Experiencing Computer Integrated Construction

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Abstract: The future success of large Japanese construction firms may well depend on the widespread implementation of computer integrated construction (CIC) concepts. Because of changes in the competitive environment, the nature of the construction industry is evolving in fundamental ways. Construction companies that emphasize CIC are likely to gain a significant competitive advantage over those that do not. In today's construction industry, information technology must be viewed as a potential resource. CIC is a strategy, incorporating computers and robotics, for linking existing technology and people in order to optimize business activity. There is no standard formula for CIC. A strategy for implementing CIC should be formulated, and each company must define its own system. The strategy must be supported and promoted at the highest company level. The objective of this paper is to describe the experiences gained in CIC research from a Japanese construction company's viewpoint, and to present a test-base model for CIC implementation. Although the model is not a comprehensive system, it can be considered as a methodology toward total CIC.

Introduction

The large construction firms in Japan are under intensive pressure to develop innovative automated technologies that can resolve some of the difficulties associated with the scarcity of skilled labor ("System cuts" 1991), clients' demand for improved quality, and the changing market environment. It is also expected that the way the large construction firms operate will change in the next decade as automated systems find their application on construction sites.

Therefore Japanese construction companies are faced with the need to optimize the way in which they function in order to achieve the best possible performance within necessary constraints. Many of the efforts in this direction are being carried forth under the concept known as computer integrated construction (CIC). CIC is an emerging technology, an approach to assisting construction firms as they respond to the difficult environment in which they currently operate. Considering the current trends in computer applications, it seems that many large construction companies are finding integration to be an attractive strategic option in meeting increased competition. However, in the same way that there are many different perceptions of the problem, there are many different viewpoints regarding the implementation of the CIC.

Today, large Japanese construction firms—which might be defined as architectural/engineering/construction (A/E/C) firms—are beginning to realize that it is vital to have a structured approach to the introduction of CIC technology. One reason for this is that, using CIC, it is likely that a different and more efficient construction operation may be developed. The other

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reason is the tremendous advantage to be gained by enabling computers in different sectors of the company to communicate and exchange information.

However, there is no standard or universal formula as to how a company should adopt CIC. Construction companies operate in different ways and in different market places, and each one must devise its own CIC strategy for success. Although major steps have been taken by many large A/E/C firms, full CIC implementation has not yet occurred in Japan.

The objective of this paper is to describe the experiences gained in CIC implementation from a Japanese construction company's viewpoint, and to present a test-base (prototype) model for CIC. The model is not intended to be an ideal CIC, but rather for the demonstration of the CIC concepts.

What Is CIC?

CIC is the adaptation of computer integrated manufacturing (CIM) concepts to the construction industry. It is defined as a strategy for linking existing and emerging technologies and people in order to optimize marketing, sales, accounting, planning, management, engineering, design, procurement and contracting, construction, operation and maintenance, and support functions.

Therefore, CIC is the synergy of existing and emerging technologies to achieve a highly integrated system. CIC usually results from: (1) An integrated information flow; (2) the widespread application of computers; and (3) high levels of automation. However, this only represents the technological aspect of CIC. It is equally important to effectively utilize all available resources to achieve the company objectives.

For many reasons, mostly economic in nature, many large construction firms in Japan have started CIC with the integration of design and construction operations. However, the ultimate goal in any company should be to integrate the entire operation. CIC is a concept of a totally optimized, and integrated company.

Strategic Planning

Today, it is the efficient integration of information technology into application systems that is of greatest economic relevance to the construction industry (Choi et al. 1989). The strategy for the automated flow of information is, therefore, of vital significance.

In the example presented in this paper the company's business ambitions has determined its CIC strategy. A high-quality strategy will have the robustness to respond to any change of priorities in the construction industry. Implementation of the strategy is expected to take place over some period of years, and once completed, the company will be set on a certain predefined path.

Extreme care and foresight were determined to be crucial to constructing a viable strategy that is robust enough to absorb changed priorities in the construction market or new technologies. Conflicting philosophies for CIC implementation must be resolved before the CIC strategy can be finalized.

CIC Implementation Planning Team

The initial step in CIC implementation was to get top management's consensus. The implementing director needed a clear policy relative to three issues: justifications for CIC; long-term commitment to computers and robotics; and the impact of CIC on the work force.

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In general, the implementation process consists of three major planning teams (task forces): conceptual; logical; and physical planning as described in the following section.

The conceptual CIC planning team documents the "as is" situations in the construction company, and builds a conceptual model. The members of the team usually have broad professional backgrounds to contribute to the conceptual CIC planning.

The logical CIC planning team defines the functional elements, determines the levels of automation required, and investigates the dependencies and interrelationships of functional elements, data, communication architectures, and training requirements. The team determines requirements for the "to be" CIC system. The team members usually have the technical depth and breadth to participate in the logical plan.

The physical CIC planning team determines the actual hardware and software requirements. The members of this team usually have the computer mechanical, construction, design, system analysis, and integration background necessary to bring the conceptual and logical CIC plans to reality. In this stage, establishing strong relationships with CIC hardware and software system developers is important. The final result of these three teams is usually a set of specifications and recommendations for the automated technology implementation. The implementation of the CIC strategy is incremental and on an evolutionary rather than a revolutionary basis.

Enabling Technologies

Currently, the technology to develop the CIC system exists. Relevant CIC computer-based technologies include: object oriented programming (OOP); knowledge based systems (KBS); data base management systems (DBMS); computer aided drawing/design (CAD) and visual computing; robotics and automated systems; computer aided engineering (CAE); and local area networking (LAN).

The company's experience shows that communication technology, which transfers information from one person and/or computer system to another, plays an important role in CIC implementation. It is this communications system that is the backbone of CIC implementation.

Communication was found to be necessary at several levels in a construction firm. There are essentially a minimum of four levels of control: company, division, department, and individual. Establishing an effective communications network is a very difficult task. It is important, however, that messages originating almost simultaneously receive the correct priority, and that accurate data arrives at the desired final destination.

For communications within a division, a LAN can be used. The technology of LAN is currently the subject of a great deal of development because of its vital importance in computer integration. Three major factors to be considered are: compatibility, expandability, and reliability.

Experiencing CIC

To demonstrate the concept of CIC, a test-base (prototype) system has been developed to investigate integration problems. Currently this system is undergoing the process of testing and completion, and further research is needed in order to achieve a comprehensive integrated system. The following section describes only the components of CIC from a Japanese company's viewpoint, which presents one way of approaching CIC.

To structure a systematic approach for applying computer and automation technologies to design/construction it is important to use an appropriate modeling technique. These modeling techniques can be most usefully viewed as a structured way to develop CIC by carefully investigating the planning, design, and construction processes.

Using modeling techniques, a thorough understanding of how a CIC system works was gained, and allowed identification of irregularity, duplication, and inefficiencies of the system. Major CIC modeling techniques are: physical, functional, information, simulation, and organizational modeling.

The CIC physical modeling describes the visible aspects and hardware issues of CIC, including computers and robots. The CIC functional modeling describes the operation (e.g., construction operation) in terms of the functions it performs (Williams et al. 1988). The CIC information modeling represents the structure of the CIC information needed to integrate functions of planning, design, and construction. CIC simulation modeling (Halpin et al. 1976) is utilized to simulate the process of automation and integration (i.e., simulating an automated building construction process) with an interactive and dynamic 3-D animation graphics system. The CIC organizational modeling describes how people should be integrated into the system. The organizational relationships should be linked to other models to establish an effective interface system.

These models provide basic techniques that are necessary to the CIC implementation. However, it should be noted that modeling CIC is very complex. These models can resolve only portions of the complex CIC problems. Care must be taken to avoid misapplication of the modeling systems.

Fig. 1 shows an overall model of the CIC system. The model is divided into three major areas: (1) Integrated design/construction planning; (2) site automation system; and (3) factory automation. These areas are described in the following section. Although no comprehensive CIC system has been developed yet, major areas have been automated.

Integrated Design/Construction Planning System

Recent innovations in computer software technology in such areas as knowledge based systems, database management, simulation, 3-D CAD systems, engineering and management application software, and object-oriented programming have provided a useful mechanism to integrate, organize, and structure complex design and construction-planning information.

The major elements of the integrated design/construction planning system, as shown in Fig. 1, consist of: initial planning (resource planning, site planning, financial planning); preliminary design; engineering; detail design by 3-D CAD; working drawings; cost estimating, procurement; cost control and planning; shop drawings; and construction planning (scheduling, temporary facility planning, etc). The integrated planning system utilizes object-oriented modeling. Each planning module is divided into subsystems such as selection of building systems, or layout of crane and temporary facilities. Currently, portions of these systems are integrated, centralized under CAD systems, and research is in progress for total integration. Further technical description on this system is presented by Yamazaki (1991).

The main challenges of CIC in this area has been: constructability in planning and management stages; development of specifications for flexible designs and engineering; and companywide construction planning and man-

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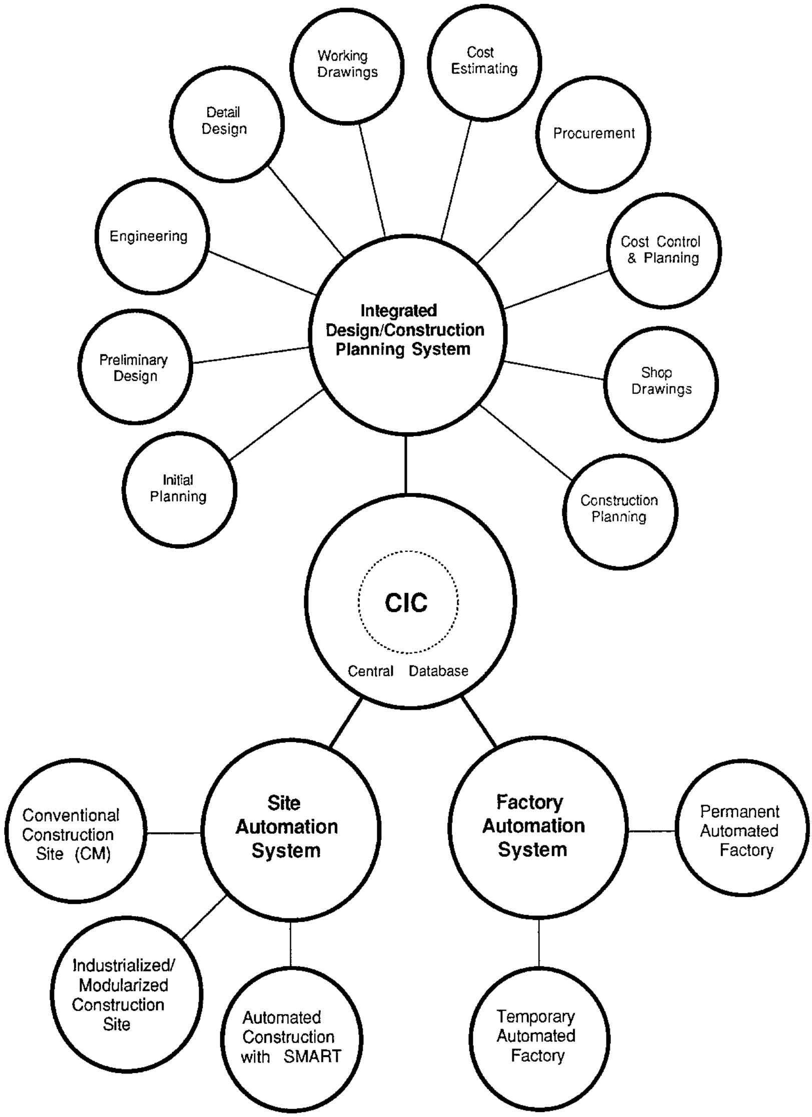


FIG. 1. Computer-Integrated Construction Model

agement. To solve the integration problems there is a need to further investigate and design well-structured data and knowledge-based systems.

Site-Automation System

The second major element of the CIC is construction site automation, which plays an important role in the overall integration process (Kangari et al. 1990). Presently, developmental efforts are being focused on fully automated construction systems, which can handle major structural assembly operations such as steel frames of medium to high-rise buildings.

The site-automation system utilizes a self-elevating automated assembly platform that provides an integrated building-construction environment. In general, the process consists of: (1) Transportation of prefabricated materials from a prefabricating factory (or material supplier) to the construction site (exterior transport system); (2) an automated material storage facility on-site; (3) automated transportation of material from the storage facility to the building by conveyor cars, overhead cranes, automated elevators, lifts, conveyors, and/or automated guided vehicles (interior transport system); (4) automated placement and adjustment of the prefabricated material elements; and (5) automated assembly and welding of elements.

An automated high-rise construction system known as SMART (Shimizu Manufacturing system by Advanced Robotics Technology) has been developed. The SMART system is a part of an overall CIC strategy for developing construction systems that integrate the high-rise construction processes including the erection and welding of the steel frames, placement of precast concrete floor slabs, exterior and interior wall panels, and installation of the various units. The system extensively utilizes prefabricated components such as: columns, beams, floorings, and walls. Assembly of these components is simplified by the use of specially designed joints. A real-time computer-control system is used for the assembling process. Fig.

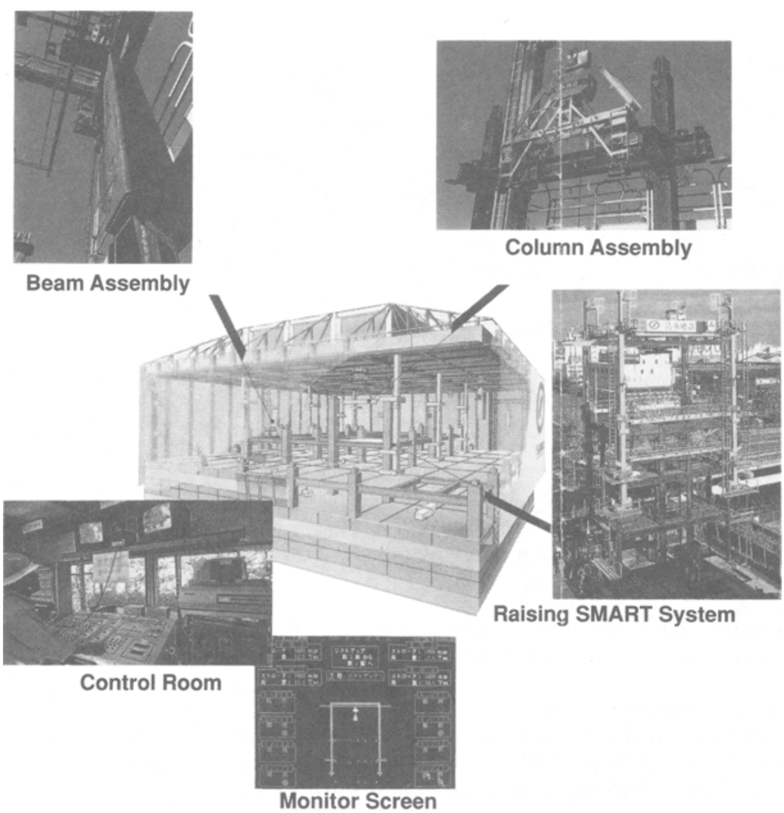


FIG. 2. First Tested System of Automated Construction Site

2 shows an overview of the first system, successfully tested and completed in 1991.

In this system, steel-frame columns and beams are automatically conveyed to designated locations, where they are properly assembled with special joints. When one floor of the high-rise is completed, the entire automated system is lifted up by vertical jacks, and work for the next floor commences immediately. Each step in the process is orchestrated by the central control room, where commands are issued and sequential progress is monitored.

The second system, as shown in Fig. 3, is a 20-story steel frame office building that is built in Nagoya, Japan. In this system, progress control, inventory control, operation control, quality control, material transportation control, and other aspects are integrated. The system consists of the following major components: (1) Operating platform; (2) jacking towers; (3) vertical lifting crane; and (4) weather-protection cover. The goal is to make the construction site operate as an automated factory.

The operating platform consists of computer-control rooms, monorail hoists for horizontal transportation (ceiling crane), and the structural steel frame, which finally becomes the top roof of the building. The operating platform is a self-elevating automated assembly system that provides a closed environment for the automated building-construction operation. After foundation work is completed, the operating platform is assembled and mounted on the top of the four jacking towers of the lifting mechanism. The control room is housed within the structure, and the monorail hoists are suspended

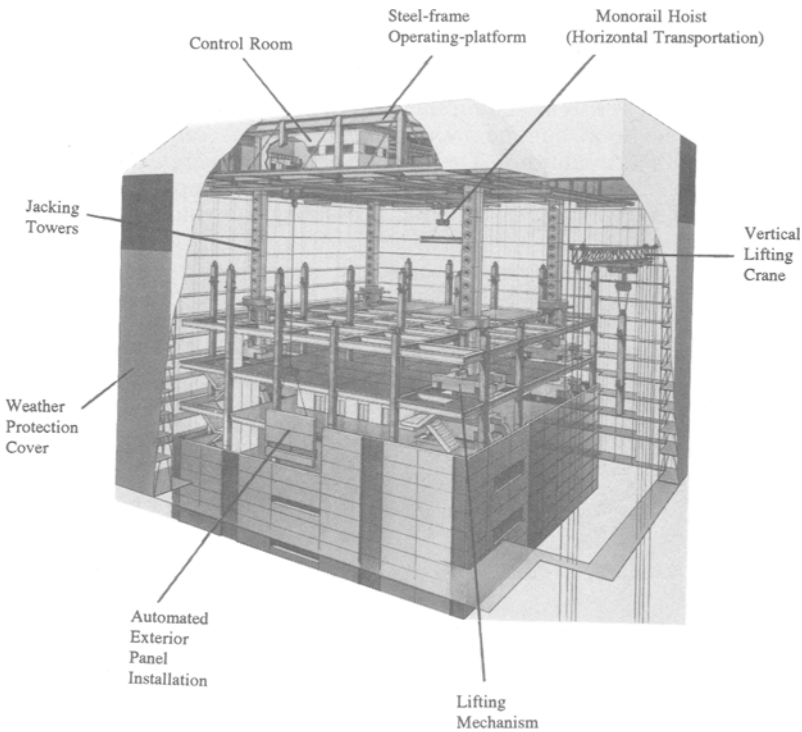


FIG. 3. Second System of Automated Construction Site

from the bottom. The control room is jacked up as the work progresses. The system requires the synthesis of many existing technologies, which is only possible with computer-integration technologies. It uses an automated erection system to construct without weather interruptions.

Steel columns and beams are automatically transported to the designated locations, where they are assembled and mounted with specially made joints. The steel frame welding process is also automated with the invention of a new automatic welding machine. When one of the floors of the building is completed, the entire automated system is lifted vertically, and the work for the next floor commences immediately. Thus, construction work proceeds systematically, floor by floor, until the whole building is completed. SMART components such as the control room, cranes, and lifting jacks are then dismantled and the steel-frame operating platform becomes the permanent roof of the building.

The company's experience shows that the system improves productivity and safety, reduces dependency on labor; protects the working environment by providing all-weather enclosure for the site; provides attractive working conditions and safety, which leads to higher quality and durability; reduces the construction period; reduces the amount of waste and damage to the materials; provides real-time site management and scheduling; improves the poor image of the construction site; and resolves some of the difficulties associated with application of single-task–oriented robots. In the future, the plan is to further advance the SMART system to reduce the labor and construction period to one-half of the traditional methods.

Applying the concepts of integrated factory automation to the construction site has also been the focus of CIC by other large construction companies in Japan such as Taisei Corporation and Ohbayashi Corporation. Taisei's T-Up system is an automated construction system for high-rise buildings. A Hat structure is assembled on the ground and elevated by a core tower. The Hat covers floors built below so that construction continues even under adverse weather conditions. The system builds a concrete core by using slipforming techniques. The concrete core provides support to the Hat. Ohbayashi has developed an automated building construction floor system

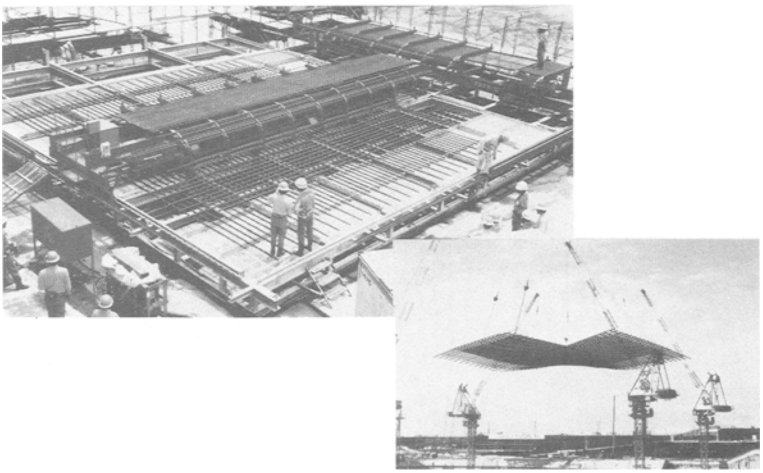


FIG. 4. Automated Rebar-Assembly System

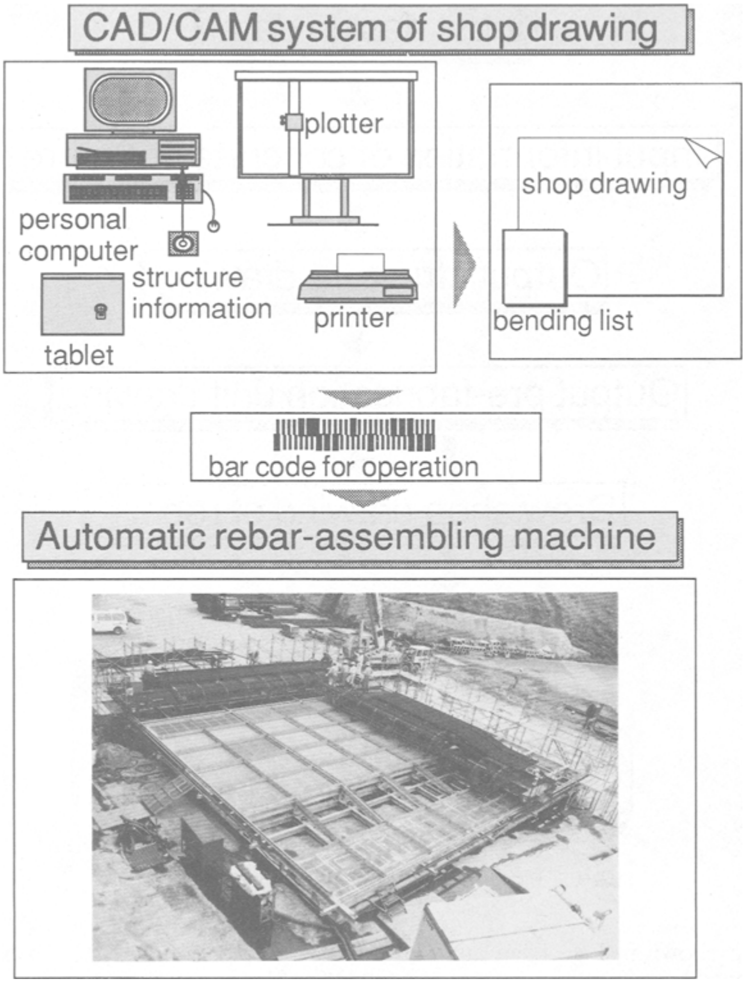


FIG. 5. Outline of Factory-Automation System

that places an automated assembly platform on the top of a building. However, the lift-up system is different than the SMART system. In Obayashi's lift-up system, the platform has a number of legs sitting on the lower columns.

Factory Automation System

The third major element of CIC is factory automation. It could be established temporarily on a construction site, or it could be a permanent factory in a remote area. The system consists of an automated prefabrication factory of construction units, and its operation is very similar to CIM. Examples of the factory automation systems are: rebar steel prefabrication units; exterior walls; prefabricated steel columns and beams with special connecting joints; prefabricated concrete slabs; and others. The next section describes an example of the rebar-prefabrication factory-automated system.

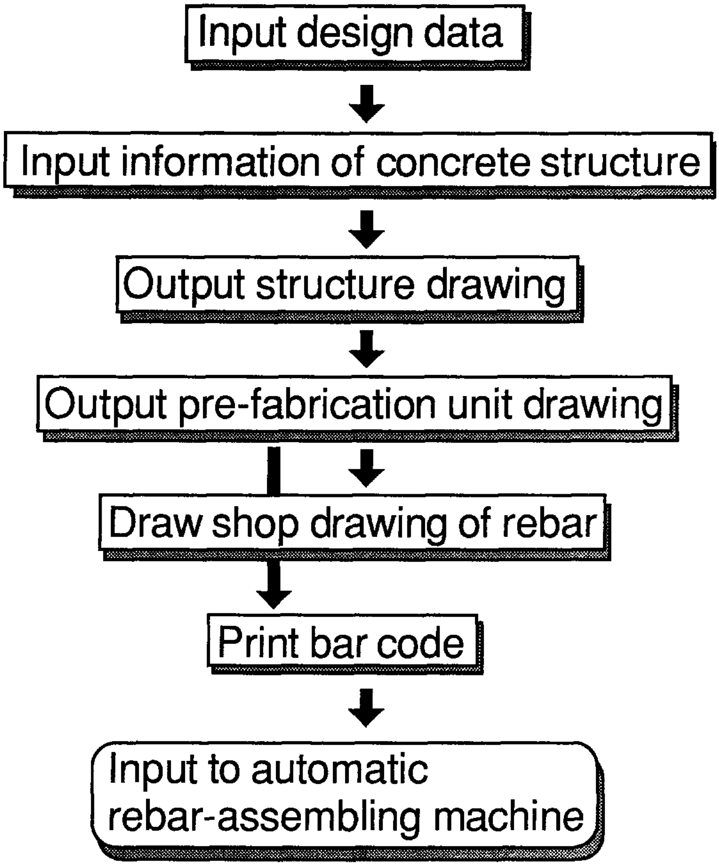


FIG. 6. Flowchart of Rebar-Assembly CAD System

As shown in Fig. 4, an automated rebar prefabrication system was developed based on the concepts of a CAD/CAM system. The system consists of two major parts: (1) CAD system; and (2) assembly unit (CAM).

As shown in Fig. 5 the CAD system consists of a NEC PC98000XL high-resolution-mode personal computer with tablet and mouse input. The output is printed on a A1 plotter. The system uses AutoCAD, DBASE III Plus, and BASIC software. Fig. 6 illustrates the functions of the rebar CAD system. Fig. 7 shows an example of the CAD's shop drawings.

The CAD system uses database systems to produce various working drawings for the structural steel rebars. The database systems include the following information: number of rebars; spacing; types and dimensions of rebars; bending shapes; and arrangement of longitudinal, transverse, support, and special rebars. Next, these units are built by the assembly system based on the information provided by CAD.

The assembly system as shown in Fig. 8 consists of three units: two vehicles, and a steel rebar-arrangement support base. The two vehicles are used for arranging bars, one in the longitudinal direction, and the other for arranging bars in the transversal direction. In the process of the rebar ar-

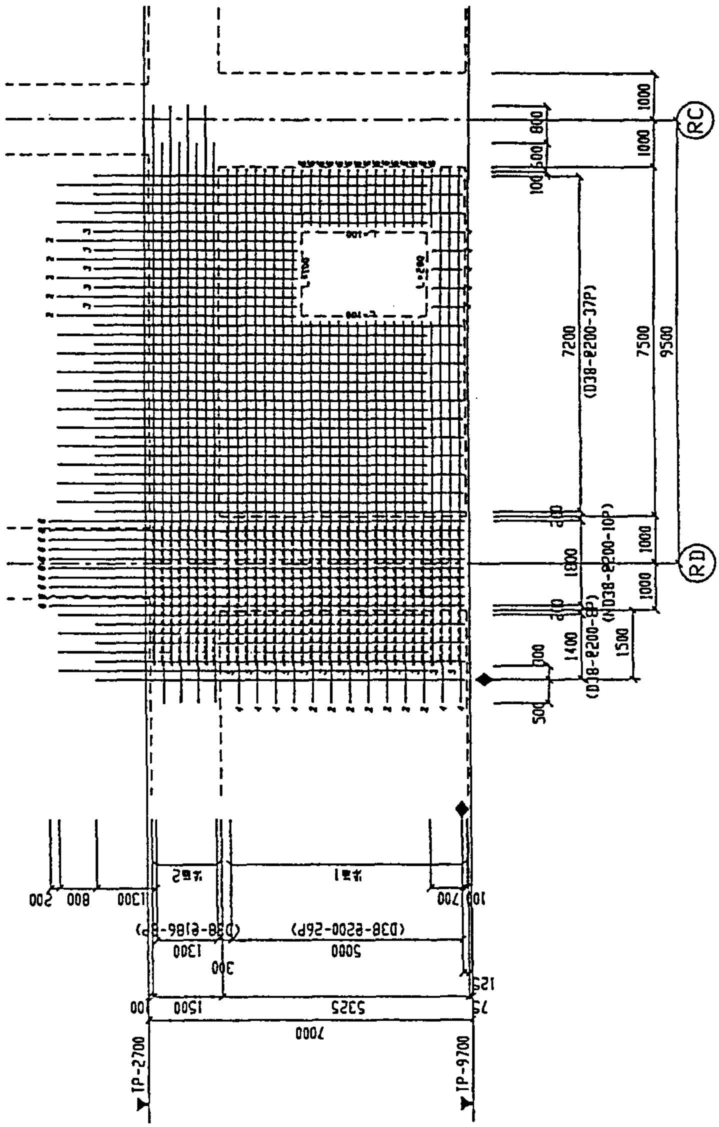


FIG. 7. Example of CAD Output

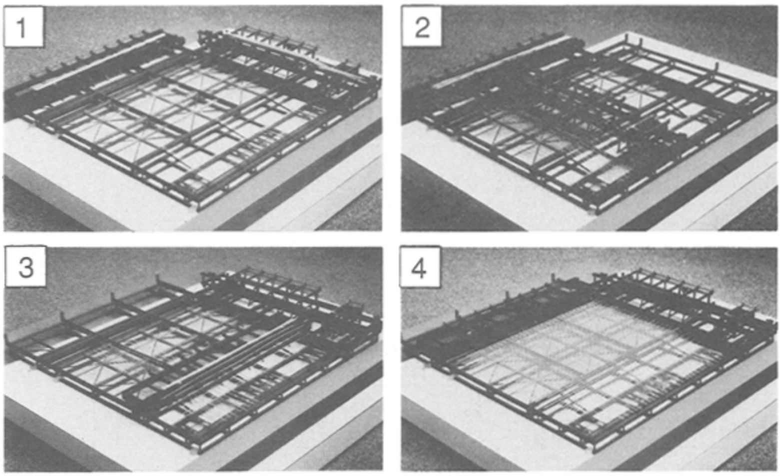


FIG. 8. Processes of Rebar Assembly

rangements, first the longitudinally moving vehicle carrying the rebars moves forward till it reaches the preset position. Then, while moving backwards, it places rebars one by one at preset intervals on the support base. After the transversely moving vehicle places the rebars in the same manner, a mesh unit is formed and then tied together automatically. The bent rebars can be longitudinally arranged by modifying the shape of the vehicle and partially modifying the support base so that they conform to the shape of the bent bars. The rebar units can be arranged in different ways with various intervals, as shown in Fig. 9.

This is an example of factory automation at a construction site. In this automated factory the processes of: material handling, progress control, inventory management, and the production line are automated and integrated. The application of this system has improved the productivity of the overall reinforcement work from preparation of working drawings to fabrication work. The system has been used in several construction sites, and the results indicate an 80% savings in shop drawings, and a 50% savings in prefabrication of the steel rebars, as shown in Fig. 10.

Lessons Learned

The company's experience indicates that usually the initial problem management faces is the lack of a methodology to explore a CIC initiative. It is important to develop the theoretical substructure for CIC implementation. Given the complexity of the problems in the construction industry, it is not useful to seek final CIC solutions. Rather, managers must establish a learning environment that will continually guide the company toward improved systems.

It is essential to recognize that moving toward a CIC system does not mean simply introducing higher levels of computers and automation into an existing system. Adding automation to an inefficient system will likely produce a highly automated, inefficient system.

It is also important, when talking about CIC, to include not only the construction and design but also other activities. The overall system must

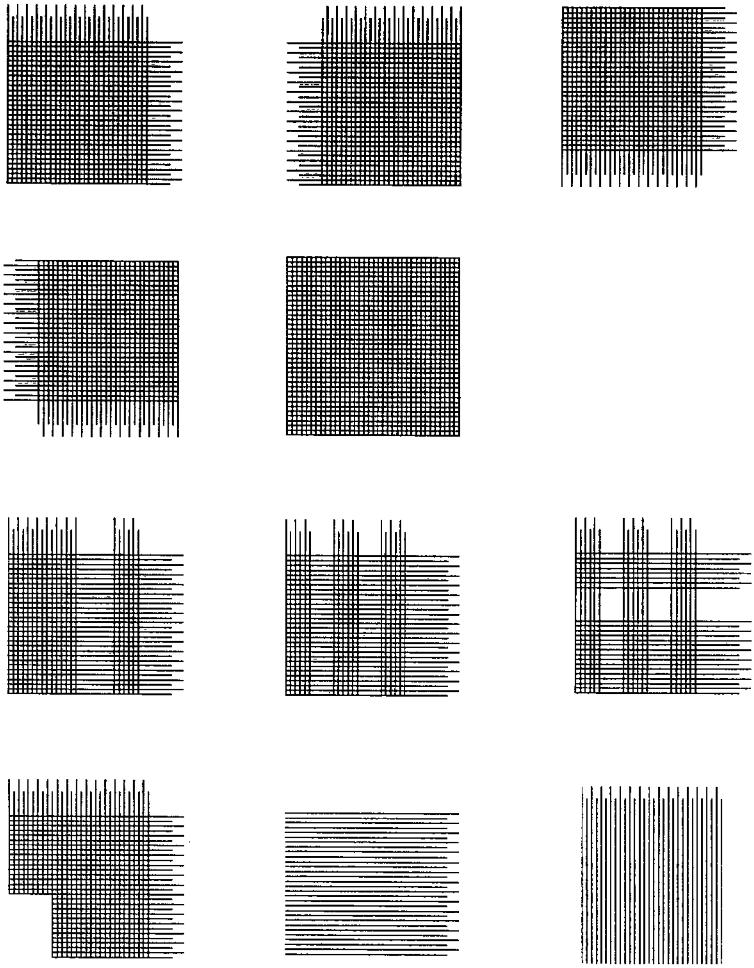
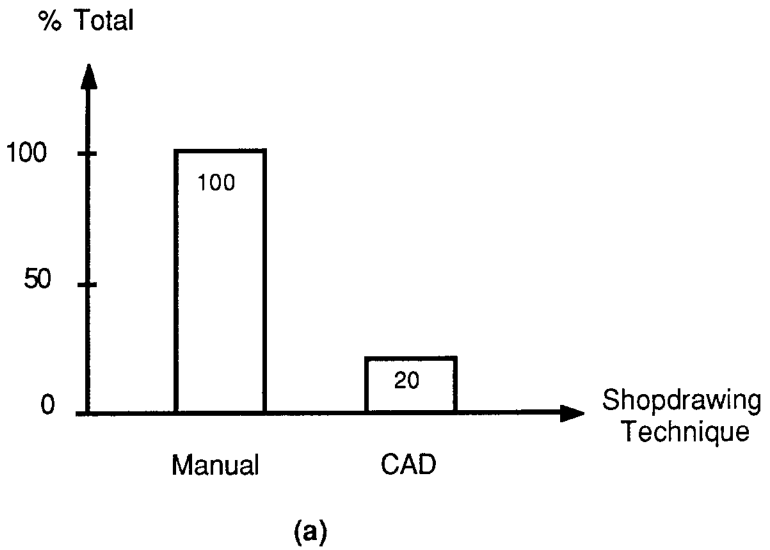


FIG. 9. Possible Types of Rebar Arrangements

be rationalized, requiring that the work flow, organizational structure, and management methods be redesigned to obtain performance objectives. The entire meaning of design must be assessed and modified as necessary to optimize system performance (Tucker et al. 1986). The most appropriate use of technology can then be selected within this context.

Introduction of CIC has provided the company with a new philosophy toward the application of advanced technologies to construction sites. It is believed that meeting such a challenge can make a company more competitive in the world market.

CIC has also presented changes in working practice. Job descriptions are becoming more multidisciplinary due to the integration of different functions. As the CIC project progresses through its different phases, the skill mix and roles of the team members change. In the early stages when the requirements are being planned and the concept designed, the work is more



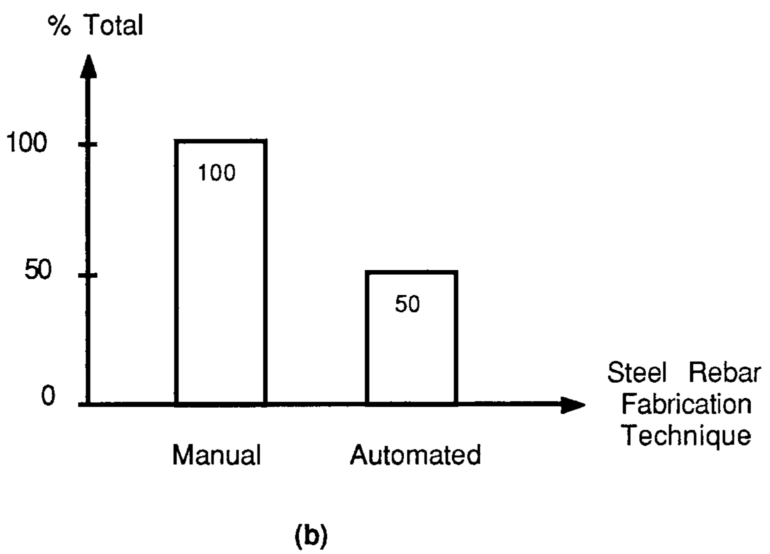


FIG. 10. Productivity Improvement: (*a*) Savings in Shop Drawing; and (*b*) Savings in Rebar Prefabrication

exploratory and analytical. During detailed design and implementation, it is more technical.

It was concluded that the move towards CIC should be accompanied by a change in philosophy and method of organization, to approach the just-in-time (JIT) way of working. Originally known as *Kanban* when it was developed by Toyota in Japan, the principal of the just-in-time philosophy is that every process in the production cycle happens just in time for the next. For instance on a construction site, material such as steel for framing arrives at the site just in time to be erected. This is an ideal state of operating for a construction site. Although it is difficult to achieve a JIT system, the philosophy presents a perfect target to have in mind when implementing CIC.

Strategic and Operational Benefits

CIC implementation provides both strategic and operational benefits, thereby enhancing a company's competitive position.

The most important strategic benefit of CIC has been the improvement of the company's competitive advantage in the marketplace by specializing in CIC. This has improved the company's image, which is expected to increase market share. This has also allowed the company to stay at the forefront of technology. It is believed that CIC will assist the company to overcome the skilled labor shortage, which is expected to reach a critical point in Japan during the next two decades. Future benefits are the enhancement from local optimization (individual department system) to global optimization (companywide integrated system).

The operational benefits are: construction and design productivity improvement through automation; cost reduction; project time-schedule optimization; quality improvement of design and construction; coordination and management improvements; design integration; flexibility in design and constructing of innovative facilities concurrent performance by various departments; communication improvement by rapid transmission and availability of data, images, and knowledge; avoiding similar data entries in design and construction processes; increasing opportunities for further construction robotization; and opportunities to electronically link with subcontractors, suppliers, insurance, banks, and vendors.

However, it should be mentioned that not all of these benefits are realized in the company at this time. CIC is still in its early stage, and it is unlikely that any significant competitive advantage will be gained, and the economic value of competitive position at this stage is small. Therefore, in the interest of recognizing the need to gain experience, the company has relaxed the traditional economic justification requirements.

Summary and Conclusions

In the next decade, implementation of CIC is expected to play an important role among the large Japanese construction companies. One reason for this is that, using CIC, it is likely that a completely different and more efficient construction operation may be developed. The other reason is the tremendous advantage to be gained by enabling computers in different sectors of the company to communicate and exchange information.

In today's construction industry, information technology must be viewed as a potential resource. CIC is an emerging technology, and also an approach to assisting construction firms in responding to the difficult environment in which they currently operate. There is no standard formula for CIC. However, a strategy for implementing CIC should be formulated, and each company must define its own system. The strategy must be supported and promoted at the highest company levels. The implementing director needs a clear policy relative to three issues: justifications for CIC; long-term com-

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mitment to computers and robotics; and the impact of CIC on the work force.

It is believed that the conversion of the large Japanese construction firms from traditional construction methods to CIC-oriented technology will be one of their major challenges in the next decade. CIC will also result in changing the work habits of a company's work force. Job descriptions will become more multidisciplinary due to the integration of the different functions. For these changes to take place smoothly, the work force must be informed of management's intention to implement CIC technology, and requisite training must be offered.

To demonstrate the concept of CIC, a test-base system has been developed to investigate integration problems. The system is divided into three major areas: (1) Integrated design/construction planning; (2) site-automation system; and (3) factory automation. This system describes a step toward a total CIC system. Given the complexity of problems in the construction industry, it is not useful to seek final CIC solutions. Rather, managers must establish a learning environment that will continually guide the company toward improved systems.

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