Applying Computer-Integrated Manufacturing Concepts to Construction

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Abstract: This paper compares the process similarities between the manufacturing and construction industries and identifies areas for cross fertilization through computer-integration techniques that have been effectively applied to solving productivity problems in manufacturing. The importance of computer integration is illustrated by the strides that manufacturing has made in their integrated approach to providing a product. A comparison of the manufacturing and construction industries describes basic functional similarities, indicates similar problems facing both industries, and defines similar solutions being applied with their respective degrees of success. The role of modeling in integrating processes is defined before integration in construction and manufacturing are reviewed. The paper compares manufacturing and construction processes by developing an integrated process model that identifies specific activities in construction and relates the model to an existing integrated manufacturing model. Finally, based on a comparison of functions, the paper describes and defines areas for cross fertilization of techniques and tools for automation of the construction industry.

Introduction

Computer-integrated construction (CIC) defines a goal to make better use of electronic computers to integrate the management, planning, design, construction, and operation of constructed facilities. In this context, integrate means to combine the individual elements to optimize the performance of the whole facility, not one of its separate organizational components. CIC is a relatively new concept, and is being implemented with different amounts of success. The manufacturing industry began work on computer-integrated manufacturing (CIM) concepts decades before the construction industry ("Integrated" 1978). This paper will examine and compare the construction and manufacturing industries, in general and via abstract models, to identify the potential areas for cross fertilization. This way, CIC can benefit from the many lessons the CIM community has learned.

A short description of the research methods employed will orient the reader. The research described herein, was conducted by an interdisciplinary team of 16 architectural and industrial engineering faculty and students, one software vendor, five industry advisors, and five academic advisors. A total of 20 building case studies were used to develop and validate the integrated building process model (IBPM) presented. The research steps follow.

1. Review existing process models, modeling literature, CIM data, and integration efforts to compare the industries.
2. Develop criteria for and select a process modeling tool.

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3. Build process models for construction processes via site visits, case studies, and expert reviews.
4. Compare construction and manufacturing processes to identify areas for cross fertilization.
5. Define successful manufacturing tools that can be implemented in construction.

The Importance of Computer Integration to Construction Productivity

The significance and possible long-term benefits of computer-integrated construction can be seen in parallel developments in the field of computer-integrated manufacturing. The parallels are striking. As an example, General Motors in 1986 began an effort to develop "simultaneous engineers"; engineering personnel who are given integrative responsibilities for both design and manufacturing. The general manager of the AC Division, J. Tannehill, states that it is becoming absolutely necessary for design engineers to be fully cognizant of how decisions concerning materials, tolerances, part selection, and assembly processes will affect the manufacturability and ultimate quality of the product. The GM experiment with "simultaneous engineers" is aimed at reducing the five-year lead time needed to bring an automobile to market and improving the overall quality of the automobile.

The problem preventing CIM, as described by Merchant (1987), is that the databases and knowledge associated with design and that of manufacturing are quite different and, for the most part, not overlapping. Merchant says:

> ". . . good progress is being made in the integration of the factory-floor portion of the system in manufacturing—the production control, production equipment and production process elements of the system. At the other end of the system lies the product design, where conceptual design, detailed design, engineering analysis and overall product modeling take place. . . . It is at the interface between design and production where the greatest difficulty in accomplishing [integration] has been experienced—it is the sticking point."

The manufacturing industry is attempting to better integrate the design and manufacturing components in two basic ways: by developing computer architectures that allow common access among all users of the information and models; and by realigning organizations and traditional job assignments to encourage broader involvement and understanding of product development and manufacturing, e.g., simultaneous engineering.

Merchant's assertion is clearly appropriate in the construction industry as well. Good progress has been made in the automation of some design and construction activities in the home office and at the work site. However, it is the integration of these activities that is severely lacking in the construction industry.

There is an important difference between construction and manufacturing that suggests that well-developed computer architectures may be even more important for the integration of construction activities than manufacturing. In manufacturing, the designers, the engineers, and the fabrication specialists all work for, or are captive subcontractors of, the same firm. The plant man-

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ager can dictate organizational and job changes that augment and encourage the desired integration. Even with suppliers and subcontractors, the trend towards just-in-time (JIT) manufacturing is resulting in tighter integration between the manufacturer and suppliers or subcontractors. By contrast, in the construction industry, architectural, engineering, fabrication, construction, and facilities management activities are often distinct economic units with different objectives and long-term business policies. As such, organizationally driven integration of these functions cannot be so easily realized. Therefore, a uniform computer information architecture is more critical in construction than manufacturing.

Comparison of Manufacturing and Construction Industries

The Construction Industry

The construction industry, at approximately $350 billion annually, is one of the nation's largest industries, yet it has consistently shown declining productivity over the last few decades. Owners are becoming more educated and are demanding "more construction for their money" (*Construction* 1982). The construction industry is fragmented. Many organizations and standards exist. The average contractor and subcontractor provides services for a small portion of the facility's total life.

The Business Roundtable's Construction Industry Cost Effectiveness Study (*Construction* 1982) showed over 200 areas for potential improvement in construction. Various study groups were formed through the Construction Industry Institute (CII), to address these needs. Twelve of the initial 14 special topics studied covered areas of responsibility that fell between company organizations, e.g., constructability.

Industry and government are also aware of the problems. Yates (1987) cites automation through computer integration as the major opportunity for construction productivity improvement in the next decade. The National Research Council ("Report" 1987), and the National Science Foundation (Wilson 1987a), have sponsored coordinated attempts to explore and define methods for improving the integration of construction through the use of computers.

The Manufacturing Industry

Parts of the U.S. manufacturing industry have gone through a successful, extensive implementation of computer tools to integrate the manufacturing process. This industry is similar in size to construction, is better coordinated, and is controlled by larger corporations with in-house management, planning, design, and production capabilities. Their productivity is increasing.

In attempting to move toward CIM, these companies quickly realized problems in communicating intent among a large group of people with disparate backgrounds. To overcome this difficulty, the integrated computer-aided manufacturing (ICAM) program ("Integrated" 1978) developed modeling methodologies and used them to describe the current position (as is) and desired future position (to be) for many CIM projects. These tools facilitated communication and helped to ensure that potential problems were not overlooked in developing a CIM solution.

Basic Processes and Functions

A comparison between the basic processes and functions of the two industries yield the following observations:

1. The manufacturing and construction industries both produce engineered products that provide a service to the user.

2. Manufactured products are typically made in a facility and shipped to their final use area, while construction products are built in place. Hence the manufacturing environment is well controlled when compared to construction's.

3. The location of manufacturing process equipment, material paths, and the physical work area remain fairly constant throughout the production of one product. The construction work face changes as each component product is installed in place. This requires that process equipment, (e.g., concrete forms), and material handling equipment, (e.g., cranes), move as the work area changes.

4. Construction products are generally more complex, heavier assemblies built to lower tolerances than manufactured products.

5. Construction and manufacturing may both include processing of raw materials and the assembly of many diverse premanufactured components in the final product.

6. Production volumes are typically smaller in the construction industry. There is a more "one-of-a-kind" production and nothing that parallels the high volume of, for example, an automated assembly line. On the other hand, manufacturing includes mass production and small batch production of components and their subsequent assembly. Examples of construction mass production are production of concrete or lumber components; small batch production—prefabrication of reinforcing steel, while the whole site is an assembly of components.

These functions are explicit in the process models presented later.

Problems Facing Industries

It is also interesting to note that both industries experience four similar types of problems that further motivated this study (Sanvido, unpublished report, 1987). These are:

1. The high cost of correcting design errors and including changes late in the design stage or early construction/manufacturing.
2. Poor resource utilization on fast-track projects.
3. Duplication of information in the same project, little information sharing, and lack of available planning information.
4. Poor efficiency in moving information from design to construction/manufacturing.

The significance of these problems are demonstrated through the intrusion of foreign competition into the U.S. construction and manufacturing markets.

Industry's Solutions

Both industries have tried to address these problems using the following three similar techniques:

1. Design for manufacturability/constructability.
2. Simultaneous engineering/fast track construction.
3. Computer-integrated manufacturing (CIM)/computer-integrated construction (CIC), which is the subject of this work.

The first two techniques have been the norm in construction over recent years, while being relatively new to manufacturing. For example, simultaneous engineering is the rule in construction rather than the exception! We believe that the fast track execution of construction projects can provide lessons to the manufacturing field. On the other hand, the third, the subject of this paper, has been implemented over the last decade in manufacturing and is new to construction. Thus it is important to look closer at CIM to explore techniques that have helped to improve the manufacturing industry and apply them to construction. The next section examines process modeling and integration in each industry.

MODELING—A PREREQUISITE FOR INTEGRATION

Integration of a process requires a common set of standards and definitions acceptable to all participants—i.e., a model. Thus a review of modeling and integration in both industries is presented.

Modeling and Integration of the Manufacturing Process

Major contributions in modeling manufacturing systems were made by the Air Force integrated computer-aided manufacturing (ICAM) program. This program resulted in the development of several modeling tools. $IDEF_0$ (ICAM 1983a), derived from the structural analysis and design technique (SADT) (Marca and McGowan 1987), is used for functional models. $IDEF_1$ (ICAM 1983b) is a type of entity-relationship model, and $IDEF_2$ (ICAM 1983c) is used for dynamic modeling of time-varying systems. A further contribution was an architecture of manufacturing, developed in $IDEF_0$, which encompasses activities from intial planning and design through maintenance and repair of the product. Harrington (1984) discussed and extended this work, and reports utilization of similar models in various manufacturing applications.

The National Institute of Standards and Technology, through its advanced manufacturing research facility (Simpson et al. 1982), is developing and demonstrating tools for integrating flexible manufacturing systems. Hierarchical control systems (Albus et al. 1984) and a data administration system (Mitchell and Markmeyer 1982), among others, have been demonstrated.

An important issue in manufacturing integration is data transfer between various computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. Initial graphic exchange specification (IGES), a specification for exchange of geometry between systems, was developed to address this problem (Schroeder 1984; Pratt 1985). Shortcomings of IGES in transferring non-geometric product design information are well known (Wilson 1987), and led to the development of product data exchange specification (PDES), a standard that addresses representation of nongeometric product data.

Communication among factory computers and intelligent machine tools, robots, inspection devices, material handling systems, etc. is being addressed through several communications standards, including manufacturing automation protocol (MAP) (Jones 1988), which was developed specifically for manufacturing applications.

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Modeling and Integration in Construction

There have been very few generic process models built for the construction industry. Some schematic flow models of certain subsections have been attempted. Al Muallem (1988) identified several process models developed for the design phase. These defined the project initiation process in an owner's organization, architectural programming, the project definition decision process, and the predesign and the early design functions.

There have been several attempts by researchers to model the functions in the construction process. These models either cover portions of the project functions or are oriented to activities associated with a segment of the industry. Howell (unpublished report, 1986) defined a simple model of inputs required to support crews working in construction in the field. Sanvido (1988) generated a series of more complete models specifying generic input, process, output, and control functions (together with rules for operation) required to improve the productivity of a construction project. Sanvido developed similar models to define functional requirements of inputs, processes, outputs, and control levels for the owners project team, the design team, the procurement team, and the contractor. Wheeler (1978) defined the life cycle of the building process as nine steps and divided each of these into subfunctions. He presented matrices of activity responsibilities to complement this.

Recently, an increased emphasis on computer-integrated construction research has resulted in several major modeling and integration research efforts nationwide. While there may be many more efforts under way, the writers are aware of the academic research currently in progress at Carnegie Mellon (Fenves et al. 1988); Lehigh (Wilson and Mueller 1988); Massachusetts Institute of Technology (MIT); Stanford; Technical Research Center of Finland; and Purdue (*Symposium* 1989). Illustrative industry research is being conducted by Bechtel, Ferguson, Takenaka, and Fluor Daniel (*Symposium* 1989). Several recent workshops at Lehigh (Wilson 1987a) and by the NRC (*Report* 1987) have also contributed to stimulate the field.

Selection of a Modeling Tool to Compare Construction and Manufacturing

Criteria for the selection of a modeling methodology to effectively compare the two industries were developed. These included categories related to technical merit of the modeling methodology, ease of use, availability, and compatibility. The criteria related to technical merit included the ability to model functions and information, provision for multiple levels of detail, procedures for configuration control, and capability to model both iterative and sequential functions. Also considered were ease of learning the methodology and explaining the model. In addition, the methodology had to be available to the modeling team as well as the architecture engineering construction (AEC) community, and be compatible with other AEC activities as well as manufacturing integration projects. After reviewing 10 prominent modeling tools (Chung 1989), IDEF_0 was selected as the functional modeling methodology.

An Integrated Building Process Model

The integrated building process model (IBPM) was developed to five levels of detail. The model was drawn from the perspective of the owner of

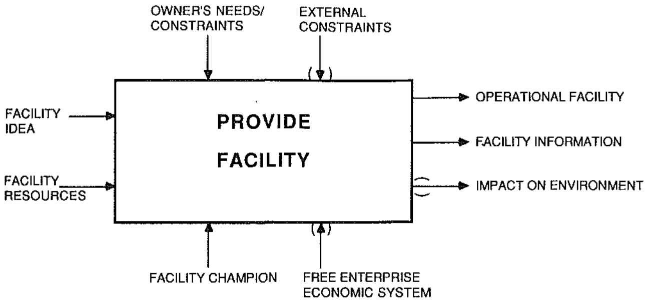

FIG. 1. Level 0 IDEF$_0$ Drawing of Provide Facility

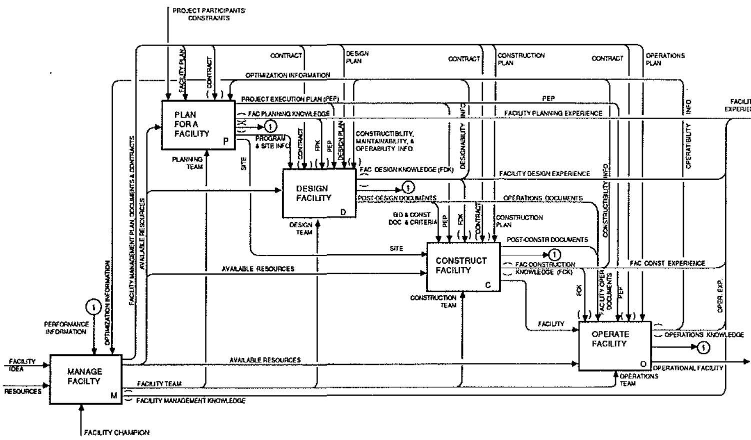

FIG. 2. Level 1 IDEF$_0$ Drawing of Provide Facility

the facility. This explanation focuses on the first three only. The first drawing (Fig. 1) is an overview titled "provide facility" that defines the boundaries of the model in general terms. The second drawing (Fig. 2) divides "provide facility" into five subprocesses. Fig. 3 explores the "construct facility" function. These drawings offer increasing levels of details. Fig. 1 has the least detail and is known as the level F model. This notation is not consistent with IDEF$_0$ but was adopted for mnemonic reasons.

The model was developed by a group of industry experts representing owners, designers, constructors, and operators of buildings. In developing this model, the group considered earlier process models developed for various segments of the industry. The research team then further refined and tested the model on 22 building projects (see Table 1). Industry and academic advisors met five times each to review the models. When collecting project data, a typical site visit lasted two days. Researchers asked selected project personnel (from project management to foremen) questions to determine the key functions required to perform their work. Deeper questioning resulted in the classification of inputs, outputs, mechanisms, and constraints

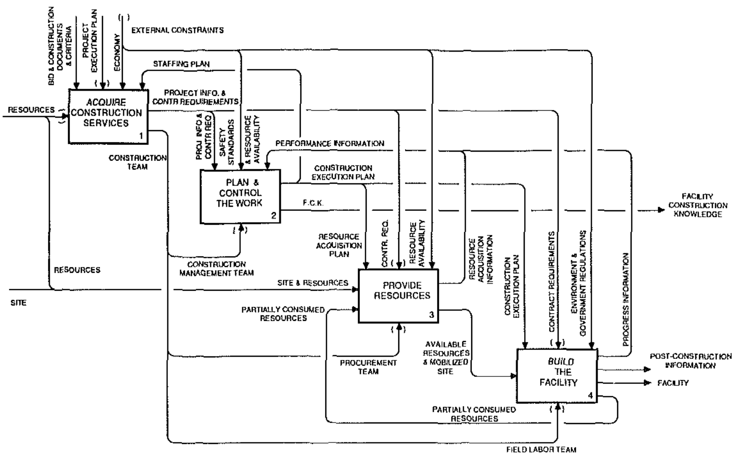

FIG. 3. IDEF$_0$ Drawing of Construct Facility

on the processes. Lower-level activities were then "rolled up" into the upper-level activities described by the managers. Further questioning then resolved discrepancies between the modeled levels. In addition, when a function was not performed, a problem in the project's execution was typically detected. This further supported the model.

TABLE 1. Description of Projects Used to Test Integrated Building Process Model

Model (1)	Company description (2)	Project description (3)
Provide facility	All projects	Average size building 125,000 sq ft
Manage facility	National insurance investment developer	Two 125,000 sq ft office buildings
	Metropolitan developer/facility operator	Four 125,000 sq ft office buildings
	Regional design-build contractor	25,000–75,000 sq ft buildings
	National supplier of preengineered buildings	25,000–75,000 sq ft buildings
Plan facility	Large institutional owner with in-house Planning capability	200,000 sq ft laboratory, conference and office space building
	Regional design-build contractor	25,000–75,000 sq ft buildings
	National supplier of preengineered buildings	25,000–75,000 sq ft buildings
Design facility	Mechanical design division of company	120,000 sq ft hospital
	Electrical design division of company	120,000 sq ft hospital
	Plumbing design division of company	120,000 sq ft hospital
	National supplier of preengineered buildings	25,000–75,000 sq ft buildings
Construct facility	Regional construction contractor	Two four-story commercial office buildings in urban setting
	Regional design-build contractor	Large high school athletic facility
	Regional design-build contractor	Large single family luxury homes
	Local construction contractor	Medium sized store
	Regional design-build contractor	25,000–75,000 sq ft buildings
Operate facility	Institutional owner	Large university campus
	Power supply utility	Power and support facilities
	Institutional owner	Medical school facility
	Institutional owner	Minimum security prison
	National supplier of preengineered buildldings	25,000–75,000 sq ft buildings

Note: 1 sq ft = 0.093 m^2.

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Reading $IDEF_0$ Models

$IDEF_0$ models are composed of blocks and arrows. The blocks represent functions: activities or processes to be performed. Arrows represent data or the means by which a function is accomplished. Inputs to a function are shown on the left side of the block and outputs are shown on the right side. Arrows entering the top of a block are controls that constrain or influence the function. Arrows entering the bottom of the block are mechanisms that perform the process or operation (people, machines, etc.). $IDEF_0$ diagrams are hierarchical, allowing gradual exposition of detail.

The Level F Model ''Provide Facility''

The level F process flow model (Fig. 1) is an overview that shows the boundaries of the model. This diagram shows that the model extends from the original facility idea through the existence of an operational facility. Inputs are the idea and the resources required to provide the facility. Controls include both owner constraints and external constraints such as government codes and regulations. Outputs include an operational facility; information such as drawings, experience, schedule and budget; and an impact on the environment. A facility champion and the economic system are the mechanisms which perform and support the function.

Three elements will be tunnelled, shown as an arrow with parentheses on one end. In this case they are the free-enterprise economic system, the external constraints, e.g., weather, and the impact on the environment. This tunnelling of arrows means that they will not be shown at the next level of detail—they essentially add nothing to the model and clutter the drawing. These elements will reappear when their influence is specific to an activity. All other arrows will appear, and be further classified at the next level.

Components of ''Provide Facility''

The level F model breaks down the process of "provide facility" into the five subprocesses shown in Fig. 2. These are: manage facility, plan facility, design facility, construct facility, and operate facility. Detailed definition of these subprocesses follow.

Manage facility includes all the business functions and management processes required to support the provision of the facility from planning through operations. These activities focus on converting a facility idea, time, and money into a facility team, contracts, facility management plans, and resources to support the project. This function runs for the duration of the facility life. It is controlled by two major factors—performance information about the facility as a whole and information to optimize subprocesses within the facility, e.g., constructibility information. The facility champion is the equivalent to the developer's project executive.

Plan facility encompasses all the functions required to define the owners needs and the methods to achieve these. These activities translate the facility idea into a program for design, a project execution plan (PEP), and a site for the facility. Major controls are constraints imposed by project participants (e.g., the owner or engineer), the facility plan, the contract, and optimization information. Other outputs include facility planning knowledge and information on the performance of the team.

Design facility comprises all the functions required to define and communicate the owner's needs to the builder. These activities translate the pro-

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gram and execution plan into bid and construction documents and operations and maintenance documents that allow the facility to meet the owner's needs. Controls or constraints include program and site information, the contract, facility planning knowledge transferred to the design team, the PEP, and the design plan. Again, facility design knowledge and information on the performance of the design team are other output.

Construct facility includes all functions required to assemble a facility so that it can be operated. These activities translate resources (e.g., materials) in accordance with the design to a completed facility. Typically, appropriate facility operations and maintenance documents are generated. As a result, facility construction knowledge and information on the performance of the construction team is generated. Controls include bid and construction documents and criteria, the PEP, facility design knowledge transferred to the team, the contract, and the construction plan.

Operate facility comprises all of the activities that are required to provide the user with an operational facility. In addition, operations knowledge and information on the performance of the team are generated by the operations team. This process is controlled by the facility construction knowledge available to the team, the facility operation documents, the PEP, the operations plan, and the contract.

This summary of the first levels of the model is supported by many levels below it. As an example, the construct facility node is expanded.

Construct Facility

As a further illustration of the model, the next level of the construct facility function is shown in Fig. 3. This function is decomposed into four subfunctions: acquire construction services, plan and control the work, provide resources, and build the facility. Each of these is described herein. Full details of this expansion can be found in Hetrick and Khayyal (1989).

Acquire construction services deals with selection and organization of the construction team. This typically involves assigning in-house personnel to the project and hiring the needed subcontractors, consultants, and other staff. Controls are the staffing plan from the plan and control function, the economic constraints, the PEP, and the bid and construction documents and criteria. Outputs are the construction team, including management, procurement, labor, and project information and contract requirements.

Plan and control the work is performed by the construction management team acquired in the first step. The primary output is a construction execution plan that establishes the strategies for organizing the construction team, providing resources, and building the facility. The execution plan consists of a staffing plan, a resource acquisition plan, and information required for the construction process such as schedules. The execution plan is revised and updated based on feedback from performing the work. Other controls include project information and contract requirements, safety standards, and resource availability. Facility construction knowledge is output from this function to a higher level, and can be seen in the provide facility diagram.

Provide resources includes acquisition and allocation of all the resources required to construct the facility. The primary output of this function is the mobilized site and the necessary resources. Resource acquisition information is fed back to the plan and control function so that any necessary revisions to the plan can be accomplished. Controls include the resource acquisition

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plan from the previous function, and contract requirements. Resource availability depends on economic conditions, and is an external constraint. Inputs to the function are the site and other resources. This function is also responsible for redeploying partially consumed resources as required.

Build the facility encompasses the physical work of converting the available resources into the designed facility. This function concludes with the start-up and turnover of the facility. Postconstruction information is also output for use at the higher function, and partially consumed resources are returned to the provide resources function for reallocation. Controls include the construction execution plan and contract requirements, as well as external constraints in the form of environmental and government regulations.

This concludes the description of the model. It is important for the reader to understand that this model has evolved from a crude view of the life cycle of a project to its current form through site visits, discussion, and major revisions.

An Integrated Manufacturing Process Model

Fig. 4 is an $IDEF_0$ model entitied "manufacture products," developed by Harrington (1984). Several similarities are apparent, including the management function, the production/construction function and the support and service/operate function. Table 2 is a summary comparison of manufacturing and construction processes as defined by the $IDEF_0$ models. The manufacturing model has planning and design functions imbedded in the "develop products" function. In the construction model, planning and design were split at a higher level because these functions are looked upon as separate activities within the AEC community and are easily identifiable as such.

In both models, the management function includes receipt of performance information from later activities. The facility model explicitly includes the task of assemblilng teams of individuals to perform the various functions,

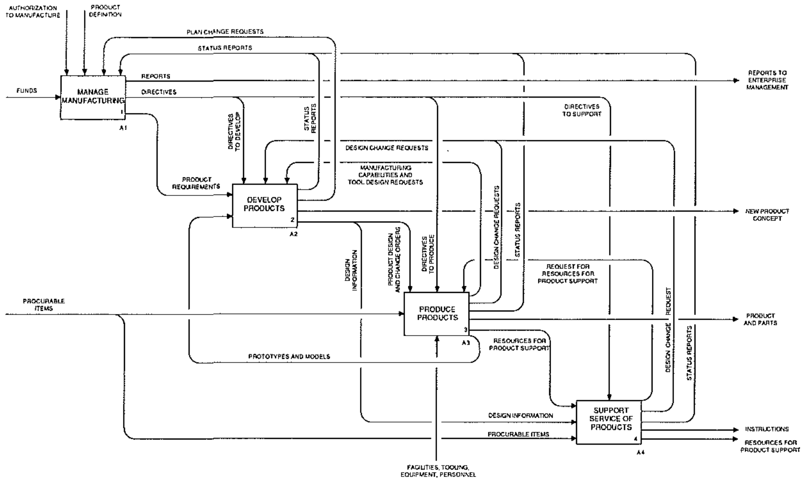

FIG. 4. $IDEF_0$ Drawing of Manufacture Products

TABLE 2. Comparison of Construction and Manufacturing Subfunctions and Elements

Function (1)	Element (2)	Construction (3)	Manufacturing (4)
Manage	Function	Manage facility	Manage manufacturing
	Feedback/constraints	Performance information	Status reports
	Output	Facility management plan, documents and contracts	Directives
	Output	Facility team	Personnel (for produce)
	Output	Available resources	Procurable items, tools facilities, equipment
Plan	Function	Plan facility	Given as product definition
	Output	Program and site information	
Design	Function	Design facility	Develop products
	Output	Bid and construction documents and criteria	Product design and change orders
	Feedback	Designability information	Plan change requests
Implement	Function	Construct facility	Produce products
	Output	Facility	Product and parts
	Feedback	Constructability	Design change requests
Support	Function	Operate facility	Support service of products
	Output	Operations knowledge	Instructions
	Output	Operational facility	Resources for support
	Feedback	Operability information	Design change requests
			Requirements for product support

since this is a major part of the construction activity. The facility model also shows the flow of funds and other resources from the management function.

A similarity of both models is feedback of manufacturability/constructability information. The CIC model includes facility experience as an output. This would include, but not be limited to, the reports to management shown in the manufacturing model. Thus, it can be concluded that many similarities exist between CIC and CIM, allowing some technology transfer. Differences, as reflected in the comparison between the models will require modification of existing methods and possibly development of new ones, to fully support the CIC environment.

Selection of CIM Tools to Support CIC

The similarities between construction and manufacturing domains are apparent when viewing Harringon's (1984) $IDEF_0$ models of manufacturing and comparing them to our construction models. However several important differences exist.

Integration is more difficult to achieve in construction because there are many different companies with different contractual relationships involved in providing the facility. This integration requires the capture of knowledge across these organizational boundaries, which may add a burden to the smaller organizations that may not benefit from this exercise.

A second major difference between the two processes is that while models are used in construction, little evidence of the formal inheritence of knowledge from previous projects is found, except in the case that the same personnel are transferred to subsequent projects. Most projects are built as "one-of-a-kind" developments.

Despite this, the similarities between the industries outweigh the differences. Several improvements to construction can be gained by implementing selected tools already developed in manufacturing. Three such tools are discussed herein.

Classification and Coding Systems (Group Technology)

It is apparent that the construction industry lacks a common classification and coding system for storing, accessing, and retrieving the data generated at various stages during its life. Numerous rigid coding systems that are developed for various subportions of the process are not useful to others. Examples are cost codes, drawing numbering systems, specifications, and material descriptions. The application of a classification and coding system that can tie the physical building to its inputs through the processes, controls, and mechanisms is desperately needed.

Manufacturing has addressed a similar proliferation of databases and part numbering systems through the development of group technology (GT). Group technology refers to the identification of similar parts, and the use of part similarly to improve design and manufacturing functions. Activities encompassed by GT include redesign of the manufacturing facility to produce a family of parts quickly and economically, development of tooling and fixtures suitable for all the items in a family, and development of an optimal production plan for each family. The philosophy of GT is to identify and exploit repetitive elements in products that are similar, thereby leading to economies of scale. It is anticipated that a similar system could also lead to process and design improvements in construction.

As a result of this analysis, we have developed and implemented a prototype GT scheme. This tool, group technology for reinforced concrete structures (GTRCS), (Sacchetti 1989) is a coding and classification scheme based on the building components, their shape and materials. An example building was input using a poly code system. Group technology principles were used to sort and identify like members by component type, material, and activity. The system is able to identify parts, e.g., columns or beams, that fall within a specified size and offer the user the option to make them all the same design. Automatic material takeoffs by zone are included as a feature.

Common CAD Databases

Manufacturing companies are developing integrated systems that allow various functions to share the same information. This information, consisting of a CAD model along with associated data (e.g., costs, manufacturing methods, materials) is used by design, engineering analysis, and manufacturing functions. One example is numerical control (NC) programming, where CAD data is used as a basis for programming machine tools to create the product. Similar links between design and construction, and between the many subcontractors in the process should be developed.

We are currently developing a prototype hypermedia-based system to store and retrieve data shared by designers, constructors, and facility managers for buildings. This will be implemented on the new Engineering West Expansion for the College of Engineering at Penn State.

Computer-Aided Process Planning

Computer-aided process planning involves automating the generation of instructions to produce a product, including operations, sequence, and tim-

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ing. This technology leads to process standardization, and simplifies monitoring and cost control.

Another tool that has been developed is an interactive formwork selection system (Hanna 1989), which allows the user to select a formwork system for each of the vertical (e.g., core walls, shear walls, columns) and horizontal components (e.g., slabs and beams) for a given building. This can also be used to provide input to the designer at the conceptual design stage when the impacts of alternative structural systems must be accurately assessed. For example, irregularly spaced heating, ventilation, and air conditioning (HVAC) penetrations, door openings and bay and column spacings have a large impact on the use of flying, jump and slip forms—all economical on high rise buildings.

Conclusion

This paper has compared the construction and manufacturing industries at a global level and at the process level (via the $IDEF_0$ models), and highlighted the similarities and differences between the two. The similarities outweigh the differences and a strategy for the implementation of successful integrative manufacturing tools in construction is defined. Finally, two of the three techniques identified have been implemented as software tools, while work to illustrate the third technique is under development. Clearly, the selective implementation of CIM tools to support CIC is a viable proposition.

Acknowledgments

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