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A Comprehensive CAD-CAM Prefabrication System

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KEYWORDS

Computer-aided-design, Computer-aided-manufacturing, Construction, Robotics.

ABSTRACT

The full benefits of prefabrication has not been realized to date due to communication problems between a designer and a contractor/precaster with a specific prefabrication system. A considerable portion of building construction works, even with prefabrication systems, is performed usually on site at low productivity.

These problems can be alleviated by an introduction of a comprehensive CAD-CAM system. The objective of the system will be to allow a maximum design freedom to an architect, even in relatively small building projects with minimum extra design and resources adjustment cost at the prefabrication plant.

Un système de CAO-FAO adapté à la préfabrication.

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Mots-clefs:

CAO; FAO; Construction; Robotique

Sommaire:

La préfabrication n'a pas eu tous les résultats escomptés à cause des difficultés de concertation entre les concepteurs, entrepreneurs et sous-traitants chargés de la préfabrication. Une grande partie du processus de construction dans le bâtiment, même lors de l'utilisation de pièces préfabriquées, est effectuée sur place de façon peu productive.

Ces problèmes peuvent être allégés par l'introduction d'un système de CAO-FAO dont l'objectif est de laisser le minimum de contraintes de conception à l'architecte, même dans les petits projets avec un surcoût minimum de conception lors de la préfabrication.

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1. INTRODUCTION

Building construction is one of the less advanced industries in terms of labor productivity in production process. Unfortunately, the productivity in building not only did not increase in most countries over the last two decades, but in some of them even declined when compared with other industries.

An extensive amount of labor is also expended in preconstruction activities. A distinctive nature of every project requires separate conceptual design; detailed design - architectural, structural, sanitary, electrical, etc., bill of quantities, specifications; managerial plans - budgets, work schedules, equipment and labor allocations, procurement schedules, etc.

The greatest effort to increase construction productivity has been done through prefabrication in the two decades following the second World War. The considerable potential of prefabrication in this respect has been, however, realized only to a very limited extent. The main reason for that was a poor communication between an architect in charge of the design, and a contractor who had to carry out the design with an aid of a prefabricated building system. The usual goal of an architect - an optimal, in terms of function and aesthetics, and therefore unique design for every project - has most often conflicted with precasters' goals - repetitiveness, simplicity and conformance to a particular system of production resources.

The various solutions offered in order to reconcile these incompatible goals often resulted in unfortunate extremes:

- highly constrained "closed" systems using a limited number of designs for large construction volumes were ideal for precasters, however often resulted in socially and aesthetically repugnant monolithes.
- unrestricted freedom of architectural design with a desperate effort of precaster to comply with it by "tailor made" solutions. This has usually required a considerable investment in design and adjustment of resources to particular features of the project, and consequently resulted in higher cost and less capability to compete with alternative, conventional methods.

The intermediate solutions, based on Modular Coordination and other conventions required a considerable sophistication on the part of an architect who was willing to conform to them, and also to be effective, a certain degree of standardization with respect to joints, structural members, partitions, finish works, etc.

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Another problem of prefabrication (in addition to poor communication) was its being very much limited to main structural elements - slabs, walls or columns, and exterior envelope. The majority of interior finish works remained very much the same as with traditional methods. Moreover, the erection of precast elements has become associated with a group of unconventional and skill demanding tasks - surveying, jointing, connecting, facade finishing, etc.

The third problem - very high sensitivity of quality to deviation from prescribed production and erection specifications resulted in many prefabricated projects in poor aesthetic and functional quality.

The following paper will outline a possible comprehensive approach to the building process, which by using new, available technologies in the field of computers and automation, may alleviate some of the difficulties outlined above. It requires an extensive Research and Development effort to be brought to an operational stage.

2. A COMPREHENSIVE BUILDING PRODUCTION PROCESS

A comprehensive building production process includes the following functions:

- a. a conceptual design which represents, in a conventional, graphical form - layout and elevations, the architect's/engineer's solution to owner's performance requirements, subject to existing standards, norms, regulations, etc. If the building is to be constructed with prefabricated system, this stage should result in the partition of layout into prefabricated components. This last task should be performed, in light of the former discussion, in such a way as to permit the most efficient execution by a precasting plant.
- b. a detailed design which produces drawings with detailed information for production or construction of all building elements.
- c. preparation of quantities, cost estimates, specifications and other information which complements the design drawings.
- d. construction planning - budgeting, work scheduling, procurement scheduling, allocation of labor and equipment, site planning, etc.
- e. production planning of elements to be prefabricated.
- f. elements production in plant, and their shipping to construction site.
- g. erection and finishing on site.
- h. monitoring of production and erection.

These activities are represented in Fig. 1. Activities a-e and h are mainly concerned with information processing and can be largely assisted by various computer based techniques, such as Expert Systems, CAD, and computerized Data Base Management.

Activities f-g, when following rationalized design process, can be made more efficient by application of automation and robotization technologies.

3. CONCEPTUAL DESIGN

A conceptual design, as outlined before, results in a layout (in 1:100 or 1:200 scale) of the various building floors, and elevations and sections,

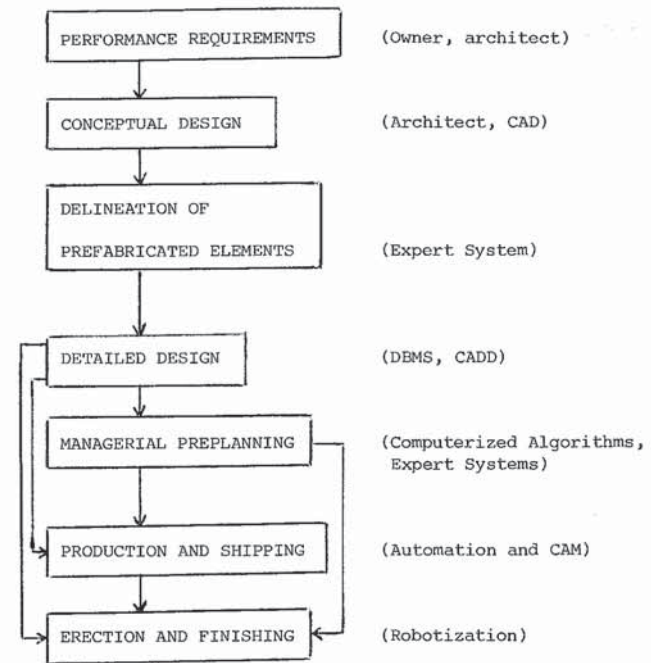


Fig. 1 - A scheme of building realization process.

necessary to convey the architectural solution. The design can be helped by computerized aided design (CAD) procedures such as CRAFT, ALDEP, CORELAP and others. These programs described in [4],[7] and other sources, use as an input floor areas prescribed for various building functions and a quantitative measure of their desired proximity. The areas for some basic functions can be derived in turn by a rational analysis as in [1] or [3]. The main weakness of these methods is the difficulty to define the desired relationships in a quantitative way. This part of the process is, however, not relevant to our presentation, and can be performed for those, or other reasons, in a traditional way.

The other part of the process - delineation of elements to be prefabricated with a particular method, can be largely assisted by an Expert System.

An Expert System in the context discussed here, will be defined as a computer program which offers solutions to problems using built-in artificial intelligence, composed of rules and factual information. The implemented Expert Systems usually consist of the following parts:

- the knowledge base composed of decision rules, based on individual experience, experts' opinions, norms, standards, regulations, technological constraints, etc. Those may be arranged in the form of IF ... THEN production rules or in numerical data bases.
- the context (or global base), describing factual information about the particular problem to be solved.
- the inference procedure (inference engine) - which examines and applies, in an orderly manner, the rules contained in the knowledge base, in order to arrive at a satisfactory solution to the particular problem.
- an optional explanatory device may explain to user the "reasoning" of an expert system and enable him to intervene at each stage of decision-making.

Expert Systems with these principles are used for medical diagnosis, structural analysis, electrical circuits design, and other non-structured decisionmaking processes, as described in [2] and other sources.

The input into the global base of an Expert System employed for partition of a building into elements to be prefabricated, consists of a graphical or symbolic representation of its main features:

- geometry of layout perimeter (with staircase openings).
- location of supports on layout (bearing walls, columns, etc.).
- partitions (if they also constitute a part of the system).
- elevations (or story height in regular buildings).
- special features - windows, doors, electrical fixtures, etc.

This information can be input through graphical (two or three dimensional) representation of the conceptual design drawing (by means of one of available CADD* Systems, as described in [5] and others), through digital representation (by means of coordinates) of critical features, or through interactive dialogue with the user.

The knowledge base will consist of a set of rules defining the configuration of elements in view of building characteristics and constraints of the system to be employed. Here are some examples of such rules:

IF span between supports is $X < 4.5^m$, And distance between (perpendicular to it) partitions is $Y < 3.60^m$.

THEN floor elements are room size solid slabs with nominal dimensions X ; Y.

IF span between supports is $X > 4.5^m$ And span is $X < 14.0^m$.

THEN floor elements are hollow core slabs with nominal length of X^m , and width 1.20^m .

IF Floor elements are hollow slabs AND L - the supporting length of perimeter segment is not a whole multiple of 1.20^m ($L \neq n \cdot 1.20$).

*Computer Aided Design and Drafting.

THEN set the width of the last element $L_1 = L - n \cdot 1.20$.

IF floor elements are hollow cores slabs AND L_1 (as above) is not a multiple of 0.30^m .

THEN round L_1 to the nearest multiple of 0.30^m and adjust L accordingly.

IF the distance between cross walls $X < 6.00^m$ AND the height of the floor is $H < 3.00^m$.

THEN set the dimensions of wall element length X^m and height H^m .

These are just a few examples of tens, or possibly hundreds of rules necessary to define general configuration of elements in accordance with constraints of a particular prefabrication system.

The inclusion of additional information - window and door openings, electrical fixtures and various inserts, may be either transferred automatically to each element (once its location and outline is determined), from general graphical information in the host CADD system, or inserted by the user into each element separately when queried by the system.

In any case, the output from the Expert System will include a general layout showing its partition into elements to be prefabricated, and also a list of elements, with each of them defined by its key parameters - nominal exterior dimensions, location and size of openings, location and size of inserts, special finishing requirements, and relation to supports and building edges.

4. DETAILED DRAWINGS

Detailed drawings for elements must contain all the information necessary for their production, i.e. exact geometrical configuration, thickness, details of joints, connections, reinforcement, various inserts, and for exterior wall also details of insulation, finish, window frames, etc. The input into this stage, from the former (section 2), includes the following information.

- a. The type of element, e.g. F - floor slab (flat), H - floor slab (hollow), B - interior wall (bearing), P - interior wall (partition), E - exterior wall, etc.
- b. The exterior nominal dimensions, derived from the partitioned layout (elevation) in the former stage. The nominal dimensions are between center lines of joints between elements, e.g. F 3.00/3.50 (i.e. floor slab 3.00^m by 3.50^m).
- c. The edge conditions on each side of the element. Examples of typical edge conditions for main elements are as follows:
 - FE1 - floor slab edge supported on interior wall
 - FE2 - floor slab edge supported on exterior wall
 - FE3 - floor slab edge unsupported
 - FE4 - floor slab edge adjacent to exterior wall
 - FE5 - floor slab edge adjacent to interior wall

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EE1 - Exterior wall bottom edge at ground level
EE2 - Exterior wall bottom edge at floor level
EE3 - Exterior wall upper edge at floor level
EE4 - Exterior wall upper edge at roof level (with parapet)
EE5 - Exterior wall side joint
EE6 - Exterior wall side joint (at interior wall)
EE7 - Exterior wall side joint at building end

.
BE1 - Interior wall bottom edge at ground level
BE2 - Interior wall bottom edge at floor level

.
etc.

- d. Openings, their type, location and site, e.g. for rectangular openings:
OW1, 1.50; 1.10, 2.00/1.00
OD2, 1.00; 0.00, 1.00/2.10
indicating opening code (window, door, etc.), location of lower left hand corner coordinates, and dimensions.
- e. Various inserts, their type and location, e.g. for electrical boxes:
IL, 1.50; 1.20 (indicating insert type and center coordinates).

The information about configuration of elements may be input into this stage either in graphical form, or in more restricted systems - by means of a code, defined through a sequence of alphanumeric symbols - type of element, nominal dimensions, type of edges, type of inserts and their locations, type of opening and its location, etc.

In addition to this information received from the former stage, the input necessary to produce detailed design must include loads, thermal and acoustic insulation requirements and desired exterior finish. The detailed design will be produced with an aid of a Data Base Management System. The Data Base will contain several types of information as follows:

- thickness of slabs and their reinforcement for different spans, configurations and exterior loads applied.
- details of edge profilation for different types of support and end location.
- details of conduits for various locations of electrical outlets.
- composition of exterior wall (thickness, insulation) for different thermal and acoustic requirements, and a desired finish.
- reinforcement of exterior walls for their different sizes and different lateral loads applied.
- details for different doors and windows.
- details of edge profilation of exterior walls for their different locations in the building.
- thickness and reinforcement of interior bearing walls for different loads applied (and other requirements).

- details of edge profilation of interior walls for different end conditions.

The data base management system must possess several advanced features to be able to produce the required information, i.e. detailed drawings. It must be able to store and manipulate graphical and numerical data, and assemble complete image from various composing details.

5. MANAGERIAL INFORMATION

The managerial information, as explained before, includes bills of materials, specifications, estimates, procurement schedules, production schedules, shipping schedules, and schedules for erection and finishing on site.

Bills of materials and specifications for various components can be produced by an Expert System strongly associated with the Data Base discussed in the former section. The Expert System will include, in its Knowledge Base, rules for quantity surveying for the various elements (slabs, facades, walls, etc.), their reinforcement and other inserts, and the specifications for their production, erection or finishing.

The Expert System will receive, as its input, the detailed information about each element from the Data Base Management System in the former stage, and will produce a bill of quantities for each element or building section, as required.

The cost estimate can then be prepared with an aid of an additional Data Base containing information about labor, material and equipment inputs per unit of each work item in the bill of quantities. It will also include predetermined allocation for indirect expenses and a desired profit margin.

The scheduling problem in prefabrication is a very involved task and requires an extensive treatment. It will be only very briefly discussed here.

The various schedules - production, shipping, erection, finishing and procurement, can be prepared from quantities of main elements, compiled earlier, from the sequence of construction (and production) activities inherent in the system, and required completion dates (or intermediate milestones). They will be prepared under constraints of available production and construction resources. Mathematical algorithms for production planning in prefabrication plant, under various resources constraints, were presented in [8]. Algorithms and computer programs for scheduling and balancing of a given sequence of construction activities, defined by a network of dependencies, under resources constraints (durations for various labor/equipment teams composition) for each activity - are also available [6].

A very interesting problem of planning of robotized construction will be mentioned in the next section.

Another managerial task - that of monitoring of construction/production with an aid of a computerized information system, has been solved in practice. Such a system controls, updates and revises schedules and budgets, pinpoints deviations between allocation and usage of various resources and cost items, disseminates this information to various managerial levels, stores historical data (productivity, output, costs, etc.). It most often performs a host of additional clerical activities - accounting, billing, payments, etc.

6. AUTOMATION OF COMPONENTS PRODUCTION PROCESS

A different problem yet to be explored is the automation of the component production process. The process should be directed by an appropriate CAM (Computer Aided Manufacturing) program fed by the design information generated at the CAD (Computer Aided Design) stages, described in the former sections.

The main objective of this process should be to enable production of elements of an arbitrary configuration (within the constraints of the system characteristics), with minimal investment in the setup of resources and minimal learning effort of operators. This will enable attainment of the overall objective of the CAD-CAM prefabricated system, as stated earlier, namely - maximum architectural freedom of design which will be feasible even for very small production series. The elements of such a system should be as follows*:

- 1) Large smooth production surface (e.g. elongated steel bed) which can be used in a flexible manner by attachment of appropriate stoppers for production of elements of an arbitrary configuration. The surface can be covered by a matrix of connection points which will allow flexible attachment of stoppers and inserts to achieve the desired mold pattern. All locations on the surface should be easily accessible by mechanical handling devices.
- 2) Standard stoppers for all cases of anticipated edge conditions (as described in section 4) which can be easily attached to desired locations on the production bed, and then, after casting and curing, easily stripped and moved to a new location. This requirement also holds for window, door frames, and other inserts with similar characteristics. The actual attachment, as explained later, can be manually assisted without affecting the system objectives.
- 3) A monitor for a handling system which will be able to direct an appropriate grasping effector to stoppers and other inserts at their current location, and move them subsequently to a new location as required for a particular element to be produced.

*These principles apply mainly to non-modular, non-prestressed elements. Production of hollow core prestressed slabs - highly automated with current methods, but inflexible due to involved prestressing process, deserves separate attention.

- 4) An offline system for preparation of assemblies to be placed in the mold, which may include reinforcement, electrical conduits and possibly insulation sheets according to design requirements, outlined in section 4.
- 5) A monitor for a handling system which will be able to guide an appropriate effector to storage areas where the assemblies will be placed and thence to appropriate molds.
- 6) A monitor to regulate the batching system at the concrete production center for the particular mixes (for structural concrete or the finish layer) required in the design. Such monitors are used at present in many large concrete mixing centers.
- 7) A monitor which will guide transportation of concrete from mixing center to molds. This task can be possibly performed manually without impairing the total objective of the system.
- 8) Effectors for appropriate finishing of concrete for the various elements. This can be also possibly done with current methods without impairing the efficiency of the system.
- 9) A handling system which can perform the tasks of moving mold elements, assemblies and concrete, as explained in 3,5,7, with appropriate effectors and also move the finished elements (after demolding) to their destination in storage.
- 10) An inspection system with sensors able to evaluate the conformance of the elements to specified visual or physical requirements.

Not all above-mentioned activities must be fully automated, and some of them can be performed, as noted, with traditional methods. The overall objective of the system requires, however, an easy and flexible assembling and preparation of molds for any desired configuration of components, and full automatic control over conformance of the process to their specified design, i.e. shape, composition and quality.

7. ROBOTIZATION OF SITE WORK

The building works on site with a prefabrication system include erection of components, their jointing, connecting and finishing.

A comprehensive study described in [9]* examined the possible robotization of these activities. They were divided into 10 basic operations - POSITIONING, CONNECTING, ATTACHING, FINISHING, COATING, CONCRETING, BUILDING, INLAYING, COVERING and JOINTING. Each of these operations was then analyzed, to establish the characteristics of main robotic components necessary for their execution. These components were:

Effector, to grasp object or tools for performance of required tasks.

*The study, carried out by the author at Carnegie Mellon University, has been published also as CIB publication No. 90, 1986.

Arm, to carry the effector to required destinations.

Feeding system, to supply materials (paint, plaster, concrete) to effector when necessary.

Sensors (contact, vision, proximity), to interact with environment.

Control unit, to monitor robot's operations and interpret the commands and signals received for this purpose.

Locomotion mechanism (wheels, treads) to move the robot between work locations.

The first four attributes do not differ in principle from those required in industrial robots, except that reach and payload required for most construction operations are considerably higher, and control capacity more powerful. The main difference is, however, in sensing and locomotion capacity not required in most industrial applications. These features are essential for construction robots which must move on site and interact with rugged environment.

To perform erection and finishing activities on site, 4 groups of building construction robots were defined:

- Assembling Robot, to be used for hauling and positioning of large building components.
- Interior Finishing Robot for connecting, painting, spraying, and other interior operations.
- Exterior Finishing Robot for jointing, painting, spraying and inspection of building exterior walls.
- Floor Finishing Robot for smoothing, covering and inspection of large horizontal surfaces - floors and roofs.

A conceptual configuration of each of these robots and their mode of operation were described in [9].

A considerable research effort along the lines suggested in the study must be undertaken for development of the robots, and some restructuring of building operations for their effective employment. A preliminary feasibility study, also included in [9], indicates, however, that even at the present stage of technology, employment of robots in construction may be feasible under certain conditions.

The planning of robotized erection and finishing should be a part of general managerial preplanning described in section 5. It involves the

selection of robot types, and their numbers for various tasks in the project, their work stations, progress paths, transfer points, feeding methods, and specific execution programs.

8. CONCLUSIONS

The full benefits of prefabrication has not been realized to date due to communication problems between a designer and a contractor/precaster with a specific prefabrication system. A considerable portion of building construction works, even with prefabrication systems, is performed usually on site at low productivity.

These problems can be alleviated by an introduction of a comprehensive CAD-CAM system. The objective of the system will be to allow a maximum design freedom to an architect, even in relatively small building projects with minimum extra design and resources adjustment cost at the prefabrication plant. The method requires, for realization, a considerable R&D effort, especially in the following areas:

- Computer aided processing of architect's design for delineation of components to be prefabricated.
- Computer aided detailed design of precast elements.
- Computer aided generation of managerial information at production/construction planning and design stages.
- Computer aided manufacturing of building components in plant, based on design information.
- Robotized building construction process.

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