro and O'Grady 1995) have pointed out that the two basic approaches to Concurrent Engineering, namely team-based and computer-based approaches, are not incompatible and, in fact, the computer-based approach enhances the team's performance. The authors understand these approaches as follows. The team-based approach is fundamental

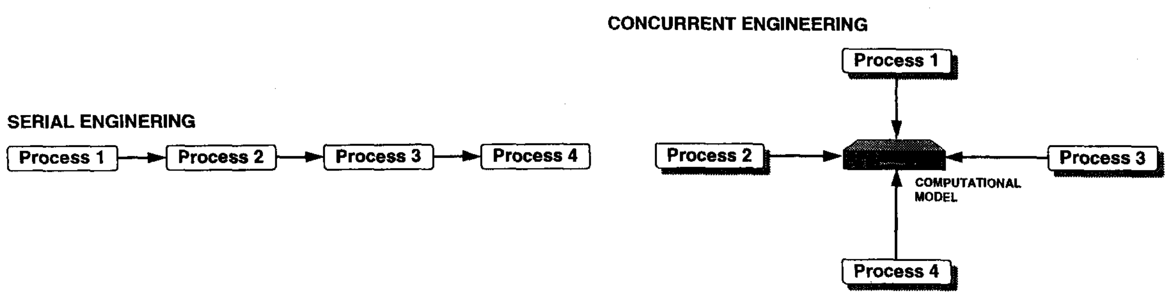

Fig. 2 Serial *vs* concurrent engineering.

to create the synergism amongst different people working in different areas and different phases of the engineering process. This approach defines the cross-functional organization and the task overlapping procedures. The concepts of empowered teams (i.e., workers invested with decision power) and situational leadership (i.e., management posts depending on the current stage of the project) are central to this approach. On the other hand, the practice of Concurrent Engineering requires effective methods for integrating people and activities. In this case, integrated CAD systems are one of the main Information Technology tools for integration and represent the computer-based approach. The questions of cooperative design, intelligent agents, distributed Artificial Intelligence and conflict management are in the kernel of the computer-based approach to Concurrent Engineering.

The kind of information that may flow within an integrated CAD system is, for example, the following: 2D drawings (architecture and installations), 3D mock-ups; 3D perspectives for presentation, quantities, progress reports, physical planning, financial planning, cost calculation, assembling instructions, supply orders, expenditure authorization and messages.

In a CAD-integrated, collaborative approach, the designers/engineers deal with a large amount of analysis data. Also, different kinds of analysis can be done simultaneously by different specialists (structural, thermal, electrical, etc.). General costs are reduced, due to better analysis and simulations. Moreover, integrated CAD systems should reduce the time of the entire collaborative process.

A concurrent way of working implies fewer concatenated or sequential phases, but new simultaneous and integrated ways of acting. The conceptual phase often begins during a phase of idea generation. Moreover, Concurrent Engineering enables the consideration of aspects of the product life-cycle during the conceptual phase. The analysis and detailing phases can be simultaneously done for different parts of the product. Different kinds of analysis can be performed simultaneously and the necessary modifications can be tested and the update processes executed during this phase. Integrated CAD/CAE systems force the design and post-design phases to be done in an interrelated and simultaneous basis.

In an innovative approach to building design, it may be shown that the use of 3D models enables a better understanding of the artefact to be built. The three-dimensional geometric modelling phase is well treated by CAD systems from the beginning of the conceptual phase (sketches, perspectives, walk-through, etc.) up to the detailing stage of the building design. From a 3D data base one can produce 2D drawings, details of the artefact, quantities, costs and progress reports. 3D models can integrate data related to the entire engineering process and represent the central idea for collaborative engineering in the construction industry.

5. 3D models

The cornerstone for the integration of CAD and planning processes with executive processes is a three-dimensional model of all the building components, usually named Digital Mock-up. The view of the processes from the 3D model represents a reversion of the traditional procedures and a relevant innovation in the construction industry. In this view, all the processes (mainly the design process) start seeing the business targets with the eyes of the constructor. This avoids constructibility problems, ill-specified orders, rework and, many times, accidents due to unsuitable design. This new view fits the requirements for Process Innovation, mainly because it promotes a review of the processes and focuses on the final product and on the needs of the client.

3D models allow the practice of the Constructibility Review with great efficiency (Reinschmidt et alii 1991). In its simplest form of Design Review, Constructibility Review uses 3D models in the following tasks: (i) to identify design inconsistencies that are, in a great extend, dimension errors; (ii) to identify geometric interference between components. In more complex forms, Constructibility Review uses 3D model in the following situations: (a) the identification of the most productive construction methods; (b) the identification of areas of difficult construction; (c) animated construction simulation for analysis and proposals for changing methods. Also 3D models are important in the following aspects: (1) automatic production of 2D drawings from 3D models; (2) flexibility for printing in different formats; (3) mobility of the digital mock-up (using notebooks, disks or the network); (4) instructions for the construction teams in the field.

3D models should not be, however, mere visualizations of the building. They should be databases of the main engineering parameters involved in the construction. Hence each 3D object in the model should be associated to a data structure containing information on costs, planning and the design and construction intents. This form of 3D model, named Structured 3D Model by the authors, enables a fast access to any kind of information: the graphical representation of the quantities, the visual representation of any stage of the construction or the quasi-automatic production of progress reports. Integrated CAD Systems can only be implemented and made effective if resorting to Structured 3D Models.

The authors propose the following classification for information structures associated to Structured 3D Models according to the level of integration achieved: internal, coupled and external database. The internal structures are offered by the CAD software (e.g., Extended Entity Data in AutoCAD). The coupled structures are data structures written by the user within the CAD software (e.g., AutoCAD Development System) or using a standard geometry bus such as ACIS. External database structures are tables defined in external database management systems such as DBase, Access or Oracle. In AutoCAD, for example, this link is made by the AutoCAD SQL Extension.

6. Design process model

An integrated CAD system requires a design process model in order to define the design problem space, organize the object structure and support integrated design procedures. The authors propose the use of the SAE model and an object-oriented approach to design entities.

6.1. The SAE model

SAE is a computable model of the design process which endorses two fundamental points of view: 1) faces this activity (design) from a cognitive perspective; 2) considers design to be a problem solving process (of a specific nature) (Feijó and Bento 1991, Bento 1992, Scheer 1993, Prates 1993). In this model, design is a cyclic process defined by three sub-processes of Synthesis, Analysis and Evaluation that are themselves recursive design processes. Furthermore, design is an evolutionary process that starts from an initial state T_0, that is: $T_0 \rightarrow T_1 \rightarrow \rightarrow T_n$, where T_n is the final state representing the desired goal. A state T_i - i.e., a description of the design problem at time *i*- is represented by a set of design entities e_j that capture both the notions of form (mainly physical attributes) and of function (i.e., the specification of the function to be executed by the form). Strictly speaking, design entity is a term $e_j(I, F, f)$, where I=identification attributes, F=form attributes and f=function attributes. A state T_i is, then, a set of design entities e_j.

The evolution of the states may not be carried out as would conventionally so, by the application of "design operators", for no clear ones may be found amongst most design activities. SAE processes may then assume the role of conventional operators in general problem solving, by promoting the evolution of states. Such evolution is guided by eight characteristics of the Design Problem Space that represent cognitive needs of the designer. These characteristics are also used as guidelines for the development of CAD systems (Feijó and Bento 1991).

6.2. The object-based structure

The design entities $e_j(I, F, f)$ may be implemented as objects with the following structure:

identification attributes (I): [label] [description] [status]
form attributes (F)
  relationship attributes: [is-a] [children] [part-of] [link-to] [alternative] [version]
  structure attributes: [physical] [geometric] [behavioural]
function attributes (f): [intent] [functional specification] [performance specification]

In this taxonomy, description is a short note in text format or even in audio format; status is the current situation of e_i (alive, alternative or version); structure attributes may be physical (e.g., colour), geometric (e.g., radius) or behavioural (e.g., temperature=35℃, obtained from a thermal analysis); intent describes the designer's intention.

According to the SAE model, a tendency of the design evolution is the progressive transformation of functional specification (e.g., "pleasant temperature") into performance specification (e.g., 18≤temperature≤25). The concept of performance emerges then as the link between function F and form f, as pointed out by Gero (1990); it is also the engine driving the cycles Synthesis-Analysis-Evaluation dynamics.

These objects' attributes can be primitives (integer, float, string, ⋯), composite items (lists, structures, vectors ⋯) or predicates. Predicates behave like attached procedures that are used to calculate, deduce or check attribute values. The relationships between design entities can be easily identified with the help of design graphs, as proposed by Prates (1993).

The proposed structure can be implemented in logic, object-oriented languages or plain (simple and efficient) C language, as long as the dynamic creation/modification of objects be enabled, at run-time.

7. Planning models

According to Morad and Beliveau (1991), the traditional network techniques for planning are limited because: (1) they manipulate only the data given during the planning process and ignore the knowledge used to generate the plan; (2) they are mainly based upon the judgement, imagination and intuition of the analyst; (3) they do not have a practical approach to deal with uncertainty to build the logic and the relationship between activities; (4) they require abstract visualization of the multiple components of the project.

Exhibiting such limitations, traditional techniques become mere tools for illustration and may not stand as problem solving techniques. Indeed, in the traditional method, the human planner (scheduler) provides the solution and only illustrates the building process in the form of a model. In this case, there is no explicit representation of the knowledge embedded in the processes and there is no clear and dynamic visualization of the physical components to be built. Morad and Beliveau (1991) point out that a new generation of planning techniques should be proposed based on the binomial "Data+Knowledge". In this context, the planning models should be based on Artificial Intelligence concepts.

From a more pragmatic point of view, a first step towards planning models of a higher level is the integration of the traditional network to the CAD and the executive processes (mainly those related to costs). The authors propose such a model based on the assumption that planning is a particular case of design and, more specifically, a variant form of the SAE Model. This hypothesis permits that many results and properties from the area of design be incorporated to planning and, furthermore, it establishes a theoretical basis for integrating CAD into planning.

Indeed, planning is a special case of design where the final goal T_n is known in advance. Another characteristic is that the evolution of the states within the Design Problem Space occurs along the axis of time. The problem may thus be seen as a search to find an efficient path to the goal T_n. In this context of planning as a special case of the SAE Model, the authors propose a model for Integrated CAD Systems in the following section.

8. Integration model

In the SAE Model, the design entities e_j can represent several types of objects (goals, functions, planning activities, 3D solids, $\cdots$). In this work, the structure of the objects e_j contains the traditional Planning Network and the 3D Model. The idea underlying the architecture of the computational model is to use this object structure as the central link for integrating the processes, as

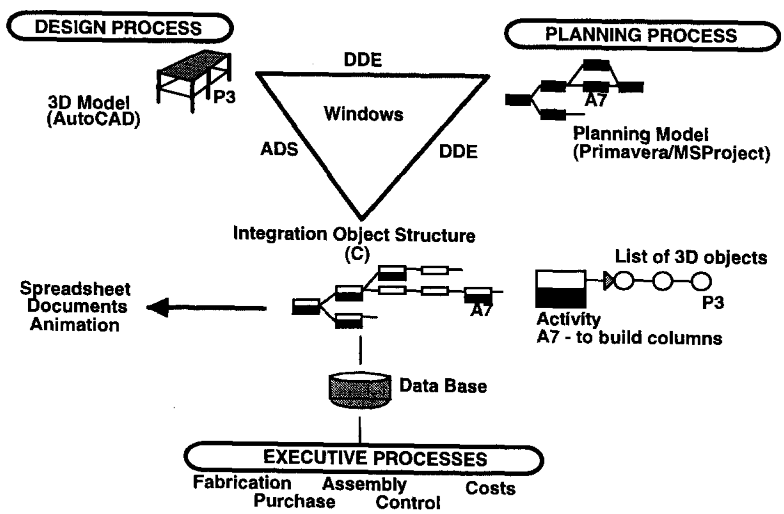

Fig. 3 Full integration model.

shown in Fig. 3. This structure is named Integration Object Structure by the authors.

Fig. 3 illustrates the proposed computational model based on AutoCAD, a program for planning and a data base management system. The operating environment is Windows and the interapplication communication component is based on dynamic data exchange (DDE). In this model, the first task may be executed by a draughtsman who builds the 3D model from a geometric point of view only. The subsequent tasks should be done by an expert in planning who sets up the planning network by making links to the 3D model.

The integration between the 3D model and the planning model consists essentially in linking graphical data to planning data. The basic units of a project plan are activities that get a tag (generally alphanumeric) and a title. The link between a planning activity and the corresponding graphic elements is made by assigning the activity tag to these elements. Data communication between AutoCAD and the planning program is made by virtue of data exchange mechanisms, such as the Dynamic Data Exchange (DDE) model made available by the Windows environment. In the proposed model, a resident application within the AutoCAD environment (written in ADS) controls the communication process with the planning program. This application program is capable of sending messages to the planning program to create a new activity and the planning program replies with a new tag that is used as an object attribute. Under this scheme, the two programs are simultaneously opened and actions from one side affect the other one by creating a visual counterpart of the planning network. The application resident in AutoCAD is able to access the data structure in the planning program, the 3D solid modelling and the external data base. Therefore, several queries can be made to this hybrid system about the critical path, its objects and dates, volumes, unit costs and resources associated to a specific object.

In the case of AutoCAD and the planning program not being simultaneously opened, a consistency test is required. This test can be made by comparing the list of tags in the 3D model with that of the planning program. It is important to note that the inverse check is not possible because some activities may have no physical counterpart.

The integration with the executive processes should be done through the link with the external data base where the basic compositions, unit prices and other information are stored. The Integration Object Structure is the core of the proposed architecture and assembles all the information about the building. Such an extremely dynamic structure also provides an open door to more advanced enhancements such as the use of Artificial Intelligence techniques and methodologies. Furthermore, the proposed structure may feed other procedures, namely those to create animation, spreadsheets and to produce other sorts of documents. More than one type of Integration Object Structure may be required depending on the type of data structure.

9. Integration levels

Different models of integration may be achieved depending on two features- the type of link between the vertices of the model and the type of the central data structure shown in Fig. 3. These models are: full model (Fig. 3), partially structured model (Fig. 4a) and partially centralized model (Fig. 4b). The degeneration of the full model towards a single link (edge) between the vertices, defines the simplest models and the lower levels of integration. These simple models are useful in supporting the initial steps of implementation of CAD systems in a construction

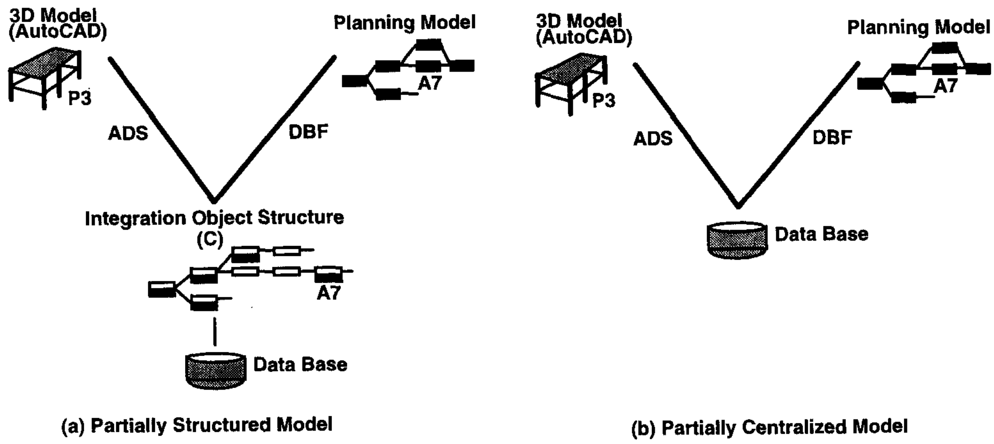

Fig. 4 Partial models.

company; they also produce effective automatic tools for quantity calculation and progress reports.

In the partially structured model-implemented by a loosely coupled approach-, the PLANNING-OBJECTS relation is achieved at a file exchange level. Accordingly, a commonly accessible database, such as dBase, enables communication through the importing/exporting of files (DBF files, in that case) between each of the applications. In this kind of model, the planning network cannot be set up within the AutoCAD graphical environment.

The partially centralized model provides the same links of the previous one and no Integration Object Structure. The PLANNING-OBJECTS link degenerates into a PLANNING-DATABASE one (through import/export file operations) and the 3D-OBJECTS link becomes a 3D-DATABASE one (through the library ASE-AutoCAD SQL Extension). The aim of this model is to centralize all information in a distributed and large relational data base system, such as Oracle, Sybase, Informix or Ingres. This model is more robust than the other ones and avoid the problem of duplicating data. However, this type of model present serious drawbacks: (1) data base systems for commercial applications are totally inadequate for CAD applications; (2) a powerful data base system is an expensive software; (3) computer network problems are incorporated into the model; (4) traditional CAD systems% libraries may have has difficulties to link with some data base systems (notably AutoCAD's ASE has so).

In what concerns the first drawback mentioned above, it may worth enumerating some of the reasons associated with peculiar requirements of CAD databases in comparison with commercial database systems, which are the following: 1) the need for abstract data types (while the relational model is based on pre-defined concrete data types from which the user may not diverge); 2) the presence of data in a traditional sense, but also complex objects (structured entities working as units); 3) graphical data besides non-graphical ones; 4) version control; 5) configuration control-a configuration being a specific sequence of parts and versions; 6) control of anchor points (to re-establish data after undo operations); 7) control of intermediate copies (incomplete and inconsistent); 8) regeneration of parts affected by changes in other parts; 9) objects by multiple representations (views); 10) n:m relations; 11) composition (objects composed of other objects); 12) recursion (objects of a given type composed by objects of the same type); 13) objects with more than a single functional property (hence, objects with a predefined hierarchy and simple trees do not qualify); 14) handling of layers (number of details; bottom-up; detail

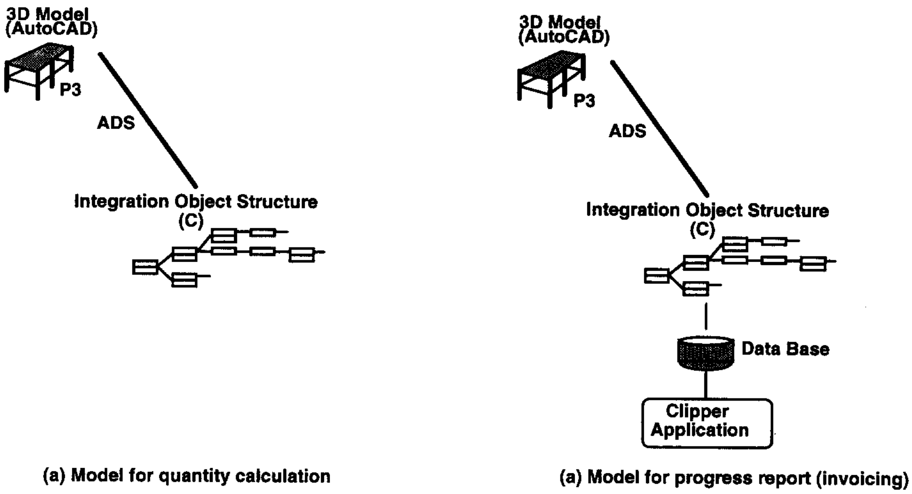

Fig. 5 Models for quantity calculation and progress report.

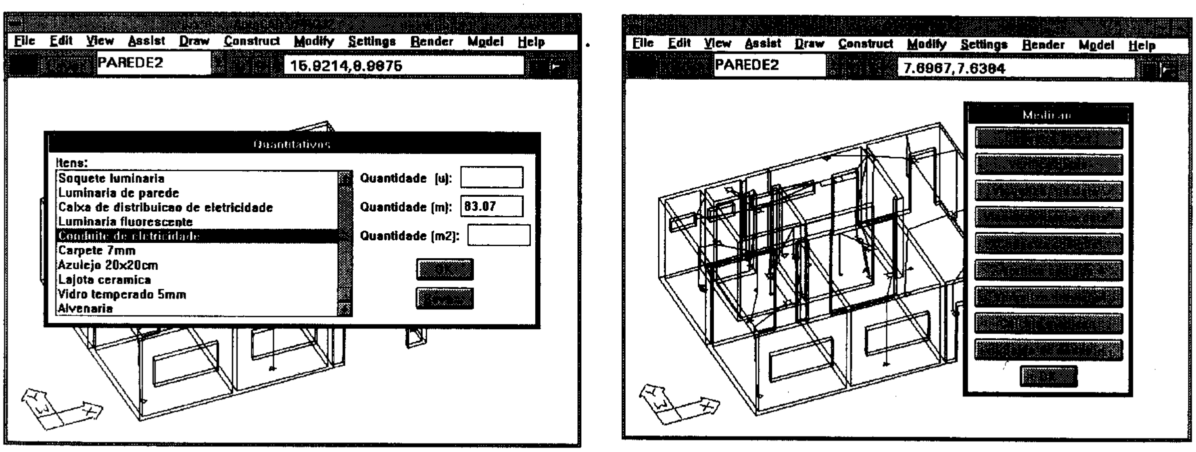

Fig. 6 Products for quantity calculation (left) and progress report (right).

hiding); 15) relative relations; 16) complex functions over a large number of objects (e.g., hidden lines removal and equivalent operations); 17) a large number of items retrieved in a single transaction; 18) high rate of modification; 19) configurable predefined libraries; 20) permanent interactive use; 21) massive derived data (from primary data), which raises consistency update problems; 22) inadequacy of abortive solutions of impasse; 23) size and type of record.

10. Experimentation

Two simple models of integration in a large construction were implemented in a very large construction company in Brazil. The main objective was to meet its needs for more efficient quantity calculation and progress report for invoicing procedures. Figs. 5a and 5b present the models and Fig. 6 illustrates the products developed.

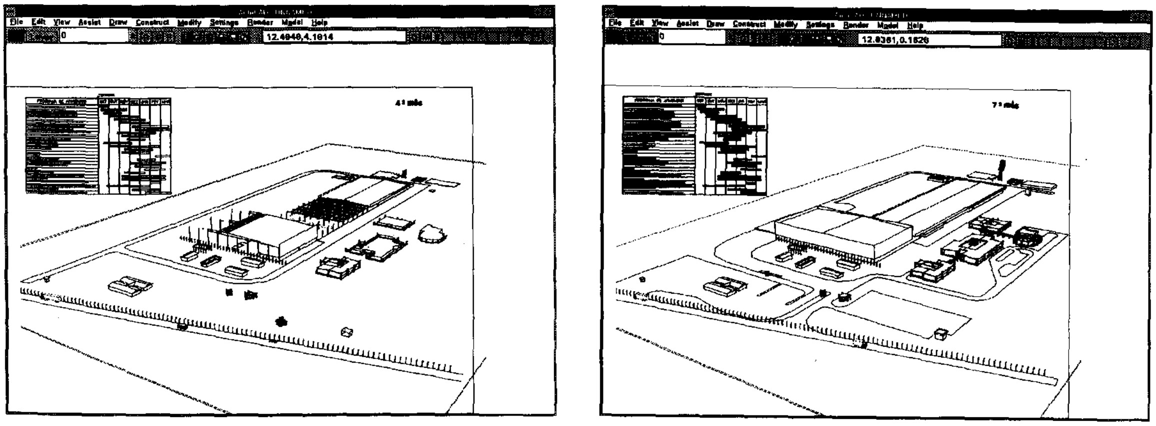

Fig. 7 Planning and 3D model-4th and 7th month (last).

In order to evaluate the possible impact of the integration between the 3D model and the planning network, a real test case was performed using the design and construction of a plant for producing cans, as shown in the sequence of Fig. 7.

The experience undertaken has revealed more adequate construction methods and lead to a schedule two months shorter than the one obtained by the conventional planning method previously applied.

11. Conclusions

The implementation of an Integrated CAD System in a construction company may not be undertaken as a trivial job. The authors' experience has revealed that the success of such an initiative depends upon the execution of a Process Innovation plan and the adherence to the so called Concurrent Engineering practice. These concepts are the cornerstones of those modern companies that wish to compete in and for the future.

The paper presents these concepts and propose basic models that should support the implementation of such an integrated system. A number of examples extracted from real situations show the feasibility of the proposed approach.

The challenge for future work is to solve the problems related to the full model of integration, such as data integrity/consistency, full implementation of the Integration Object Structure and, from a technological side, computer performance enabling multiple applications to execute simultaneously and effectively under a windowing environment.

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References

Bento, J. (1992), "Intelligent CAD in structural steel: a cognitive approach", PhD Thesis, Expert Systems Laboratory, Imperial College, London, UK.

Bowen, W. (1986), "The puny payoff from office computers", *Fortune*, No. May 26th, 20.

Davenport, T.H. (1993), *Process Innovation*, Ernst & Young.

Feijo, B. and Bento, J. (1991), "A cognitive approach to design", CMEST Report AI 5/91, IST, Lisboa.

Gero, J. (1990), "Design prototypes: a knowledge representation scheme for design", *AI Magazine*, No. Winter 90, 26-36.

Gomory, R.E. and Schmitt, R.W. (1988), "Science and product", *Science*, No. May 27, 1132.

Hamel, G. and Prahalad, C.K (1994), *Competing for the Future*, Harvard Business School Press, Boston.

Hammer, M. and Champy, J. (1993), Reengineering the corporation-a manifesto for Business Revolution, Harper Collins.

Jo, H.H., Parsaei, H. and Sullivan, W. (1993), "Principles of concurrent engineering", in Parsaei, H. and Sullivan, W. (eds.), *Concurrent Engineering*, Chapman & Hall, London, 3-23.

Loveman, G.W. (1988), "An assessment of the productivity impact of information technologies", *Working Paper* No. 90s: 88-054, MIT Sloan School of Management, Management in the 1990s, July.

Morad, A.A. e Beliveau, Y.J. (1991), "Knowledge-based planning system", *J. of Construction Engineering and Management*, **117**(1), 1-12.

Naveiro, R.M. and O'Grady, P. (1995), "A concurrent engineering approach for design assistance of casting parts", *Proc. Int. Conf. on Engineering Design*, ICED 95, Praha, August.

Prates, A.J. (1993), "Fundamentos e especifiçao de um ambiente de design baseado em Lógica e objetos", Msc Thesis, Intelligent CAD Laboratory, Dept. Eng. Civil, PUC-Rio, Rio de Janeiro.

Reinschmidt, K.F., Griffs, F.H. and Bronner, P.L. (1991), "Integration of engineering, design, and construction", *J. of Construction Engineering and Management*, **117**(4), December, 756-772.

Roach, S.S. (1991), "Economic perspectives", Morgan Stanley, January, 6-19.

Scheer, S. (1993), "Uma análise crítica sobre o tratamento cognitivo de design em sistemas de CAD", PhD Thesis, Intelligent CAD Laboratory, Dept. de Informática, PUC-Rio, Rio de Janeiro.