BUILDING MANUFACTURABILITY AND ROBOTICS

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ABSTRACT

Manufacturability of buildings at the same levels of effectiveness as other products has been a long struggle with mixed results. Current advances in CAD/CAM and Robotics promise to make it more plausible today than at any other time. Difficulties of building manufacturing relate to a number of factors; diversity of buildings, transportation problems, complexity of the building design and construction processes, fragmentation of the building industry, lack of building standards, non-uniformity of local building ordinances, large capital investment needs, restrictive labor and union practices, and practial non-existence of research. Emergence of automation in manufacturing promises important advantages for the building industry: quality of product, speed of production, economic potential, international business potential, humanitarian benefits and strategic importance for rapid deployment of buildings. This work outlines strategies in several broad areas of application -- design, construction, industrial, financial and regulatory -- where robotics is useful.

1.0 Background

In many ways the Building Delivery Process (BDP), even in highly industrialized countries, is retarded. BDP in one form or another is deeply entrenched in manual, customized processes which have been long abandoned by every other consumer production industry. The task or robotization of the BDP thus requires the realization of industrialization before automation.

1.1 Manufactured Building Delivery Process

It seems that the objectives of manufacturing buildings in the factory have to do with the improvement of the building process while trying to make the product less expensive and easier and quicker to erect. Historically, prefabrication of buildings have had both successes and failures in a number of places: U.S.A., Russia, Scandinavia, Japan, Eastern Block, England, Germany, Israel, and France. Each of these developments have their own peculiar histories, largely as a function of the demand created by wars, other housing shortages, and financial backing from the government and industry. Also, numerous attempts were made by industrialized countries to solve housing problems in undeveloped countries by exporting building systems to these countries, often with tragic results.(1)

Today many of these developments have realized a degree of success in some respect and have become part of the main stream of the construction activity. Particularly in Japan and Sweden the industrialized housing technology dominates their housing markets. In spite of these developments the process of industrialization of the BDP has by no means been completed. Many of the techniques used in the factory are still manual, customized and inefficient when compared to those used in the manufacture of other consumer products. Furthermore, strengthening this testimony is an awful lot of conventional construction going on in the building sector, particularly in the U.S.A. Significant changes in this picture cannot be expected unless fundamental changes in the technology infrastructure of the BDP are realized. This is a distinct possibility today owing to the surge of advances in both computing and robotics, and their application to manufacturing.

1.2 Manufacturing Robotics

Robots are generally classified into six classes: 1) manual manipulator; 2) fixed sequence, 3) variable sequence, 4) playback, 5) numerical control, and 6) intelligent.(13) Each of these categories provide a different level of efficiency and adaptability to the requirements of the tasks to be automated. Intelligent robots, at one end of the spectrum, are the most adaptable to complex and changing operations and are the least robust and efficient in absolute terms. At the other end of the spectrum, fixed sequence robots perform their designated tasks with efficiency and rigidity but fail to adapt to changes in production requirements, except the simplest ones such as, number of tasks performed, and so on.

Applicability of robots to diverse tasks such as those needed in the building sector is contingent, then, on the fit between the operations needed to complete a task and the parameters of each category. Operations which are repetitive and environmentally controllable, such as mounting of panels on wall frames on an assembly line, can be delegated to fixed sequence robots. While operations which are variable and without a controllable environment, such as laying conduit in an already assembled room, require intelligent robots.

Recent advances in robotics promise greater sophistication on sensory interface with the environment and programmability of the robotic unit. Depending on the desired independence from central control units, various types of programmability are possible: lead through teaching, walk through teaching and off line programming.(14) Hardware interfaces are the safest strategy for shipping complex code to remote robots yet program down loading is necessary to perform more complex and variable tasks. However, due to the risk involved in independent, programmed robots better protocols for communication with large databases and control software are needed. One of the shortcomings in this area is the lack of interface standards between robot controls and CIM systems.(14) Current developments indicate the possible integration of multiple machines, each with a range of capabilities into flexible work cells with multiple function capabilities, so that these work cells can perform multiple tasks as dictated by inventory and manufacturing needs through programming and scheduling.

In spite of these difficulties robots provide tremendous opportunities for the automation of the BDP. At the most general level robots provide the missing link for the integration of automated building design and automated construction. Simon's definition of the design process (12) includes four essential components, Affectors, Receptors, Processors and Memory. There have been important advances in Computer Aided Design and Artificial Intelligence to address the automation of the latter two components. Robotics is the most significant, recent development to respond to the former two components, Affectors and Receptors, which enable the interaction of the design and production functions of the process. Ultimately the success of design in architecture, engineering and CAD/CAM systems will be measured by the effectiveness of these interface components.

At a more specific level robotics provides tangible opportunities for profitable introduction of automation in building construction. Today, robots are efficient operators when it comes to welding, material handling and simple assembly. The wholesale introduction of these operations into the construction process is only a matter of time and their potential impact, in the event that they are introduced at such a scale, is enormous. Some of the most critical areas of inefficiency in the industrialized building factory floor are the moving of materials to work cells, integration of diverse assembly operations within the same work cells, and the flexibility of the overall production process.(4) Developments in robotics technology indicate that adaptive Computer Instructed Manufacturing will be widely available. This evidently will make it possible to design the factory floor in such a way that each work cell will be adaptable to production requirements dictated by volume, type and standard customization of the product; factors essential in the success of manufactured building construction. In order to understand the potential impact of robotization and automatization of the BDP, then, we must first consider the manufactured building process, and obstacles and opportunities related to it.

2.0 Industrialized Building in the U.S.A.

In the United States as in many European countries, interest in prefabrication developed in response to housing shortages caused by WWI. Companies such as General Houses in 1933, formed to "design, coordinate, and assemble standard parts to be produced by a number of prominent specialists."(9) General Houses based its organization on ideas from the automobile industry, where the manufacturer acted as assembler rather than the actual producer of individual parts.(10) The prefabricated building industry, unlike the automobile industry of that time, however, did not enjoy a product monopoly.

In the thirties only a small number of prefabricated houses were ever produced and occupied. However, there was a great deal of interest in it by non-commerical institutions, government agencies, and large corporations. This led to a profusion of structural ideas which failed to achieve commercial success on a large scale because only a few were technically and economically sound.(7) During WWII, prefabrication was used because of three requirements: "speed, demountability, and the reduction of on-site labor and congestion to a minimum."(7) However, due to the effects of the war, difficulties in marketing and stereotyped images of manufactured housing, the effort was stifled.

These attempts by architects to revise housing technology referenced inappropriate models of industrialization. They invariably linked the technology of housing production to a particular esthetic.(8) Prefabrication and manufactured housing did not enjoy widespread use in the 1950's and 1960's either. Unlike Europe, there was no massive state intervention in the housing process, no assured and continued market, and no large scale development of comprehensive building systems. Even government programs such as the Department of Housing and Urban Development's (HUD) 'Operation Breakthrough' did not succeed in generating practical, economical and viable manufactured building systems.(6)

There were other lessons learned from these early experiments. Primarily, these were the success of the mobile home industry due to the economy and utility of the product and the understanding that manufactured housing is not merely a technological system but a total system. Even today there are many small manufacturing companies showing profits which is sufficient to convince skeptics that the traditional barriers against manufactured housing may be gradually disappearing.(2)

2.1 Obstacles

2.1.1 Diversity of Building as Product

As marketable, industrial products buildings go against the grain of most other products. This is largely due to the diversity and complexity of the processes, agents and materials needed in their production. Buildings require the input of a myriad of professional specialists at different stages of development.(1) The products used in buildings have a great variety of material and physical specifications, ranging between a few hundred thousand to a few million in number, depending on the type and size of the building. To complicate matters even more, buildings are site specific. That is each building has a set of unique conditions in relation to foundations, neighboring buildings, users, and the socio-cultural context of the site. Consequently, the skills and knowledge brought to bear on the BDP is virtually impossible to formalize in its entirety. Without a formal representation, automation of the manufacturing process is also problemmatic. Standard designs usually do not exist or are frowned upon by occupants and professionals alike. Customization without standardization, thus, places the BDP outside the domain of automated manufacturing.

2.1.2 Complexity of the Construction Process

There are a half to a full dozen different building sub-systems which make up a complete building: foundation, structural, moisture control, heating, lighting, glazing, roofing, ventilation, electrical, water, sewer, storm sewer, communications, acoustic, circulation, and so on. Each subsystem has its internal design and performance requirements at the same time requirements for this integration with one another. This integration requires the accommodation of each subsystem spatially as well as in terms of the potential interferences between the performance of each subsystem. In many instances either by design or by accident these spatial or performance conflicts have to be resolved during construction phase or even later. Addenda to specifications, programmatic modifications, and shop drawings are some of the formal mechanisms commonly used in the building industry to deal with these issues. Thus, the construction process reflects the same level of complexity as the design process.

2.1.3 Difficulties in Transporting Manufactured Building Parts

Production of larger building components, particularly when large numbers of units are to be produced, makes the entire manufacturing process more economical.(4) Due to this need to manufacture large size components which need to be moved from factory to site, transportation is a key issue in building manufacturability. Time, cost and feasibility of delivery become important considerations not only for transportation but also for the design and construction processes that preceed it.

2.1.4 Fragmentation of the Building Industry

Purchase of a house represents the largest proportion of single time expenditure of funds by any one household. A parallel to this is the relatively large proportion of investment towards the purchase and maintenance of buildings and plants by businesses and large corporations. In spite of the volume of production implied by this demand, the production side of the industry, both in terms of materials and building suppliers, is relatively inconsistent. Housing starts, real estate share of national economies and the value of real property are often as unpredictable as speculative commodities of the financial market. One of the consequences of this is the high volatility in the size and tenure of manufacturing operations in the building market. This creates a highly fragmented industry with numerous companies of varying sizes unable to form any sort of united voice or concerted effort for development and research.

2.1.5 Lack of Standards

Owing to the market condition and the complexity of the design and construction processes, standards in terms of performance, quality, deliverability, cost, parts, and systems, generally are nonexistent. Since each building often represents a unique circumstance with considerable capital, the cost of development of "one time standards" are usually absorbed in the initial cost. The need for long term standards for buildings are seldom stated, found or required. Even in industrialized products, standards fluctuate considerably from one company to another, from one product line to another, and even one site to another.

2.1.6 Non-uniformity of Building Codes and Ordinances

Until recently, there has been practically no uniformity in the building codes accepted in different administrative units of the nation. Today the choices have been narrowed down to a select few, the National and the Uniform Building Codes. Even so the differences that exist between practices in one area versus another are great enough to make manufactured, mass produced building a cumbersome process. Even with a consistent building code, it is difficult to adapt a highly standardized, manufactured building system to local conditions. In countries where prefabricated housing is advanced, special provisions are made for approving manufactured systems' conformance to building codes.[11]

2.1.7 Large Capital Needs

As we reviewed earlier, buildings constitute large investments both initially and for subsequent maintenance. On the average, a house, the smallest unit of building is at a minimum ten times more expensive than the next most expensive consumer product, the car. In the context of manufacturing this difference is even more critical, since each unit must be produced at such large quantities. Furthermore, profitability in large panel or modular building systems depends on volume of production.[3] This means that manufactured housing requires very large investments implying considerable risks as well as potential benefits.

2.1.8 Lack of Universal Acceptability

Manufactured or industrialized buildings, especially when used as mass housing, have met with considerable resistance in all corners of the globe, even when their recipients are under dire circumstances. The stigma of the impersonal, factory-like look makes the manufactured house the least attractive alternative for occupants. Housing is one of the indispensible, culturally loaded artifacts of human use and its industrialization has to overcome this subjective, imagistic problem in order to succeed.

2.1.9 Restrictive Union Practices

Labor unions in the U.S.A., even in the case of conventional construction, restrict the scheduling of different skill jobs on the construction site. In the factory setting the retaining of various skills helps this circumstance to a certain extent. Still even the smallest delays in job shopping can cause significant inefficiencies in an industrial setting and current union practices in the U.S.A. are not favorable for efficient manufacturing of buildings.

2.1.10 Non-existence of Research

Research about manufacturable buildings is virtually non-existent in the U.S.A. Due to the fragmented nature of the industry large sums of money and explicitly identified research goals do notcoexist within building manufacturing firms. Immediate turn around of investment rather than long term investments are the norm, understandably, in an industry where risks are high and the economic base is unstable. Significant research in the area is generally government sponsored, such as in Japan and Sweden. Conversely in countries where this kind of support lacks the industry has not succeeded.

2.2 Potentials

Manufactured building systems, potentially can remedy the long standing shortcomings of conventional construction. The primary problem in conventional construction is the unreliability of schedule, budget and performance expectations. The reasons for these shortcomings are as complex as the BDP itself. Yet, many of these reasons have to do with uncertainties inherent in the factors we already reviewed. Manufactured buildings as a result of the better controlled environment of the factory, provide the best opportunity for combatting these problems in terms of the building subsystem which can be dealt with, away from the site. These include virtually all subsystems with the notable exception of the foundation and other site systems.

Let us now review these benefits more explicitly.

2.2.1 Quality of Product

In the purchase of most consumer products there is sufficient understanding of the level of performance to be expected and the conditions under which such performance can be replicated. For example, most refrigerators keep food from spoiling, most computer keep files of data in tact, and most cars can get us from here to there in one piece. Furthermore, we can even adjust the temperature of the refrigerator, add new memory to the computer, or cruise at a constant speed in the car with the virtual touch of a button. While sometimes this performance defies perfect predictability, such as the variance that exists between EPA predicted versus actual gas mileage, there are no big surprises for the consumer. He is warned against variances; and hidden costs do not exist. This is not the case with buildings since the actual performance expected from a building design completed on paper still cannot be adequately controlled. Major mishaps are commonplace; large temperature variations between rooms, integrity failures in moisture seals, delays in completion times, cost overruns. These are largely due to unpredictable conditions at the site -- weather and soil conditions -- rigidity of labor unions, custom fitting of building materials, hidden design issues which surface during construction and unpredictable interferences between different subsystems. Some of this is due to a lack of theoretical knowhow. Yet, if the construction process, in its entirety, or in part, can be moved into the factory many of these issues can be controlled or at least their monitoring can begin in earnest.

2.2.2 Speed of Production

In the factory delays due to weather, labor problems and customized construction can be alleviated. This is one of the principal reasons for improving productivity in the construction process. On top of this, automation, either in fixed special purpose, programmable, or in flexible form, can mean additional savings in time, particularly if the quality of the product is high.(5)

2.2.3 Customization

In the automated factory, or the conventional construction site for that matter, customization is very costly and therefore is intentionally avoided. Yet individual expression and identification with home, work place, etc., are important factors in the customer's choice of building products. This requires some degree of customization, at least in the form of standardized customization, as it exists in the automobile and appliance industries. This is a viable possibility in the BDP with the use of intelligent robots.

2.2.4 Economic Potential

Unlike in other industries, deliverability of high-quality, low-cost buildings is the one echelon the industry has not yet realized. For example, in the automobile industry price/wage ratios for comparable models: i.e., 1904 Ford 2 Touring Car, 1924 Ford Model T, 1982 Ford Escort 4-cylinder, are 3.72, 02 and 0.33, respectively.(5) The dramatic drop from year 1904 to 1924 due to the efficiencies realized in mass producing already developed technologies. Even though the building industry is much older, new technologies are constantly introduced. Yet similar recoveries from high, initial costs of these new technologies are rarely realized. One of the obstacles for this is the steadily increasing complexity of the building process and the unmanagability of advanced construction technologies along side age old construction techniques which are still in use in the factory. With breakthroughs in this area the building industry can rise to presently unprecedented levels of productivity.

2.2.5 Technological and Business Exchange Potential

Although buildings are site specific, current advances in building technologies, especially in Japan dnd Sweden, suggest the feasibility of transfer of certain building products, such as wet cores, glazing, panel systems, along international lines of commerce. This kind of international trade and technological cooperation can possibly spur economic, technological and regulatory improvements for all industrialized nations, in the long run.

2.2.6 Humanitarian Benefits

From a humanitarian standpoint, low cost, high quality buildings which can be deployed rapidly, especially when it comes to emergency and low cost housing problems are one of the greatest promises of automated building manufacturing. Particularly systems which can be adapted to local conditions and integrated with indigenous building materials can make a difference in their local acceptability and use in economically depressed or disaster ravaged parts of the globe.

3.0 Strategies for Robotics in Building Delivery

While the obstacles for industrialized production of buildings are nontrivial, it also has many potential advantages. With the advent of robotics as the cure-all for a wide range of productivity, safety and quality issues in manufacturing this opportunity becomes even more attractive. Below, we propose a number of strategies which are essential for the marriage of robotics and building manufacturing.

3.1 Design

In order to robotize building manufacturing the tasks to be performed on the factory floor must be sufficiently standardized. The obstacles for this have been the need for buildings to be customized to the site, the budget, the use and the "taste" of interested parties. Consequently, building systems must be standardized on the one hand and equipped with custom features on the other. This means that subsystem design must be parametrized to accommodate special constraints surrounding each building yet fit into a finite set of standard options. In order to develop these standards greater predictability of performance of building subsystems and their interface are needed.

Another important design concern is how to make the industrialized building system acceptable to the client, occupant in cultural and visual terms. This requires that the designs produced from standard components relate in some fashion to indigenous forms of architecture found in the area. One way of achieving this is to conceive of a hybrid building system with the most critical subsystems, such as structural, fenestration, mechanical and roofing, manufacured in the factory and the others, such as foundations, infill walls and interior finishes, constructed in situ. In this way the critical issues of time, quality and cost are addressed through the manufactured subsystems, and the environmental acceptability issues are addressed through the subsystems derived from indigenous materials. Also, in order to realize a degree of standardization coupled with customization, large scale cataloging of prototype components and subsystems is necessary. This in turn requires computerization. Computerization of the design process is an indispensable feature for CAD/CAM interface issues, as well.

3.2 Construction

Assembly of buildings present several challenges: efficient scheduling of materials and skills according to the sequence of assembly, assembly line execution of repetitive operations, adaptation of assemblers to the changing envio-nment of the work area. Buildings are complex enough in themselves and require a large repertoire of materials, components and skills during assembly. This situation is further complicated due to the customization of each product to fit its context. Thus scheduling of skills and materials at the work cell is a highly complex operation requiring intelligent robotics for its automation.

Execution of repetitive operations, such as applying fasteners, packing insulation, and so on, can readily be automated. The complication occurs due to the constantly changing configuration of the work cell which in some sense is identical with the building components being assembled. This requires the robotics operators, particularly those used during composite system and subsystem assembly stages, such as wall panels, ceiling systems, etc., to be endowed with some intelligence, sophisticated sensory input, motor output capabilities and reliable access to large data bases. Ultimately, robotization of construction will introduce precision to the building products to a much larger extent than is possible today, and make adaptation to local ordinances easier as a result of parametrized design options which can respond to local constraints.

3.3 Industrial Impact

Robotization is the necessary step towards industrializing building production at a level of efficiency commensurate with other manufactured products. Due to the complexity of the building construction process this is realizable only if the process of design and construction become highly systematized and technical. The state of the art in industrialized building is such that traditional construction methods are simply moved into the factory, bringing with them a set of conventional inefficiencies, largely, due to materials scheduling, custom fitting and manual labor problems. Efficiencies realized result from the avoidance of weather problems and economies of scale when inventories are high. Other areas of efficiency: assembly line production, customized-standardization, materials scheduling and safety are still awaiting the next generation factories. This will arrive with robotization of the BDP.

3.4 Financial

Capital is perhaps the biggest obstacle to the development of robotized building construction, since robotization means significant financial additions, in terms of investments for R&D, initial setup of automated facilities, retraining of labor, and so on, to the already high capital demands in the building sector. Big business and government backing is mandatory to realize these goals. In this area the track record of big business, and the government for that matter, is not impressive, in the U.S.A. The threat of outside investment into the housing sector is the only remaining vestage of provocation to usher the government or big business into the robotized building construction area.

3.5 Regulatory

The second most significant obstacle to the development of robotized building construction is the lack of regulations appropriate for standardized and manufactured buildings. The variance that exists among building ordinances in different localities in the nation, makes it very difficult to obtain blanket approvals for a line of products, as would be the case in cars, refrigerators, etc. An effective measure against this problem is the institution of a centrally coordinated approval system for industrialized buildings, such as the one used in Sweden. Other examples of similar but perhaps less relevant applications to the U.S.A. exist in the Soviet Block. The resolution of this problem would become less problemmatic if government or big business invest in this area.

4.0 Conclusions

The building industry in many ways still exists in a pre- or quasi-industrial form. Although some industrialization has occurred, particularly in the U.S.A., little has been accomplished in the way of bringing the building as a consumer product to the same level of performance as other consumer products. The reasons for this are obviously quite complex and have to do with the site specific nature of buildings, their complexity, the labor laws, and so on. These obstacles are significant yet are not unsurmountable. With the potential offerings of robotics and computer technology many if not all of these difficulties can be overcome and significant advances in terms of quality, productivity and reliability can be introduced into the building delivery process. The strategies necessary for reviving industrialized building through robotics include development of new techniques and guidelines in several areas: design, construction, industry, finance and regulatory measures.

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