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Industrializing the Residential Construction Site

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Disclaimer

Foreword

Despite the dramatic increases in housing production and home ownership in recent years, the home building industry still lags behind others in widespread technological innovation and adoption. Many new techniques, materials, tools, and organizational means are often localized in nature and face numerous obstacles to becoming commonplace. Automation and industrialization efforts in home building have been particularly thwarted though factory manufacturing processes in other sectors are considerably advanced. Indeed, a directed change in the housing delivery system is imperative for the home building industry to reap similar benefits and, in turn, share those benefits with the nation's homeowner.

The current home building industry's resource-intensive nature suggests that there is much promise for changing current design and construction practices. Through this publication and the research which supports it, HUD is directly addressing such concerns. This report describes the history of and possibilities for industrialization in the home building industry. Even more interestingly, organizational strategies are suggested that take advantage of these possibilities: information integration, physical integration, performance integration, production integration, and operations integration are each studied as contributors to the systematic development of the home building industry's technological capacity. Such a comprehensive and integrated approach to all of the techniques in home building will have dramatic consequences for home production.

HUD has been directly and significantly involved with ongoing efforts towards advancing housing technology by sponsoring fundamental research in manufactured and modular housing, in improved methods and materials for traditional housing, and in the numerous regulatory and policy issues related to housing production and technology. For example, HUD's administration of the Partnership for Advancing Technology in Housing (PATH)—the Federal initiative to accelerate the creation and widespread use of advanced technologies to radically improve the quality, durability, environmental performance, energy efficiency, and affordability of our nation's housing–has resulted in a dramatic vision for housing technology. As such, research initiatives and results like those in *Industrializing the Building Site* directly support the home building industry's future production capacity and the quality and cost of American homes for years to come.

Susan M. Wachter
Assistant Secretary for Policy Development and Research

Summary

This report examines the means and methods available for integrating and industrializing the housing construction site and the housing industry.

Historically, governmental leadership in the development of advanced materials and construction techniques for housing has been successful at focusing attention on new technologies but has not been able to significantly shorten adoption times due to extreme fragmentation in the materials production and construction industries. International efforts at industrialization have experienced similar fragmented successes but also have struggled with widespread adoption of advanced methods of industrialization by the homebuilding industry.

Faced with significant competition from abroad, many industries in the manufacturing sector have developed or adopted broad organizational strategies, such as Just-in-Time (JIT) supply and Design for Manufacture and Assembly (DFMA) to reduce production costs, improve productivity, and improve product quality. Underpinning these strategies are information systems that are fully integrated across the business enterprise. The rapid adoption of these Enterprise Resource Planning (ERP) systems was helped by the close scrutiny of business systems provoked by Y2K issues, increases in data network speeds, and the rise of the Internet as a business environment. Implementation of these ERP systems required industry to closely examine business and manufacturing practices and construct information models that integrate data across the research, design, inventory, production, and sales departments. The broad adoption of Object Oriented CAD software is a key step towards information integration in the housing industry. However, still to be developed are a comprehensive information model, viable linkages to field operations, and real-time tools for analysis of structural, mechanical, production and economic performance.

When manufacturing made the transformation to ERP systems, the complex interrelationships between management, product development, production and distribution departments were further rationalized. Localized optimization practices were evaluated in terms of the impact on the whole enterprise. The results were significant gains in productivity and profitability due to highly integrated product development, production, and business systems. Similar gains are likely as information integration rationalizes commonly conflicting subsystems (heating/cooling, electrical, structural) reducing field modifications and common performance and operations losses. Information integration will enable higher levels of physical integration, higher levels of production integration, higher levels of performance integration, and higher levels of operations integration.

The advanced industrialization resources available to builders vary according to the size of the builder's business. This report includes strategies for four scales of builders:

- The small volume builder producing fewer than twenty homes per year
- The medium volume builder producing several hundred homes per year in regional markets
- The high volume builder producing over one thousand homes per year using on-site construction methods in a national market
- The production builder using off-site fabrication methods to produce modular, manufactured (HUD code) and factory-based panelized housing.

For the small volume builder not having the resources to develop a full ERP, regional and national building supply companies could lead the industrialization effort linking the builders' object oriented CAD files to the component-design software and ordering software currently in use.

Medium volume homebuilders are more likely to be influencing their supply chains to make use of larger scale building components such as wall panels and roof trusses. The medium volume builders are also more likely to have company-wide purchasing and accounting systems, lacking only design production modeling and field construction information tools to have an integrated ERP system for builders.

High volume builders have more extensive supply chain influence, existing purchasing and accounting systems and sophisticated project management tools. Their steps toward industrialization will require the integration of business and project management tools, the development of design and production modeling tools, and extension of the information management systems to field construction personnel and practices.

Production builders who are producing large-scale components such as wall panels, HUD code units and modular housing in fixed plant locations are making extensive use of industrial processes. These builders have closely studied their in-plant materials movement, have considerable supply chain influence and are likely to be employing Just in Time methods to manage inventory. They are most likely to have some form of materials requirements planning (MRP) within their production environment. The production builder group is most likely to benefit from application of design for manufacture and assembly (DFMA) techniques and increased use of new materials scaled to the machine-based handling and placing methods currently in use. Production builders are the closest to implementing enterprise resource planning (ERP) systems with the development of production modeling and field construction information tools.

The strategies outlined in this report represent a first step in moving the residential construction industry forward using integrated industrialized systems to deliver an affordable product with improved performance and operation. The techniques identified as most promising are:

- enterprise resource planning (ERP) systems,
- object oriented CAD,
- Just-in-Time supply,
- design for manufacture and assembly (DFMA) and
- prototyping and analysis tools.

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List of Acronyms

APICS	American Production and Inventory Control Society
APS	advanced planning system
BETEC	Building Environment and Thermal Envelop Council
BOM	bill of materials
BRI	Building Research Institute
CAD	computer-aided design
CARB	Consortium for Advanced Residential Buildings
CIDM	customer-integrated decision-making
COMBINE	Computer Models for Building Industry in Europe
CORBA	common object request broker architecture
DFA	design for assembly
DFMA	design for manufacture and assembly
DOE	(U.S.) Department of Energy
EDI	electronic data exchange
EPS	expanded polystyrene
ERO	enterprise resource optimization
ERP	enterprise resource planning
HATDE	Housing Affordability through Design Engineering
HUD	(U.S.) Department of Housing and Urban Development
HVAC	heating, ventilating, and air conditioning
HWI	Hardware Wholesalers, Inc.
IBACOS	Integrated Building and Construction Solutions
IBDS	integrated building design system
ICF	insulating concrete form
IDM	integrated data model
IFC	industry foundation class
IT	information technology
JIT	just-in-time
KBS	knowledge-based system
MRP II	manufacturing resources planning
MRP	materials requirements planning
MSDS	material safety data sheet
NAHBRC	National Association of Home Builders Research Council
NRC	National Research Council (of Canada)
OSB	oriented strand board
OVE	optimum-value engineering
PATH	Partnership for Advancing Technology in Housing
PROMIS	Product Model Based Integrated Simulation Environment
QFD	quality function deployment
RCI	residential construction industry
SCSD	School Construction System Design
SIP	structural insulated panel
TALC	Textile Apparel Linkage Council
UPC	Universal Product Code
VE	value engineering
WMS	warehouse management system
WTCA	Wood Truss Council of America

Figures List

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Chapter One: An Introduction to Industrializing the Construction Site

This report investigates means and methods for industrializing the housing industry. Although automation of factory manufacturing processes is considerably advanced in many fields at present, the design and construction of houses has seen only limited progress in automation and industrialization. The home construction industry is still very much dependent on manual labor and labor-intensive processes. Furthermore, when compared to other industries, home building has a reputation of low productivity, waste, and antiquated technology. The introduction of industrial methodologies and technologies to the housing industry promises to change the current practices of building and construction.

An industrialized housing industry is a vision that is attainable through practical innovations in current systems and technologies. We have already seen a move towards industrializing the industry, like small site factories, modular homes innovations, and prefabricated structural panels. However, for the industrialization of housing to have the same benefits that the industrial revolution offered to other products (lower cost, better quality, and faster production), there needs to be a directed change in the current housing delivery system.

The introduction of industrial methodologies and technologies to the housing industry promises to change the current practices of building and construction.

Linking current technology with an overall integration approach promises to make industrialization a reality. Tools available for this change involve advanced computer-aided design systems, numerical control methods, and advanced production technologies.

This report analyzes currently available manufacturing and home-building technologies and reviews past efforts at the industrialization of the housing industry. It then proposes a path forward to increasing the level of industrialization at all levels of the residential construction industry.

Chapter 2 reviews the state of industrialization in both housing and other industries. First, a review of selected national and international efforts in industrialization of the building industry is presented. Important governmental programs such as Operation Breakthrough, PATH, and Building America are also discussed. Next, paths to industrialization in other manufacturing industries are identified. Technologies used for automation and industrialization in these industries are discussed for their potential application in housing construction.

Chapter 3 presents the current state of systems integration in residential construction and discusses the advantages and shortcomings of current systems integration practices. Intersections between industrialization strategies and systems integration are identified and analyzed. Conditions of integration as applied to housing are grouped into five primary areas of influence and analyzed: information integration, physical integration, performance integration, production integration, and operations integration. The chapter concludes with a several technologies that are currently brining systems integration thinking into the housing industry.

Chapter 4 reviews and assesses currently available industrial technologies for their potential transfer into the home-building industry. The chapter starts by presenting an overall scheme for the residential construction industry. This includes a proposed information exchange system for industry participants. Next, the home-building industry is divided into four categories and relevant technologies are discussed for each sector. Strategies for their introduction and technological requirements for systems integration into the industrialized housing industry are also discussed.

Chapter 5 summarizes the report's findings and recommendations.

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Chapter Two: Existing Technological Obstacles to Industrializing the Construction Site

Home construction has changed little in the last 150 years. Homes are still constructed predominantly with sticks of wood nailed together. With the exception of some masonry construction found in limited geographical areas, homes are constructed with a framing technique slightly improved from that originally developed in the midwestern U.S. around the 1830s. By accepting the premise that the fundamental nature of home building is unchanged, discerning the current state of the technology is quite simple. The advances in technology have been not in home-building methods, but in material substitutions and building locations. This incremental development involves newer materials and pre-assembled components. For example, the current focus on steel-frame construction simply replaces wood with steel and nails with screws, with the basic construction processes remaining identical to conventional wood-frame construction. The incremental approach has meant that the home building industry has not, in general, undergone a comprehensive industrialization and therefore has not realized the rationalization and benefits that industrialization has delivered to many other industries.

Home construction has changed little in the last 150 years. Homes are still constructed predominantly with sticks of wood nailed together.

A review of the current state of residential construction reveals the existence of two distinct classifications of residential construction: (a) site-built, often called “stick-built” due to its conventional, wood platform–framing methods and (b) factory built, with four sub-classifications. Over 75 percent of the 1.2 million annual new housing starts in the United States are classified as site-built, although many use some prefabricated components, most notably roof trusses. Factory built housing represented approximately 25 percent of the new single-family housing starts in both 1998 and 1999 and approximately 20 percent over the last 20 years. Thus, site-built, wood-frame construction is the dominant method of residential building in the United States (Manufactured Housing Institute 2000).

Site-built housing has its roots in a craft-based enterprise system with societal perceptions of a house as a distinct and unique creation. This is, however, not the only way to perceive housing, as demonstrated in the late 1940s through early 1950s in places like Levittown, New York. Following World War II, there was an urgent need to house 12–16 million Americans as rapidly as possible. At Levittown, site-built housing used industrialized production similar to an on-site factory. Production techniques mimicked industrial processes, with workers following a lot-to-lot, assembly-line process. The construction consisted of a limited number of standard models that were repeated throughout the subdivision, using precut lumber combined with conventional construction techniques and technology.

The concept of industrialized housing in its most rudimentary form goes back to the mid-1800s, when prefabricated components were shipped from the east coast of the United States to California and Australia during their gold rushes, as were army field barracks during the American Civil War. In the late 1800s and early 1900s, precut kit houses could be ordered directly from catalogs from companies like Sears and Roebuck. During the 1920s and 1930s, many prominent architects and engineers began to experiment in mass-produced housing. Steel, sheet metal, tubular pipe, aluminum, wire, and glass were materials considered appropriate for manufactured housing. In the 1930s Howard T. Fisher, in an effort to make home building friendly to the average homeowner, pioneered the system of prefabricated, wood-stud panels still in use today. Following Fisher into the 1940s was the development of "trailers." These trailers were constructed based on current aircraft manufacturing techniques, with Spartan Aircraft building the first trailer designed as a house. In 1954 Marshfield Homes introduced the revolutionary "ten-wide," and the prototypical "mobile home" was born (Obiso 1998). From the 1950s to the mid-1970s, mobile homes were constructed without any building regulatory approval. Lacking permanent foundations, these homes were not considered primary housing, nor were they considered automobiles. Therefore, they were without any construction code standards.

In 1974, the Department of Housing and Urban Development (HUD) received congressional approval to enforce a construction code on the mobile home industry. By 1976, a nationwide standard was in effect governing the construction of mobile homes. "Mobile homes" as an acceptable designation ceased to exist in 1979 and was replaced by manufactured housing now referred to as "HUD code housing." Many of these early mobile home codes were oriented more toward manufacturing a product that would survive being transported on the nation's highways than toward a manufactured home. The 1980s and 1990s have seen another type of factory built housing, modular housing, appear in the market. In this period, modular housing has become a well-developed product and has led to some impressive gains in consumer acceptance of manufactured housing.

Figure 2.1: Manufactured housing is transferred to the construction site and lowered onto its foundation *Source: HUD*

CLASSIFICATIONS OF FACTORY BUILT HOUSING

Factory built housing is subject to much consumer confusion and subjective rejection of the product as inferior. A review of the classes of factory built housing may lend insight into current characterizations of industrialization that are perceived as advances in home-building technology. These classifications of manufactured housing, unique in code requirements and design, are, as follows:

Panelized housing consists of factory-built housing components, transported to the site, assembled and secured to a permanent foundation. These houses are subject to the local building codes of the site where the house will be assembled. These panels consist of open-wall, closed-wall, and structurally insulated panels. Open-wall panels are traditional 2x stud framing at 16- or 24-inch spacing nailed to top and bottom plates. These interior and/or exterior wall panels are cut and assembled in a plant, then shipped to the site for field assembly in the conventional, platform-framing manner. Closed-wall panels are similar to open-wall panels except that the exterior sheathing is fastened to the studs in the factory before shipping to the site. Structural insulated panels (SIPs) are 2- to 12-inch-thick cores of rigid foam insulation that has wood sheathing bonded to both surfaces. The material is received at the site in maximum sizes up to 8 feet wide by 24 feet long. Openings for doors and windows can be precut in the panel at the plant before shipping to the site.

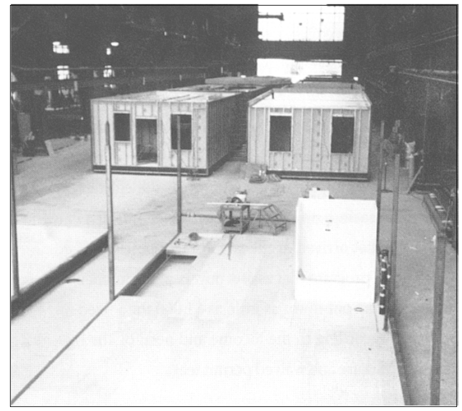

Figure 2.2: Modular housing on the factory floor *Source: HUD*

Precut housing is factory-built kits that have been cut at the plant, with components assembled for shipping, and then shipped to the site for assembly on a permanent foundation. These kit homes include traditional designs, log cabins, and dome homes. As with panelized homes, these homes must comply with the local codes in the jurisdiction where they are being assembled.

Manufactured housing is a specific term used to define a particular type of factory-built home construction in which one or more units will be transported to the site and usually installed on nonpermanent foundations. These units are typically constructed on steel chassis, using conventional platform-framing techniques. Upon completion of construction at the factory, the units are transported to the site on wheels and installed on a foundation. Although this classification of housing is shipped with wheels, these units seldom leave their "temporary" foundations. This housing must comply with manufactured housing codes within the jurisdiction of plant's location. Commonly referred to as "HUD code housing," this product has replaced the mobile home that was built from the 1950s through 1975. This report will use the term "manufactured housing" in the larger context of housing classifications, while "HUD code housing" will be used to designate this particular sub-classification of manufactured housing.

Modular housing (figure 2.2) is factory-built homes of one or more units typically using platform-frame construction. These multi-room, three-dimensional units are pre-assembled complete with trim and finishes. Upon completion at the factory, these units are shipped to the site for installation on permanent foundations. Modular housing must comply with the building codes in the jurisdiction of their permanent foundation.

DEFINING INDUSTRIALIZATION

Modern history books describe two industrial revolutions (Halsall 1997). The first industrial revolution was in the 17th and 18th centuries and involved great advances in the industrialization of agriculture, in power with the invention of the steam engine, and in the textile industry. England was the main player in the first industrial revolution, which was also accompanied by a scientific and political revolution (sometimes called the "three revolutions"). The second industrial revolution took place around the turn of the 20th century and was characterized by new technologies like steel manufacturing, the chemical industry, electricity, aviation, and automobiles. The United States has led many of the advances developed during this industrial age; however, there have been many stumbling blocks along the way. For years, U.S. manufacturers resisted change in production methodology. Both production and manufacturing management lacked the ability to meet the changing needs of the marketplace. In fact, many critics agree that it was the Japanese who introduced quality, efficiency, and customer value into the manufacturing vocabulary.

Using machines and repetition for mass production are characteristics commonly associated with industrialized manufacturing of a particular product. This industrialized manufacturing process is intended to improve production by replacing the traditional, crafts-based production process with standardized, machine-based production process giving a consistent affordable high quality product.

PREVIOUS EFFORTS AT INDUSTRIALIZATION: OPERATION BREAKTHROUGH

Studies performed by the government in the late 1960s established a need for new housing units well beyond the capability of the current industry to produce. The Douglas and Kaiser commission reports specifically forecast the national housing requirements to be 26 million new and rehabilitated units over the next 10 years, or 2.6 million units a year (Real Estate Research Corporation 1976). The perception of the residential construction industry was that it was incapable of meeting the new demand without adding to the cost of the final product. Another report in 1968 stated that half of all Americans were unable to afford permanent housing (Real Estate Research Corporation 1976). These factors and the threat of the effect of inflation on housing prices were the driving force behind Operation Breakthrough.

Six rationales were offered as driving forces behind the formation of Operation Breakthrough:

- A Congressional mandate for "the construction or rehabilitation of twenty-six million housing units, six million of these for low and moderate income families" in the decade 1968–78.

- A housing industry that had never achieved such levels of production, with a 10-year output record of 15 million units and a historic one-year high of just under 2 million units in 1950.

- A housing industry that was highly local in character, with local codes and code officials, local marketing, local labor supplies, local material dealers, all oriented around local land development.

- A pattern of low capital investment, very small firms, little sophistication in modern management methods, and little management depth. All of these inhibited innovation in technology, production, and marketing.

- Limitation in the supply of skilled labor, some materials, available land, and adequate financing, which would adversely affect opportunities for a significant expansion of the existing industry pattern. All of these were contributing to severe cost-push inflationary pressures on the price of housing.

- A growing recognition within and outside the industry and government that dramatic changes would be necessary to respond to the mandate placed before the nation by Congress.

The main premise of the program was to sponsor a change in the way houses are built and in the way people perceive manufactured housing in general. The original project was considered to be a project-specific program and not a long-term federal aid program to industrialized housing (HUD 1970b). It was designed to have three distinct phases of operation. The first phase was essentially system design and testing. A call for proposals was issued. Over 400 submitted proposals were reviewed and cataloged. The final list of 22 funded projects, resulting in the construction of approximately 2,800 housing units, seemed to focus on SIPs, precast-concrete structural systems, and factory-produced modular components of various material makeup (HUD 1970b).

Of the 22 funded proposals, 21 projects were built under Phase II—Prototype Construction. Only 195 (7 percent) of the units produced were single-family, detached dwelling units. Roughly 1,400 (half) of the prototype units actually constructed were buildings of four or more stories, and the other 1,200 units were townhouses and garden apartments (GAO 1976).

Two of the major hurdles that Operation Breakthrough identified were lack of unified codes and the fragmentation of the housing market. These two hurdles together provide an insight into the lack of a national character of housing in the United States. First, performance-based criteria were found unacceptable in some localities, and prototype-housing systems required modification to meet the local building codes. Secondly, housing markets remain regional in character. No data was presented to determine whether local codes are a response to the regional character of housing or regional character is partially determined as a response to local building codes. Either way, these two factors are credited with imposing an economic and administrative burden that increased the cost of Operation Breakthrough housing to a point of being far from competitive in the marketplace (GAO 1976).

The 2,794 housing units constructed under Phase II were placed at a total cost of $72 million dollars (1976 dollars), 40 percent more than its fair-market resale value (GAO 1976). On the positive side, most sites reported that the prototype units were assembled on schedule and with few surprises. The final per-unit costs demonstrate quite clearly how expensive the industrialized construction process can be if there is a low volume or a small combined (aggregate) market created to support the overhead and capitalization costs.

IMPACTS OF OPERATION BREAKTHROUGH

A "requirement for change" was established in the parameters of Operation Breakthrough (Finger 1971). The changes were to be industry-wide and involved ideas and processes well beyond just "building a better wall." The local character of the building codes was identified as being one major hurdle thwarting industrialization, and thus work towards national code unification was begun in earnest. Success at the statewide level was evident within three years of the project conclusion, but the nationwide unified building code for residential construction as proposed in 1972 is not scheduled for release until the end of year 2000. Other non-construction issues identified through the Operation Breakthrough work include the following:

- a public perception of factory-produced housing as being inferior to site-built housing,
- reluctance of financial institutions to provide mortgages or other permanent financing for factory-produced housing units,

- resistance by the residential construction industry to make the capital commitments in new and unproven technologies and processes, and

- marketing hurdles with any type of public-funded housing.

There has been little advancement in these areas since the conclusion of Operation Breakthrough. The public still perceives factory-built housing as an inferior, low-end product compared to site-built housing. Coupling these perceptions with the regionalism of the housing industry and the character of current builder/subcontractor relationships, there is little to promote national home builders to invest in the capitalization, equipment, and processes to alter the basic technology associated with conventional housing construction. The ability of public funding to alter the conventional home-building process faces the volatility of political administrations and national economic policy, which change frequently.

Operation Breakthrough achieved only limited success in reaching its goal of long-term change in the housing industry. The limited success can be attributed to economic conditions, market characteristics, public perception of large-scale housing, and the degree of fragmentation in the housing industry.

SELECTED INTERNATIONAL EFFORTS AT INDUSTRIALIZATION

Within the international construction research community six trends have been identified as likely to have the most influence on construction research (Bakens 1997):

- growing partnership between the research community and industry,
- internationalization of competition and collaboration within the research community,
- growing emphasis on integrated topics and approaches in research,
- electronic collaboration,
- information technology (IT) in construction, and
- sustainable development and construction.

This section highlights several interesting developments in international construction that may have implications for the industrialization of house construction.

Robotics and Enclosed Building Systems in Japan

To sustain a large research and development sector in the Japanese construction industry, the six largest domestic construction corporations are required by law to "invest some 0.5 percent of annual turnover on research and development" (Wing 1993). With each of the "Big Six" showing net sales of several billion dollars, a considerable pool of research dollars is formed. In addition to fulfilling the legal requirements, Japanese construction corporations allocate additional funds to maintain large research and development departments to stay ahead of their competitors. Private endeavors in combination with publicly funded institutions such as the Building Research Institute (BRI), established in 1946, provide Japan with the largest construction research base in the world.

Coupling a government-endorsed and -enforced research agenda in construction with large manufacturing companies, Japan is at the forefront of construction technology and development, especially in the areas of robotics and computer control systems. Robotics such as automatic floor finishers (Figure 2.3), reinforcement fabrication machines, painting robots, welding robots, unmanned forklifts, and giant manipulator arms have been developed to respond to the skilled labor shortage problem. Although all of these robots have proved effective in specific applications, they cannot be widely applied to the construction process. To fully utilize such technologies, a basic revision of the building process needs to be developed to integrate the robotic construction into the design of the building.

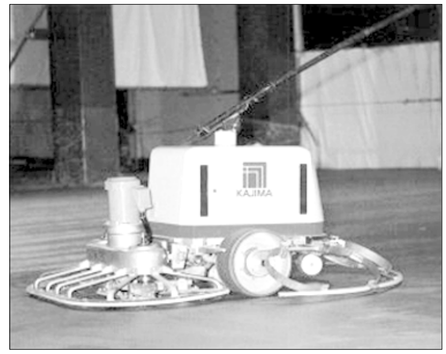

Figure 2.3: Concrete finishing robot

One of the more promising technological innovation developed by the Japanese is the floor-jacking method of high-rise construction. "Instead of automating individual tasks, the new approach aims to turn job sites into factories for the assembly of prefabricated components" (Normile 1993). This method, currently used in varying forms by several of the leading construction corporations in Japan, begins by constructing a staging platform composing the top floor of the building. The staging platform is jacked up story by story as the floors are completed below. In addition to providing a weather shield, this heavily automated platform incorporates computer-controlled gantry cranes, automatic welders, laser measurement devices, computer-integrated construction concepts such as bar-coding technology for material management, expert systems, and knowledge-based engineering. The combination of these methods is claimed to produce estimated man-hour savings of 30 percent for a 20-story building.

In the residential industry, several of Japan's largest manufacturers—including Toyota, Sekisui, Kubota, Misawa, Mitsubishi, and Daiwa—are involved in housing construction. Japan's strategy, based on cultural and corporate attitudes and stimulated by labor shortages, is to convert construction processes into manufacturing processes. Despite both government and corporate Japan's commitment to advanced manufacturing and technological innovation in construction, much of Japan's housing is post-and-beam or wood-frame wall and floor modules constructed in factories and shipped to the site for assembly and erection (U.S. Congress 1986).

However, several new housing construction innovations utilize manufacturing and product technology. Sekisui is refining machine-controlled cutting, milling, and welding of integrated, exterior load-bearing steel frames and insulated panels for housing. Other areas of innovation are microprocessor-controlled smart kitchens linked to wet cores and amorphous, thin-cell solar energy panels integrated into roofing material. These are, in effect, solar shingles able on a sunny day to supply sufficient power to meet the needs of an average Japanese family (Sekisui House, Ltd. 1999).

Open Systems in Denmark

In Denmark, a partnership was started around 1960 between the various parties in the building sector and the government for the purpose of establishing basic principles for the industrial development in building (Kjeldsen 1988). This policy has now come to be known as the Danish open-system approach.

"The basic philosophy behind the Danish Open-System Approach was to create an open market for factory produced—dimensionally coordinated—building components that could be combined in a variety of individual building projects. In accordance with this fundamental policy, it was the government's task to establish the framework for a development in which the building trade itself could create the necessary technical innovations" (Kjeldsen 1988).

The government's contribution consisted of determining uniform building regulations for the country as a whole, based on performance requirements; determining a long-range plan for the first five years of development, and requiring that all subsidized housing be planned according to a set of modular principles and standards to ensure the possibility of applying individually manufactured building components of modular size.

As a result of the collaborative effort, capacity of the Danish building industry tripled in less than 10 years.

Open Systems in Canada

The concept of an open-system building approach has also been successfully used in other countries. In 1965, the Department of Education for the Province of Ontario began development of a performance-based specification system for school construction. Building on the School Component Systems Development program implemented in California in 1961, Canada designed the Study for Educational Facilities program to "improve the quality of the schools and to reduce the time and cost required for planning and construction" (Sullivan 1980).

The open-system method required that "the manufacturers would assume responsibility for the research and development of the sub-system components of the building system, and the client would have the responsibility of supplying detailed specifications for those sub-systems and evaluating the performance and compatibility of the numerous [systems]" (Sullivan 1980). The primary advantage of the open-system approach was that various manufacturers operating with different technologies in different regions could meet the specifications set forth for the different subsystems. Because of the common specifications pertaining to dimensional coordination and performance, subsystems designed by different manufacturers could be integrated to form a complete system. An additional benefit to the dimensionally coordinated subsystems is that an individual subsystem such as the electrical system could be replaced as needed without major renovation of the existing structure. This method opens the door for components marketed under a lease-rent agreement, allowing the structure to develop along with changes in technology.

Information Technology in Europe

In the past decade, Europe and the surrounding countries have focused much of their research efforts on the development of knowledge-based systems (KBSs) such as the European Strategic Program for Research in Information Technology (ESPRIT) initiative begun in 1992 (VTT 1999). The ESPRIT initiative is primarily concerned with artificial intelligence and expert systems in industrial processes. Research conducted during the ESPRIT program identified three critical problems in the construction of