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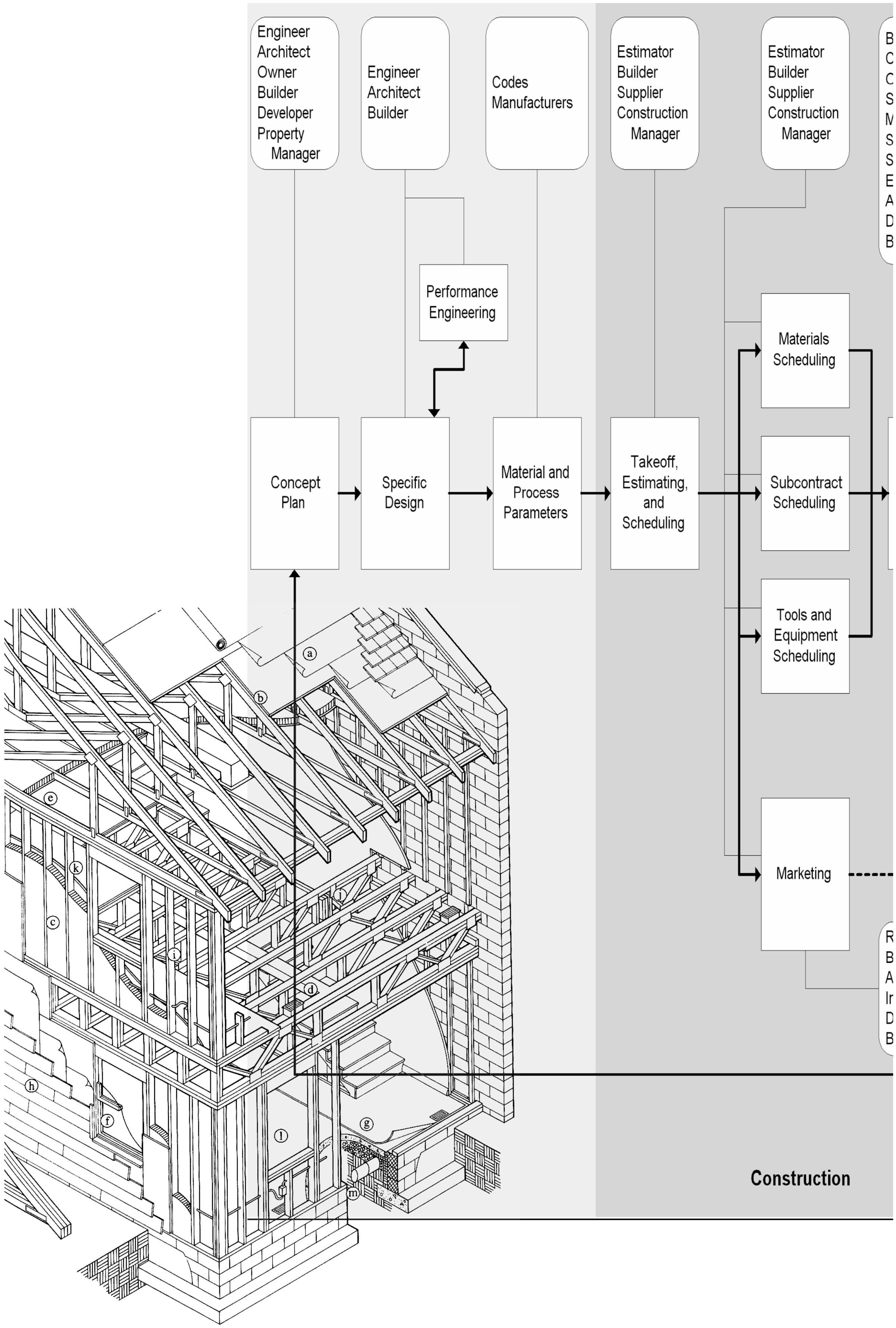

U.S. Department of Housing and Urban Development
Office of Policy Development and Research

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Industrializing the Residential Construction Site

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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.

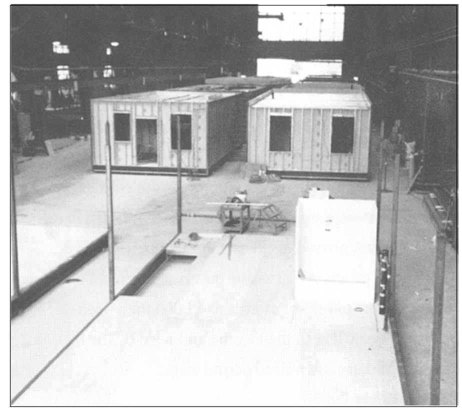

Figure 2.2: Modular housing on the factory floor *Source: HUD*

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.

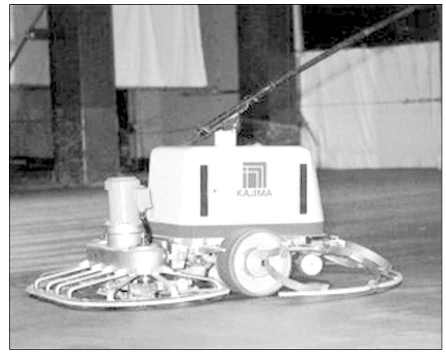

Figure 2.3: Concrete finishing robot

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

KBSs, including the following:

- the lack of an effective process model for KBSs,
- insufficient guidelines about when to use various knowledge-engineering methods and techniques, and
- the bottleneck produced in acquiring expert knowledge.

In addition to research in the field of industrial systems, the European Union has also focused on multidisciplinary integration in the field of commercial construction. This focus has led to the initiation of programs such as the Computer Models for Building Industry in Europe (COMBINE) research project conducted by the VTT research organization in Finland. The COMBINE 1 project, which was completed in November 1992, identified all essential building energy, service, functional, and performance characteristics so that they could be linked into the same computer modeling process (VTT 1999). This linkage allowed for the construction of an integrated data model (IDM) that provided for the interface of six performance tools covering heating, ventilating, and air conditioning; internal space planning; thermal simulation; energy analysis; energy-economic design; geometric modeling; and the design of external building elements. The COMBINE 2 project that followed utilized the IDM created in COMBINE 1 to develop an operational integrated building design system (IBDS) that could be used for both architectural design and building services engineering.

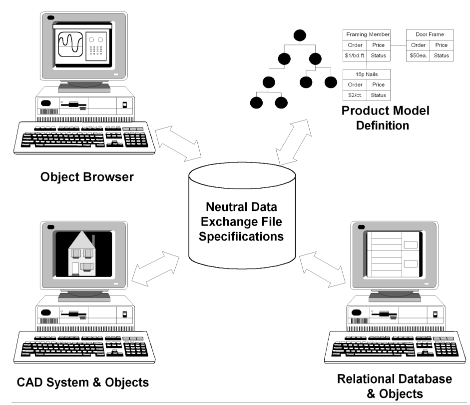

Figure 2.4: Object-oriented CAD project. *Source:* Seren et al. 1993.

Subsequent projects, including the Product Model Based Integrated Simulation Environment (PROMISE) project and the object-oriented CAD tool (OOCAD) project (Figure 2.4), have been conducted to further refine and expand the VTT modeling process.

One of the most inclusive of the object-oriented systems is OSCONCAD, an integrated system for combining CAD and construction-related applications. This system, developed in the United Kingdom in 1998, "addresses the problems of design fragmentation and the gap that exists between construction and design processes. It provides a vehicle for storing architectural design information in an integrated construction object-oriented database that can be shared by a range of computer applications" (Eastman 1998). The OSCONCAD model uses an object-oriented modeling approach to create standard architectural models complying with both industry foundation classes (IFC) for common interpretation of construction design objects and common object request broker architecture (CORBA) for distribution of the objects within construction applications. It also attempts to produce independence from the display environment by providing a set of abstract factory and abstract design classes that can be used by the design model classes to render themselves in any display environment. A distinct advantage of this system is that graphical and textual information about the building design components is directly saved in an object-oriented database as instances without passing through the existing CAD databases.

Current US Efforts in Building Technology

Several notable efforts are currently under way in the United States to provide a greater return on investment for residential housing dollars spent. Most seem to involve some sort of optimal value engineering or systems engineering process, while others are focused on the discovery and dissemination of specific new products or technologies. Generally private/public-based consortiums are promoting these investigations, with federal research dollars helping to sustain the effort. Several national programs, largely led by HUD and the Department of Energy (DOE), have resulted in marked improvements in residential technology.

Building America

The DOE program labeled "Building America" is aimed at reducing the overall energy use of new homes through design and construction improvements. DOE has formed a partnership with four other groups supporting the same objectives and acts as a "catalyst for change." The other groups are the Building Science Consortium, the Consortium for Advanced Residential Buildings (CARB), the Hickory Consortium, and Integrated Building and Construction Solutions (IBACOS).

The Building Science Consortium works to produce energy-efficient, cost-effective, single-family home designs in 12 states. A private consulting firm based in Boston, the Building Science Consortium heads a team of five industry members and four building partners, including Pulte Homes (Nevada and Arizona) and Shaw Homes. Reports indicate that energy savings of 50–60 percent over typical regional building practices are provided at a small cost increase over normal construction techniques.

With building partners Ryan Homes and Beazer Homes, **CARB** focuses on taking a builder's existing house plan and formulating an architectural solution that produces a more efficient mechanical and structural system. Of the four completed prototype homes, energy savings are reported to be between 20 and 35 percent over project control houses. CARB's Web site (www.carb-swa.com) specifically requests submission of housing designs and innovations that can be integrated into the residential construction industry in the near future.

The Hickory Consortium is led by a team of energy and environmental design experts who work towards producing more sustainable construction practices that result in significant energy savings. Focusing their work on multifamily housing, including factory-built modular housing, the Hickory Consortium has recently completed work on the Cambridge Co-Housing Development in Cambridge, Massachusetts. This community has shown early energy savings of up to 50 percent over the Massachusetts Energy Code (prior to the adoption of the 1995 Model Energy Code).

The fourth team currently composing the Building America Program is **IBACOS**. Its Web site (www.ibacos.com) states that "IBACOS serves as a catalyst for the delivery of new ideas, products and processes to the residential building market." IBACOS is using a three-tier approach to achieve its goal: delivery of ideas, delivery of products, and improvement in process.

The Building America program uses a systems engineering approach that models the house holistically instead of looking at each individual subsystem separately. This systems approach allows segments of the building industry that would normally work independently of one another to function in a cooperative fashion.

Design and construction decisions using a systems approach incorporate a process of weighing the overall final benefits obtained against short-term subsystem considerations. This type of critical thinking has led to ideas such as placing ductwork within the conditioned space, thus reducing insulation needs; using advanced modularization concepts; and enabling an overall reduction in mechanical system size due to the benefits of a tight building envelope (www.eren.doe.gov/buildings/building_america).

PATH—Partnership for Advancing Technology in Housing

PATH is another national private/public joint venture in the residential construction arena. HUD acts as the federal administrator but many other government agencies are partners in the 10-year project. A Presidential directive formally initiated PATH on May 4, 1998, with the aim of drastically improving "the quality, cost-effectiveness, durability, safety, and disaster resistance of housing in the United States." In fact, PATH lists its four main goals as follows (www.pathnet.org/goals.html):

- *Affordability:* Reduce the monthly cost of new housing by 20 percent or more.

- *Energy efficiency and durability:* Cut the environmental impact and energy use of new housing by 50 percent or more, and reduce energy use in at least 15 million existing homes by 30 percent or more.

- *Durability:* Improve durability and reduce maintenance costs by 50 percent.

- *Disaster resistance and safety:* Reduce by at least 10 percent the risk of loss of life, injury, and property destruction from natural hazards, and decrease by at least 20 percent residential construction work illnesses and injuries.

The PATH operating plan for fiscal year 1999 states, "During the next decade, the partnership aims to develop approaches, innovative housing component designs and production methods that will reduce by 50 percent the time needed to move quality technologies to market." These technologies will make it possible to produce housing that is affordable and attractive (www.pathnet.org/about/opplan.doc). Partners for the PATH project include large homebuilders, product/material providers, and academic institutions that are working to research and develop new technologies in the housing industry. PATH and its partners have worked to catalogue over 150 distinct technologies and have held field evaluations and national demonstrations for many of these innovations.

Technology development for PATH is sponsored with mandated federal funds and grants, along with active searches for new and better ways to solve existing housing problems. PATH's commitment to refurbishing existing housing through weatherization is helping to raise the energy-efficiency of many homes. It is interesting to note that one major objective of PATH is to reduce the "monthly" cost, not the overall cost, of a new home by 20 percent. PATH's goal here seemingly is to maximize the long-term affordability of the home. Government sponsorship of higher debt-to-income ratios for mortgage applicants is mentioned as one non-technical means of making housing more affordable.

Each of the PATH program's goals is broken down in an extensive organizational chart. These charts describe the attainable steps, or actions, that need to be taken over the next few years. PATH's progress report from April 1999 states, "Each of the actions in the plan is targeted at meeting both the PATH operating objectives as well as the overall goals of the PATH program." See the PATH Web site for a more complete list of future actions ("A Report on Progress Toward Meeting the Objectives Outlined in the Operating Plan for the Partnership for Advancing Technology in Housing [PATH]," April 22, 1999, available at www.pathnet.org/about/progrpt/intro.html).

INDUSTRIALIZATION IN OTHER INDUSTRIES

Today, manufacturing and retail industries alike have pioneered change into the information age. The affordability, portability, and power of computer systems have increased the number of stakeholders who can access and manipulate project data. This new change has led to the resurgence of U.S. manufacturing in the marketplace. In addition, advanced three-dimensional object modeling, CAD, and computer-aided machinery have raised the level to which a product can be consistently and accurately produced. These value-adding processes allow manufacturers to compete on a world-class level.

This section examines some of the lessons of industrialization from the manufacturing industry and assesses potential application of industrialized manufacturing techniques in residential construction. In particular, ideas that focus on enterprise-wide business-support systems (IT), process and production management tools, and assembly industrialization techniques are reviewed. These include JIT manufacturing, supply chain management, material/resource planning systems, and design-for-assembly systems.

Just-in-Time Manufacturing

In the manufacturing industry, much research and effort has been made towards eliminating product inventories and waste. One program, the JIT manufacturing system, is believed to have started in the mid-1970s with Toyota Motor Company in Japan (Schroeder 1993). However, Schonberger (1982) suggests that JIT may have actually originated in the Japanese shipbuilding industry 20 years earlier. Nevertheless, the JIT manufacturing system has helped many U.S. and foreign companies increase their overall profitability. Ford, General Motors, John Deere, Mercury Marine, Black & Decker, Rockwell, Honeywell, and IBM are only a few of the U.S. companies utilizing this management technique.

Schroeder (1993, p. 662) defines JIT as "an approach which seeks to eliminate all sources of waste, anything which does not add value, in production activities by providing the right part at the right place at the right time." Meredith and Shafer (1999, p. 302) refine this definition to three basic tenets:

- minimizing waste in all forms,
- continually improving processes and systems, and
- maintaining respect for all workers.

To achieve this tightly knit system, Hernandez (1989) states there are two main principles that should be followed for JIT manufacturing: use only quality materials and make a conscious effort to reduce lot sizes to one. Some of the gains experienced in the implementation of a JIT system include lower inventories, quicker product throughput, and higher-quality products.

"JIT takes its name from the idea of replenishing material buffers just when they are needed and not before or after" (Meredith and Shafer 1999, p. 302). To develop this replenishment cycle, the JIT system uses the *Kanban* (the Japanese word for "card" or "signal") system to pull parts from one work area to the next. The rules of the *Kanban* system entail the use of a pull-system replenishment logic, the production of the right amount at the right time, the production of defect-free parts, and the implementation of continuous improvement processes (Chausse, Landry, and Pasin 1997).

Additionally, partnerships with component suppliers have played a key part in developing a successful JIT system. When companies are willing to team up with their suppliers, the quality, convenience, and economics of scale take over. General Motors' JIT system focuses on early supplier selection, family of parts sourcing, long-term relationships, and paperwork reductions in receiving and inspection for its success (Schroeder 1993, p. 679).

Many commercial and large residential construction companies are currently pursuing a JIT system for their production units. However, the value of JIT can be seen in the entire construction realm, from multibillion-dollar federal projects to small, residential remodeling jobs. The key is a combination of two doctrines established by the manufacturing industry. First, lot sizes must be reduced to one. This solution is probably the most simple to implement for a residential homebuilder. In manufacturing, customers often order products in large quantities. It is not uncommon for some manufacturers to fill orders for thousands or even millions of goods for a single customer. In construction, on the other hand, homes are usually sold to individual homeowners. It is very easy to adapt a system where the customer drives the production lot size to one. This production lot size reduction will lead to easier project scheduling, reduced project cycle times, and increased profits through lower inventories. In addition, mass customization, a feature held as a competitive edge in the manufacturing industry, will be easier to accomplish.

The second ideal that must be adopted is the implementation of a close-knit relationship between the material/product supplier and the constructor. This solution is much more difficult for the residential builder. The residential construction market is highly fragmented. However, efforts must be made by construction companies to form key alliances with their vendors and suppliers. Only with partnerships like those found at General Motors and Bose will quality and significant cost savings be realized. In fact, supply chain management is the key to implementing all three key success factors (enterprise-wide business support systems, process and production management tools, and assembly industrialization techniques) in industrializing the residential construction site.

Supply Chain Management

"Supply chain management" broadly describes a system that monitors and controls all aspects of production. Meredith and Shafer (1999, p. 285) define supply chain management as "the supply, storage, and movement of materials, information, personnel, equipment, and finished goods within the organization and between it and its environment." Palevich (1997, p. 1) defines the term similarly: "[Supply chain management] encompasses all of those activities associated with moving goods from raw materials through the end user. This includes sourcing and procurement, production scheduling, order processing, inventory management, transportation, warehousing, and customer service. Importantly, it also embodies the information systems used to monitor these systems."

Supply chain management has become a technology-based approach to increase a company's or an industry's return on investment. Whether electronic data interchange (EDI), bar coding and scanning, or use of the World Wide Web, technology appears to be the key enabler to supply chain management. In addition, supply chain management can be used with other production and manufacturing management technologies to facilitate the information flow from raw materials to consumers.

Two studies in Appendix A, Supply Chain Management Case Examples, detail how supply chain management has helped industry. The first, a study in the textile manufacturing industry, explains how several key EDI standards were established by the Textile Apparel Linkage Council (TALC) to help facilitate communication between different parties. The second, a study at Hardware Wholesalers Inc., shows how supply chain management is be implemented in a product distribution network.

In the "information age," it has become fact that those companies that manage and control information flow quickly and accurately increase their chance for success. The construction industry is a perfect example of the importance of information management. Software tools that perform document management and project scheduling are all but overflowing the product shelves. However, these tools are internal systems. To reap the benefits of full information flow, constructors and suppliers alike must work on creating a system by which communication can flow from the manufacturer all the way down to the craftsmen and laborers who install the product in the field. Initiatives like A/E/C XML, a unified descriptor language for use in the construction industry, must create a common dialect that all parties (architects, engineers, constructors, and manufacturers) can speak. Partnerships between constructors and manufacturers must establish the value of implementing a supply chain management system. Immediate benefits include up-to-date product data and specifications (e.g., size, weight, MSDS), possibilities for customization, and increased on-time delivery. Additionally, a supply chain management system would enable all parties to reduce costs through the elimination of both work duplication and labor idle time.

Material and Resource Planning Systems

Over the past 20 years, the development of resource planning systems has quickly generated a plethora of software solutions that attempt to monitor, control, and plan the amount of inventory within the manufacturing industry. Materials requirements planning (MRP), manufacturing resource planning (MRPII), and enterprise resource planning (ERP) systems all attempt to control raw material, finished product, and work-in-progress inventories. Additionally, the more complex (enterprise-wide) systems look at integrating more and more management functions within the resource planning tools.

Materials Requirements Planning System

The heart of the MRP is its inventory control power. The MRP system releases manufacturing and purchase orders for the right quantities at the right times to support the master schedule. This system launches orders to control work in process and raw materials inventories through proper timing of order placement. However, the MRP system does not include capacity planning (Meredith and Shafer 1999). There are three main inputs into an MRP system-including the master production schedule (MPS), the bill of materials (BOM), and the inventory master file. “The master production schedule is based upon actual customer orders and predicted demand. This schedule indicates exactly when each end item will be produced to meet the firm and predicted demand” (Meredith and Shafer 1999, p. 268). The BOM is an engineering document that can be “represented as a symbolic exploded view of the end items’ structure” (Hax and Candea 1984, p. 441). This detailed component breakdown is used in a process called “parts explosion.” “The process of parts explosion will determine all the parts and components to make a specified number of [production]

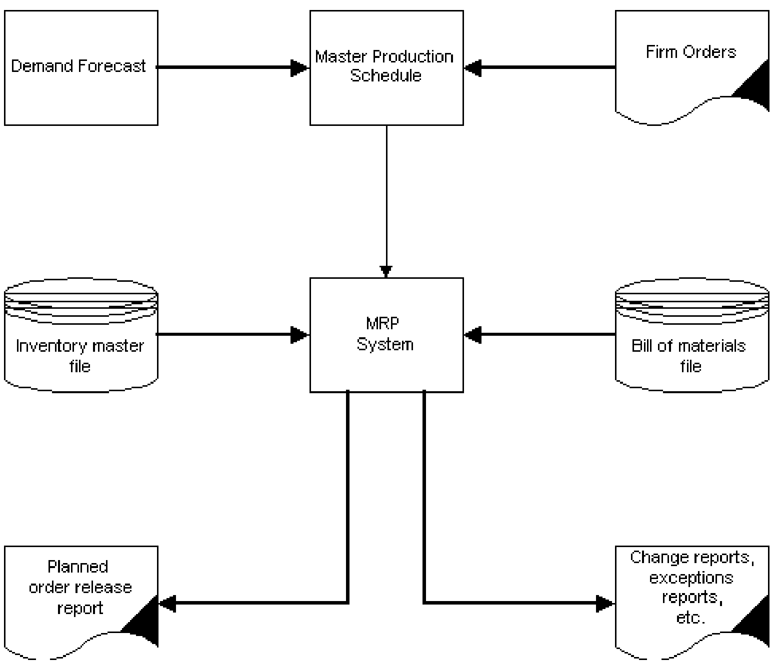

Figure 2.5: A materials requirements planning system schematic. *Source:* Meredith and Shafer 1999, p. 276.

units” (Schroeder 1993, p. 625). MRP systems access the BOM information to learn exactly what materials will be needed at what times and in what quantities (Meredith and Shafer 1999). The last part, the inventory master file contains detailed information regarding the exact part numbers, quantities, slated uses, costs, and lead times are generally included in the inventory master file records. Figure 2.5 shows an adapted schematic of an MRP system detailed by Meredith and Shafer (1999).

Manufacturing Resource Planning System

An MRPII system is "used to plan and control all manufacturing resources: inventory, capacity, cash, personnel, facilities, and capital equipment. In this case the MRP parts-explosion system also drives all other resource-planning subsystems in the company" (Schroeder 1993, p. 626). If there is not enough capacity, either the capacity or the master schedule is changed. MRPII systems have a feedback loop between the order launched and the master schedule to adjust for capacity availability (Schroeder 1993, p. 626). Forecasting, customer orders, engineering data control, purchasing/receiving/stores, and plant maintenance all serve as inputs into the scheduling process. Both purchasing/receiving/stores and plant maintenance also serve as feedback loops to ensure proper non-production work items will be performed in time with the production schedule.

In short, MRPII systems attempt to incorporate accounting, sales, engineering, and many other functional areas into their planning strategy. "Once this information is available, the purchasing, capacity planning, and operations scheduling components take over to produce purchase-order requirements, route the product through operations, generate capacity requirements by individual operations, and load and schedule operations for production" (Meredith and Shafer 1999, pp. 276–77). Figure 2.6 shows what components make up a typical MRP II system. Most MRP II systems are tailored to each company, and therefore some modules may be found in one company that may not be found in another.

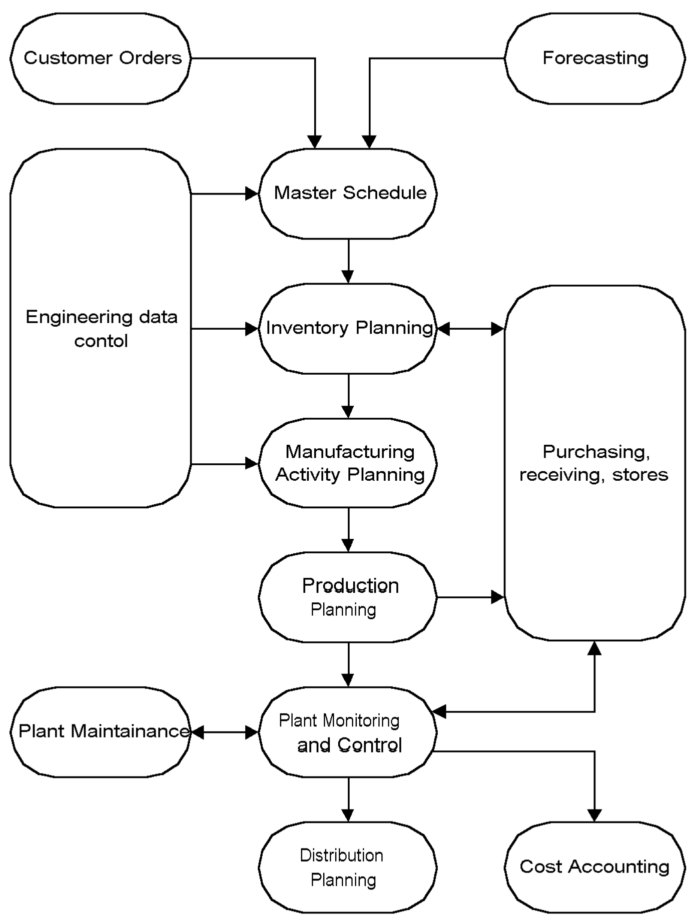

Figure 2.6: Typical MRP II system and its modules. *Source:* Meredith and Shafer 1999, p. 276.

Enterprise Resource Planning System

"As the name suggests, the objective of [ERP] systems is to provide seamless, real-time information to all employees who need it, throughout the entire organization (or enterprise). ERP extends the idea of a central database to all areas within an organization" (Meredith and Shafer, p. 278). ERP is the newest resource planning system to undergo investigation by numerous manufacturing companies. The ERP system is built upon computer client/server architecture. Information from all aspects of the company—including sales, finance, human resources, accounting, production, engineering, etc.—is stored on a central database. Functional groups use software that pertains to their duties within the organization but store their data in the same location as everyone else. Figure 2.7 shows an example ERP system.

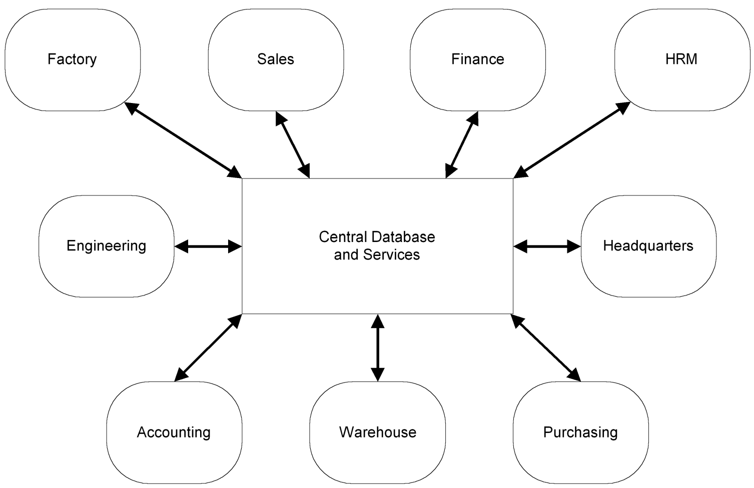

Figure 2.7: Typical ERP system. *Source:* Meredith and Shafer 1999, p. 278.

"Clearly, this approach eliminates the incompatibility created when different functional departments use different systems, and it also eliminates the need for people in different parts of the organization to reenter the same information over and over again into separate computer systems" (Meredith and Shafer 1999, p. 279).

Resource planning systems provide manufacturers with a competitive advantage. MRP, MRP II, and ERP systems help manage both increasingly complex product designs and decreasing product-to-market cycle times. In fact, a resource planning system for residential construction should deliver two needed interactions. First, an MRP, MRP II, or ERP system will help develop the information flow between independent-demand (home sales) and dependent-demand items (BOM). A parts-explosion process for home building will enable a detailed take-off, material ordering, and scheduling process based on customer orders. Second, a resource planning system will enable increased communication between entire business units. Production must be able to communicate with human resources, marketing, sales, and management teams. Alignment among these usually independent functional groups will be the key to increasing productivity, cost-effectiveness, and quality in the construction industry. When home sales, a customer-driven activity, can drive marketing, production, and accounting functions, savings in company overhead will arise. This change will lead to customer savings in the long run.

Design for Assembly

A common roadblock to the manufacturing industry is the ability of a design to be manufactured. Industrial designers play the leading role in determining a product's form and appearance. What these designers sometimes fail to realize is that their designs also affect the way in which a product will be manufactured and assembled.

Traditionally, it was expected that engineering students should take "shop" courses in addition to courses in machine design. The idea was that a competent designer should be familiar with manufacturing processes to avoid adding unnecessarily to the manufacturing costs during design. Unfortunately, in the 1960s, shop courses disappeared from university curricula in the U.S.; they were not considered suitable for academic credit by the new breed of engineering theoreticians (Boothroyd, Dewhurst, and Knight 1994, p. 1).

This lack of practical "know-how" has hurt the design of manufactured goods. "If the designer creates forms on paper using pencil or marker, there is a danger that he or she is not only removed from an understanding of what the manufacturing ramifications are but is another step removed from dimensional reality and material behavior. It takes a real-world understanding of materials and manufacturing methods to create successful products" (Lesko 1999, p. 3).

To counter the growing effects of the removal of design from real-world application, a detailed system for product design for assembly was necessary. Geoffrey Boothroyd and Peter Dewhurst led the development of design-for-assembly (DFA) systems, starting in 1977 with funding from the U.S. National Science Foundation (Huang 1996, p. 21). Design for Manufacture and Assembly (DFMA, a trademark of Boothroyd Dewhurst, Inc.) is a computer-based system where savings in both manufacturing and assembly costs can be achieved through parts reduction. "In order to give guidance to the designer in reducing the part count, the DFMA methodology provides three criteria against which each part must be examined as it is added to the product during assembly" (Boothroyd, Dewhurst, and Knight 1994, p. 5):

- During operation of the product, does the part move relative to all other parts already assembled? Only gross motion is considered—small motions that can be accommodated by integral elastic elements, for example, are not sufficient for a positive answer.

- Must the part be of a different material than, or be isolated from, all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.

- Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of the separate parts would be impossible?

The answers to these basic design questions lead to the establishment of the critical parts necessary for the assembly. In addition, these parts form the baseline for manufacturing and assembly evaluation. Mathematical formulas involving theoretical part counts and design efficiencies help put a quantifiable cost on various designs. In fact, Boothroyd and Dewhurst's system establishes the systematic procedure for analyzing a design prior to assembly and manufacture (see Figure 2.8).

The DFMA system has been a documented success in many industries including automotive, electronics, and aviation. The DFMA system has also been applied on low–assembly cost and low-volume operations with the same success as high–assembly cost, high-volume operations.

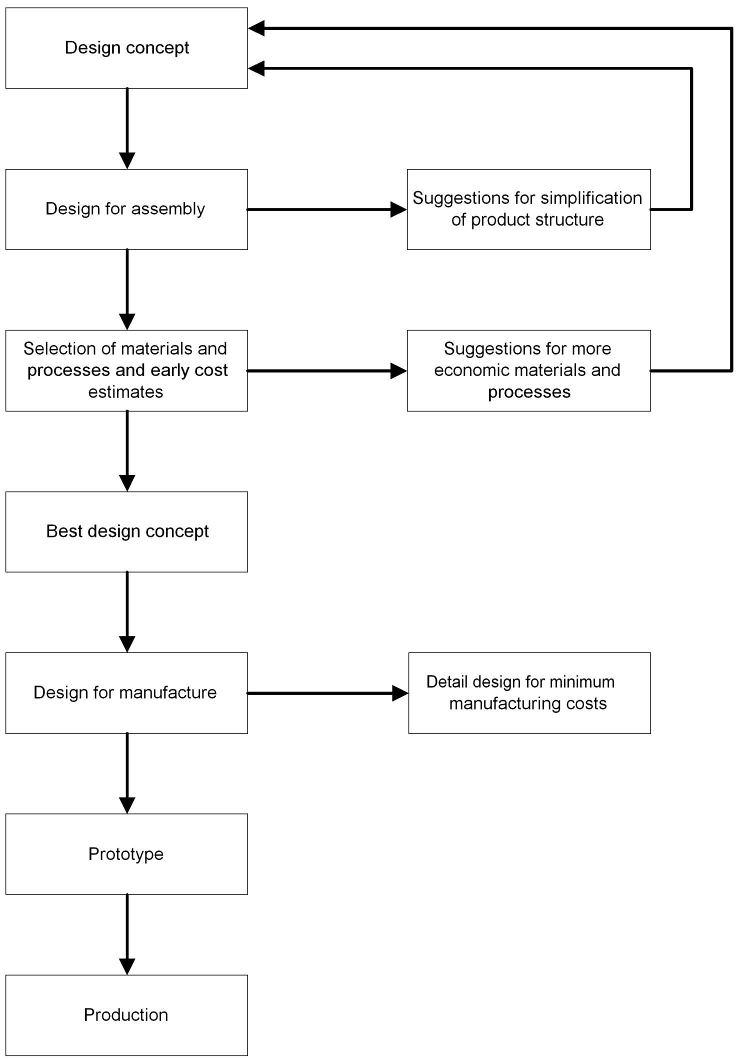

Figure 2.8: Typical steps in a design for manufacture and assembly study.

The construction industry has already instituted a technique similar to the manufacturing industry's design for assembly. It is called "value engineering" (VE). VE is a technique by which a project's value is increased. Since value is a function of worth divided by cost, VE attempts to increase a project's worth while decreasing a project's cost. In the same manner, DFMA attempts to increase the value of a product by decreasing cost and increasing product quality (a form of worth). However, the major difference between DFMA and VE is the stage in the product design-production cycle at which the process is applied. VE is usually applied in construction after the design stage, whereas DFMA in manufacturing is applied as part of the design phase. DFMA can be successfully applied in construction if used during the design phase, similar to the manufacturing industry. Outputs from the DFMA process could help reduce project duration, reduce project costs, and increase project quality. Current potential systems that could greatly benefit from a DFMA analysis in residential construction include foundations, wall systems, roof systems, and plumbing systems. Tremendous monetary savings could be generated and passed on to homeowners if these systems could be designed around manufacturing and assembly.

CONCLUSION

Construction has been a conservative industry. Potential liabilities, personal resistance to change, and contentious project relationships have limited the development of construction production methodology. However, the manufacturing industry has shown that industrialization in information management, production management tools, and assembly techniques can change not only a company but an entire industry.

The construction industry must first assess the potential idea transfers from the manufacturing industry leaders. This section has identified several high-potential manufacturing techniques that can be applied to construction: JIT manufacturing, supply chain management, material/resource planning systems, and DFA systems.

In particular, there is a need to focus the construction industry on three thrust areas: enterprise-wide business-support systems (IT), process and production management tools, and assembly industrialization techniques. The results of efforts in these three areas will bring reduced project costs, increased productivity, and increased project quality by improving information management, resource utilization, and assembly techniques, all of which both consumers and the industry desire. These techniques have the potential to become the vehicle for integration of the residential construction industry. Concepts and methods of integration will be discussed in the next chapter.

3

Chapter Three: Integrated Systems for Industrialization of the Residential Construction Site

A significant characteristic of contemporary industrialization, be it aerospace, automotive, electronics, or food processing, is the linkage of marketing needs, product design, purchasing, production processes, inventory, and shipping sales.

The construction industry in general and the housing industry in particular have not made these linkages. As a result, productivity in the housing industry lags behind other industries. This has obvious consequences for the performance and affordability of housing.

Linking all aspects of product design, production, and sales to perform as a single system is the essence of systems integration. The current state of systems integration in housing treats each major building system discretely. The structural system is designed and fabricated with little concession to the design and fabrication of mechanical, electrical, and enclosing systems, and little thought to the overall production efficiency. Within each major building system, various stages of component prefabrication, assembly simplification, and labor time reduction are practiced. The plate roof truss is a common example of structural subsystem component integration. Equally common is the modification of these trusses by building trades installing ductwork, plumbing, or electrical wiring. The advantage of this approach is the reduction of development costs. However, this comes at the expense of subcontractors and the homebuilder.

Information integration is the "umbrella strategy" that must become the backbone of the housing industry.

The absence of coordination between subsystems is attributable to uninformed design, the lack of prototyping, absence of production simulation and lack of understanding of the consequences of field modification on performance. This current state is largely a product of reduced design resources and the system of discrete trades subcontractors. Each as a small business whose priority has to be the efficient conduction of their defined contract. These discrete subcontracts are not often coordinated in the design stage. As often, houses are adaptations of models seldom with the full involvement of design professionals. On-site resolution of system conflicts requires the attendance of each (often three or more) subcontractors and a convening (mediating) general contractor. This seldom occurs due to simple scheduling conflicts and slim profit margins which together work as effective disincentives to physical, performance, and production integration.

Industrialization strategies used by major manufacturers have produced tools and processes that promise to enhance the overall level of systems integration increasing production efficiency, performance, and thus affordability. As discussed in chapter two, techniques such as JIT, MRP, MRPII, ERP, and DFMA are the best potential methods for achieving systems integration in construction.

Information integration has been the key strategy employed by major manufacturers to raise productivity while reducing costs and increasing quality. Information integration is the 'umbrella strategy' that must become the backbone of the housing industry to support industrial design, production, and operations methods common to major manufacturers.

The concept of overall process control through information integration, using object oriented design, virtual prototyping, production simulation, design for assembly, supply chain management, cross-trained trades, and sensor networks/system controls for normal and extreme service performance will be described in the following five sections on integration.

THE CONDITIONS OF INTEGRATION

The conditions of integration as applied to housing construction fall into five primary areas of influence:

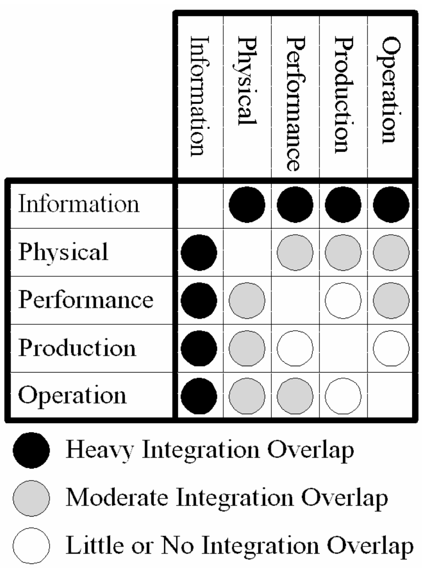

Figure 3.1: Integration overlap

Information integration – making the many pieces of information used by homebuilders accessible as one data source.

Physical integration – making the many parts fit together as one.

Performance integration – making the many systems perform as one.

Production integration – conducting the many processes as one.

Operations integration – operating the many subsystems as one.

These five conditions of integration are difficult to separate in practice. Actions taken to increase the level of physical integration for one subsystem often improve the performance of another subsystem (e.g., by avoiding cutting or notching). Performance integration benefits operations integration (e.g., using shading to reduce heat gain, avoiding increased air conditioning operation). Information integration extends across the process of design, construction, and operations to enable physical and performance integration. Ideally, these five conditions of integration are integrated with the physical materials and labor used to assemble the house, resulting in a house that is a single, integrated system. The following sections present each of these five conditions of integration in greater detail.

INFORMATION INTEGRATION

The order of listing the conditions of integration generally corresponds to the sequence of steps required to achieve an integrated system. A conclusion of our industry studies is that information integration (making the many bits of information that are part of every house into one accessible information resource) leads the way to systems integration and associated performance gains.

One of our major findings from industry has been that both the information and its representation are critical to rapid acceptance by management and labor in addition to improving production, performance, and profit. When industries develop integrated information systems, extensive research and design time is allocated to determining who will need what kind of information and what form that information will take. Depending on the user level, information is presented in text, numeric table, graph, chart, or pictorial diagram in two or three dimensions. The key seems to be not to overwhelm a user with information that is not necessary to the task at hand and to enable the user to customize the information presentation for increased effectiveness. While standard reporting forms are designed for the different user levels, most integrated information systems include some form of “data warehouse” listing all the data fields available to the user, enabling the user to pick and choose what data appears where and in what form.

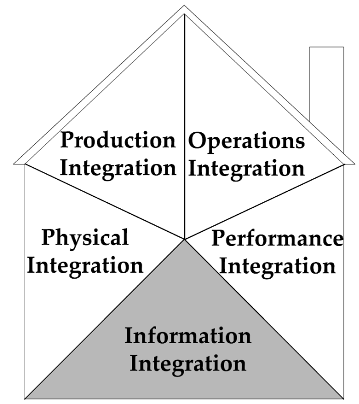

Figure 3.2: Information integration

Given that some 135 people, including order processors and shippers, are involved with the process of making a house from design to final inspection (see Appendix B. How Many People Make a House?) and given that a house is the largest investment most Americans make, changes are requested during the construction phase. Most changes require that the work stop, the change be evaluated, existing work be removed, new materials be ordered and installed, and schedules be pushed back. Many owner-initiated changes can be tracked back to the owners’ misunderstanding of what the completed house would be like. Many production builders (those producing thousands of homes per year) currently work to minimize misunderstanding with full-scale model homes used as the sales center. Product upgrades and customization costs are prepared manually (and are often limited to a package of pre-priced upgrades) with the final price taking some days to determine. Recent developments in the three-dimensional visualization of buildings, linked to object-oriented CAD databases, are already enabling owners to view “their” house in its final color, material, and upgrade configuration, with rapid pricing of changes (Evans 1999). This three-dimensional visual presentation can significantly reduce misunderstandings and reduce owner-initiated changes.

This design, personalized for each client and connected to an inventory and scheduling program, provides the builder a fairly accurate projection of completion time, taking into account suppliers’ backlogs for materials and labor utilization across the production builder’s project list. The impact of design changes can also be evaluated at this point. Monthly expenses for heating, cooling, lighting, and maintenance of the house could be projected at this time by connecting performance analysis software to the database.

The object-oriented CAD tool further facilitates physical and performance integration by rationalizing all subsystems (drawing all required components and finding the most efficient method of connecting like-subsystem components). This rationalization enables the program to check for physical collisions between subsystems, thereby decreasing the need for field personnel to diagnose, anticipate, or guess at solutions to systems conflicts. The process of construction and the design of pre-engineered components for the house can also pass through an interference detector while being “virtually constructed” within a simulation environment.

Simulation environments appear similar to three-dimensional animations but differ in that the degree of movement, speed, mass, of a crane carrying a beam is not controlled by “eye.” The behavior of models and machines in the simulation environment are controlled by mathematical formulas, which account for the laws of physics when moving, bending, or colliding with other elements in the simulation environment. Simulation programs are commonly used in industry to pre-fit parts and pretest assembly procedures, saving millions of dollars in time and physical prototypes.

For residential construction, a simulation environment can couple the object-oriented model to a process modeling program currently used in industrial applications to determine staging points for materials and components and locations for cranes and lifts. This simulation environment could enable the production builder to view the whole development's progress through a three-dimensional progress chart. This proposed use of the simulation environment for design, production planning, and production progress reporting is based on existing industrial production planning and evaluation tools and will be more cost-effective for the home builder when existing object-oriented, three-dimensional CAD files are imported into the simulator because it will reduce repetition of model construction.

When the people involved in the decision making, design, production scheduling, production, finance, operation, and maintenance of the house have access to the current information about the house, the remaining four conditions of integration, described in the following subsections, will be easier to achieve. For the shift towards the industrialization of the residential construction site, similar broad reconsideration is useful for identifying key knowledge to be developed and key tasks to be undertaken.

PHYSICAL INTEGRATION

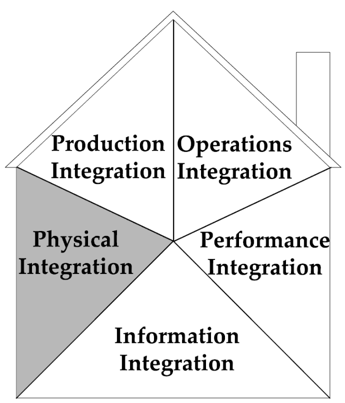

Figure 3.3: Physical integration

Physical integration, making the many parts fit together as one, is the next step towards enabling higher levels of integration. These include production integration (DFA), performance integration (multiple subsystem coordination/optimization), and operations integration (long-term durability and serviceability). With the computing skills on hand in most home builders' offices, information integration—beginning with object-oriented CAD systems—will likely be the key to addressing higher levels of physical integration. Performance gains will be realized by simply reducing the number of places where one subsystem has crushed, punctured, or cut key components of another subsystem.

In construction, there are few examples of all subsystems integrated into one unified system. The work of architect Ezra Ehrenkranz stands out among the attempts at total-system physical integration. The School Construction System Design (SCSD) project for California school districts is the most successful effort to date in physical integration (see Appendix C. SCSD—A Physical Integration Success Story). The intensive coordination between designer, engineer, manufacturer, contractor, and owner necessary to achieve an open, integrated system is a major obstacle for home builders producing only a few dozen or even a few hundred houses based on the same design. Ehrenkranz overcame this obstacle in SCSD by bringing together school districts needing to build. This coalition assured manufacturers that sufficient system/material quantities would be contracted to profitably pay the cost of retooling product lines.

Object-oriented CAD-based physical integration tools can be applied to the interface between adjacent subsystems such as plumbing and framing during the design phase. The same position-checking and interference-detection tools can be applied to the relationships among components and subcomponents of a subsystem, such as the relationships among a roof framing member, a roof sheathing panel, and a fastener. Simple software-based coordination of material sizes, chemistries, fastening schedules, and component design can accelerate production rates, reduce first cost and life-cycle maintenance, and ultimately increase performance.

Anecdotal evidence suggests that the most common problems arising from a lack of physical integration are as follows:

- excessive floor-to-ceiling cavity depths due to limited planning of the path for subsystems,
- inadequate access for maintenance,
- missing backing material for finish-material installation,
- ductwork placed outside the conditioned building envelope,
- ductwork compressed after installation,
- inadequate space for drain-line slopes,
- cuts through critical structural assemblies for waste piping,
- cuts through critical structural assemblies for electrical wiring,
- engineered-wood structural elements modified in the field to accept mechanical equipment,
- missing or improper flashing installation, and
- missing water pipe insulation.

The lack of statistically sound data documenting the productivity and performance losses due to physical integration failures is a significant barrier to benchmarking current practices. It is also a barrier to evaluating the costs and merits of design and construction practices aimed at increasing the level of physical integration. Statistical sampling and analysis of designed and on-site practices leading to physical conflicts between subsystems must be completed prior to the development of tools and practices for physical integration.

Modularity in Residential Construction

Since the development of the balloon frame in the mid-1830s, the home-building industry has adopted the 16-inch framing increment as an industry standard. Manufacturers of plywood reinforced the 16-inch planning module with the 48- by 96-inch panel dimension to ensure the rapid adoption of plywood by the home-building industry. Since the 1930s, window, cabinet, insulation, and drywall manufacturers have developed products compatible with the 16-inch dimension.

Programs such as the American Plywood Association's MOD 24 (APA 1970) and Engineered 24-inch Framing (APA 1981) and techniques such as the planning principles used in optimum-value engineering (OVE) sought to reduce construction material waste by working to modular dimensions of materials and modifying traditional framing practices with engineering-based designs for the spacing and dimensions of framing elements. These programs advocated the 24-inch framing increment to better utilize the structural capability of standard wood studs and plywood products. The 1978 HUD publication *Reducing Home Building Costs with Optimum Value Engineered Design and Construction* (NAHBRC 1978) documents research conducted by the National Association of Home Builders Research Center (NAHBRC) on design and construction methods for wood construction intended to reduce material waste and framing and sheathing costs. MOD 24 documented cost reductions on the order of 6.45 percent, or $219 (1970 dollars; $967 in 1999 dollars), while Engineered 24 inch framing was documented to save 12 percent of construction costs, or $929 (1981 dollars; $1,824 in 1999 dollars) by simply changing the spacing of framing members from 16 to 24 inches. These methods continue to be employed by builders of entry-level and low-income housing to decrease time and materials costs.

These programs concentrated on framing and superstructure systems which manufacturers of windows, wall insulation, and drywall could support with little redesign of their products or manufacturing methods. Foundation, heating, cooling, plumbing, and electrical systems have not yet entered this open system. In residential construction these subsystems are fabricated by hand on the construction site. This method affords great design flexibility but does not bring these systems into the world of integration. Without a modular or integrative approach, improvised, on-site solutions for routing electrical, water, and waste lines will continue to drill, cut, and weaken structural members in critical locations.

Physical Integration in Large-Scale Construction

Due to the constructed quantities involved and longer-term ownership, larger buildings such as museums and office buildings often approach physical integration with production efficiency, maintainability, and system replacement in mind. Meshing of subsystems was a popular strategy in the early 1960s. Meshing strategies carefully wove the mechanical, structural, electrical, and plumbing subsystems together to reduce the overall floor-to-floor height of office buildings. This approach also required additional time and resource investment in the late design stages of the project. Coordination of subsystems during the preliminary, schematic, and design development stages of the design project required architects and engineers to invest more coordination time during each stage than alternative “space reserving” strategies. For cost reasons many designers slowly abandoned the meshing strategy of total system integration. Designers and project managers also noted that the tight sequencing of trades exposed projects to significant delays if one key union had a labor dispute.

A dominant strategy currently used in the design phases includes the development of “reserved space” in ceiling and floor structures for each subsystem. For example, the ceiling subsystem might have 1–1½ inches reserved from the face of the ceiling finish to the top of the channels suspending the ceiling, lighting would have the next 6 inches above the ceiling, plumbing the next 8 inches, mechanical the next 18 inches, and the structural system 28 or so inches remaining to the top of the space.

These strategies require that subsystem components be planned (designed and drawn) at an early stage of design. Knowledge of component sizes, insulation, and slope are critical to conflict prevention and field improvisation. This is not standard practice for many designers and builders due to costs (and lack of compensation) involved in the design, drawing, and coordination of subsystems in housing. Current practices often send the design out to the field with only framing diagrams and plan locations for lighting and plumbing fixtures. Beyond locating the primary vertical waste line (which often does not fit in a standard 2 x 4 wall), those making the drawing assume field personnel will find a way to route power, switch, vent, and drain lines. Often field personnel must improvise locations and routing for primary heating and cooling ducts. The lack of complete rationalization of subsystems in the design phase continues to be a significant obstacle to achieving higher levels of physical integration.

Consequence of Modular Planning Ideas in Residential Construction

Use of these material efficiency methods in the residential construction industry has been strong among the production builders who are mass-producing house designs. The larger numbers of same or similar house designs produced by these builders enable the cost-effective distribution of design refinements (across many units constructed) necessary to optimize spatial functionality, user desires, and material use.

The “fail-safe” assembly method (Hernandez 1993) practiced in conjunction with total quality management programs by many manufacturers of components for the machine tool, automotive, and aerospace industries has all but eliminated discrete quality control departments. Use of the fail-safe assembly method makes the next downstream operation impossible to complete with an improperly assembled part or subassembly, shunting the defect to a rework cycle.

It would be hard to find residential construction workers who have not had to spend more time or material on their subcontract because the crew who just installed a subsystem ahead of them did not know or care that some other trade would be installing in the same location. These “over the wall” problems (“It’s not my problem; it’s YOUR problem”) made by discrete subcontractors can be dramatically reduced with a combination of redefined labor boundaries and implementation of “fail-safe” design of subsystem connections and components. Redefined labor boundaries must focus responsibility on complete construction assemblies, rather than on single subcontracts. The architecture and engineering research firm IBACOS is experimenting with cross-trained trades organized as the grounds team, superstructure team, envelope/enclosure team, and systems/finishes team. Ideally, this approach would reduce the performance impacts on subsystems by training the assembly teams in the relationship of their particular work to the performance of the whole house.

Many design tools currently supporting the physical integration of subsystems and subsystem components for housing are limited to CAD software with minimal object-orientation intelligence. The cost-competitive environment for housing design limits or eliminates rationalization of subsystems and interference checking necessary for physical integration. At this time there is an opportunity to take advantage of the dominance of CAD software in the design and construction communities to begin the transition toward object-oriented CAD software. Object-oriented CAD enables designers to select predefined objects (manufactured products) from menus and place them in the design. The objects bring intelligence with them. With this intelligence, a window can determine the type and thickness of the wall it has been placed in, bring the necessary framing and lintels to the drawing, update specifications, and send its performance characteristics to linked engineering software. These links enable real-time feedback to the designer on the cost, productivity, and performance impacts of a design decision.

The residential design and construction industry does not have a standard format for the data each object should carry. Development of an object-oriented resource kit for residential design and construction is a necessary step towards systems integration in housing. The use of object-oriented CAD systems is not new to the heavy industry segment of the design and construction communities. For years the designers and builders of heavy industry (chemical refineries, manufacturing) have employed interference checking, ergonomic analysis, production planning, and engineering-based analytical tools. Adapted to the unique materials, tools, and practices used in housing, similar tools could provide near-term gains in physical integration.

PERFORMANCE INTEGRATION

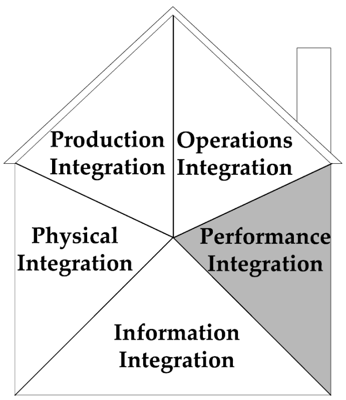

Figure 3.4: Performance integration

Performance integration—making the many parts perform as one—can be considered from within a subsystem (ductwork seals and heating, ventilating, and air conditioning [HVAC] performance) and across multiple subsystems (cooling duct, insulation, vapor barrier). Designing for performance of discrete subsystems is well matched to the current form of contracts and subcontracts (it is not difficult, for example, to hold a plumber responsible for drains not draining). But as performance expectations increase, it is necessary to coordinate the interactions of one subsystem on another. (For example, if the windows are larger on the south side and the floor mass is increased, the design can support a reduction in furnace and duct size.) Software tools such as "Energy Scheming" (Brown 1997) or "Energy 10" (National Renewable Energy Laboratory 1999) supporting this kind of "what if" method of performance increase are readily available to housing designers. But tools supporting the "what if" method generally do not consider the subsequent impact on structural members. Structural analysis tools do not consider the impact of ductwork or air conditioning on condensation or its subsequent impact on fiber saturation and so on. Each tool assumes its own discipline is at the top rung of the ladder when decision making occurs.

At the commercial scale of construction, there is a trend towards benchmarking the performance of subsystems through a process known as total building commissioning. This process involves third-party certification of performance, consumption, and maintainability, which may have a place in housing as subsystems and controls become more complex and as consumer tolerance for adjustment, rising operating costs, and frequent maintenance decreases.

Beyond the minimum levels of performance required by building regulations, there is little agreement on whole-house performance across the fragmented residential design and construction industry. Contributing factors include the following:

- minimal communication between standards groups across disciplinary lines;
- geographic variation in hazards and operating environments;
- competing values between housing producers, buyers, and government (thermal, structural and disaster performance);
- lack of agreement of singular design methodology for housing;
- absence of design tools for integrated assemblies (discrete disciplinary tools are available, but connections between structural, electrical, mechanical design are not on the market);
- lack of agreement on the criticality of spatial performance across user/owner age and physical ability grouping;
- lack of agreement on the criticality and assessment of indoor air

quality between housing producers, buyers, and government;
- lack of agreement between product manufacturers, housing producers, buyers, and government on durability and responsibility for the durability of a house.

The inability of the housing construction and research communities to rapidly document and disseminate critical (endangering life, health, investment return) interactions between subsystems, materials, climate, design, and production practices combined with higher annual production volumes increases the likelihood that a particularly low-performing combination will be implemented by a home builder. There are too many products, used in too many ways, in too many locations to continue design and production practices that assume since this new way is similar to the old way, the new way will work out fine. Broader testing protocols testing products and practices in construction assemblies in climatic conditions found in the United States are needed to help homebuilders avoid problems caused by poorly performing materials and practices.

Current Efforts at Performance Integration

Government agencies are active in promoting subsystem performance. Methods for improving indoor air quality and improving health through low-toxicity materials are being promoted through HUD's "Healthy Homes" program. Energy subsystem performance-based design is being advanced through programs such as "Energy Star" from the U.S. Environmental Protection Agency and the U.S. Department of Energy. A key tool in this program is "Energy 10," a user-friendly energy-modeling system enabling rapid evaluation of the performance of design and construction alternatives. Postdisaster publications from the Federal Emergency Management Agency actively promote performance upgrades based on the nature of the subsystem failure.

The residential construction industry is active on a number of performance fronts, with significant research on cost reduction of framing being most notable. Structural subsystem performance-based design for residential construction has roots extending from the OVE methods previously discussed to the current initiative of NAHBRC titled "Housing Affordability through Design Engineering" (HATDE), supported by HUD. Both the OVE and HATDE apply contemporary engineering principles to the structural design of the wood frame house.

Professional and scientific standards institutes are also active in the discussion of residential performance. The National Institute of Building Sciences subcommittee Building Environment and Thermal Envelope Council (BETEC) has facilitated the national and international discussion of building envelope performance and impact on air quality. Initial steps towards the development of design methods and tools for performance integration–based design are in the early stages of development with the American Society for Testing and Materials.

Home buyers represent another party that holds strong performance expectations in addition to minimums established by building regulation. Home buyers across market segments have widely varying expectations for affordability, investment return, acoustical performance, durability, maintenance, and security that need to be regularly surveyed and applied to performance integration methods.

Approaches to Performance Integration

Performance integration includes

- minimizing adverse loading of one subsystem by another,
- minimizing operating costs over the life of the loan,
- minimizing carbon dioxide contributed to the environment by the construction and operation,
- optimizing subsystems towards total house behavior rather than discrete subsystem behavior,
- protecting the indoor environmental qualities of the house (acoustic, air quality),
- protecting inhabitants during extreme service conditions, and
- facilitating the full use of the house by users with disabilities.

"Performance" definitions vary according to geographic location, market segment, and the person doing the defining. Building regulations establish minimum levels of performance for thermal, life safety, ventilation, lighting, plumbing, and structural systems. For the purposes of this study, construction performance must be considered from the following perspectives, which vary across large regions of the country:

- structural loading,
- thermal/moisture protection,
- environmental impact,
- economic return, and
- production rate—constructability.

The design or optimization hierarchy may vary not from state to state, but by markets from region to region. For example, in Minot, North Dakota, the hierarchy may be thermal/moisture protection, economic return, structural loading, production rate, and environmental impact, while on the Outer Banks of North Carolina the hierarchy may be structure, economic return, thermal/moisture protection, environmental impact, production rate. The hierarchies of which system makes concessions to which system need to be based on economic, climatic, market, labor, and disaster threats unique to each region. These performance hierarchies would be considered primary in the performance design and analysis. Additional and more localized performance perspectives may also include acoustic performance (airport or interstate locations), soil capability, and pest resistance.

A next step for the development of performance integration methods is to assemble an inventory of performance standards to identify conflicting measures and subsystems or performance measures left undefined at present. This inventory should include the following:

- building regulation performance minimums,
- home builder measures of performance across market segments,
- home buyer expectations across market segments,
- standards institutes performance measures,
- government agencies expectations for performance,
- standards for thermal loading by lighting and appliances,
- standards for thermal loading by envelope,
- standards for moisture loading by vapor/cooling ducts within structural assemblies,

- standards for moisture loading of structural assemblies,
- standards for volatile organic compounds, radon, and mold/mildew lev els in air,
- standards for acoustic levels from indoor sources,
- standards for interior acoustic intrusion from outdoor sources,
- standards for structural loading by envelope (roof vent/snow load),
- standards for structural loading by interior furnishings,
- standards for smoke and fire contribution by house components,
- standards for smoke and fire contribution by house furnishings,
- standards for accessibility.

Performance levels for the above are held at minimum levels by regulatory agencies, professional and trade associations, and code writing bodies. Minimum performance levels are usually the result of negotiations during the process of developing standards and codes and are adjusted as new knowledge is acquired and the political will of constituents brings this knowledge to bear on existing standards.

Tools commonly used in research institutions for analysis of housing subsystem behavior include sophisticated energy and structural modelers and modelers of lighting analysis, air flow, vapor transmission, ergonomics, fire, carbon debt, acoustics, security, and accessibility. Housing designers and producers commonly use structural analysis tools, occasionally use thermal analysis tools, but use other performance analysis tools infrequently, possibly due to poor interface design and the need to reenter data about the design (the software cannot pick up data from CAD drawings).

Industries such as aerospace, automotive, and chemical production commonly use virtual prototyping tools to understand the performance impacts of design and construction decisions. Virtual prototyping enables structural, environmental, extreme service, ergonomic, and accessibility analysis prior to the production of a physical prototype, saving considerable cost in both the short term (reductions in the number of prototypes constructed) and the long term (losses related to product liability). Current generations of these tools are beyond the investment possible and expertise available within the housing design and construction communities. Object-oriented CAD systems are taking the first steps towards virtual prototyping by including databases and intelligent objects as part of the system. These same systems will make sharing data with more sophisticated subsystem analysis software simpler. This advance, coupled with a user-friendly interface, could make whole-house performance analysis as cost-effective and straightforward as structural analysis is today.

PRODUCTION INTEGRATION

Production integration, conducting the many operations as one (or fewer), is relatively more advanced among the five approaches to integration (information, physical, performance, production, operations) in terms of adaptation of industrial processes. Production integration continues to be developed along four primary fronts:

- design for rapid construction,
- planning and coordination of the stages of construction through construction management principles,

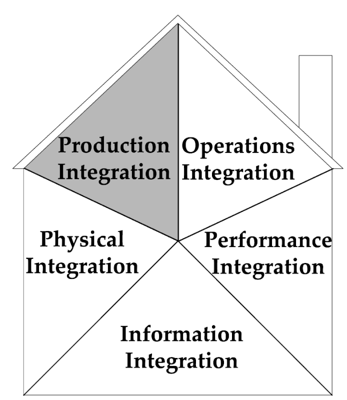

Figure 3.5: Production integration

- use of materials that incorporate the performance of many discrete parts of an assembly into one material (structural insulated panel systems, insulated and precast concrete foundation systems), and
- panelization and the use of pre-manufactured components to speed site installation.

The application of industrial product design, materials handling, project management, and production planning techniques is not a recent phenomenon in the residential construction industry. The late 1890s and early 1920s saw an explosion of "precut" house kits. Manufacturers of these kits precut, marked, and bundled materials to ensure material quality and size, minimize waste, maximize productivity, and reduce costs. The Gordon Van Tine company promoted its "ready-cut" line of houses as being able to be "dried-in" in less than seven days (Tine 1923). By 1919 the company was offering "turnkey" services in the greater Moline, Illinois, area.

As early as 1947, the designers and builders of the first Levittown development had extended a vision of the construction site as "the outdoor factory" (Hoefstra University 1994). Model house plans were designed with production efficiency in mind. Prototype construction was carefully documented using time-and-motion methods similar to those used in the automotive industry to refine the design for enhanced production rates. The production process was divided into 26 main processes, each having subsequent materials-handling and installation breakdowns. Even landscape materials were part of the industrial thinking, with layout, excavation, soil enrichment, tree delivery, soil replacement, and tree staking handled by separate crews that literally ran across Levittown completing their work. Independent subcontractors (who thought of themselves as Levitt employees) were paid on a piecework basis to encourage productivity. Supply chain obstacles were overcome by purchasing lumber mills and nail production plants. Transportation limitations were overcome by installing a railroad siding for the project, with product purchases scaled to rail-car quantities. Over the four-year build-out of Levittown, 17,447 homes were constructed and sold for as little as $7,990 ($66,300 in 1999 dollars) with a completion rate of 25 to 30 homes per day.

The major difference between the Levitt model and a large percentage of the homebuilder industry is enterprise integration. As a homebuilder, Levitt had in-house departments for land acquisition, design, engineering, construction management, finance, and legal. With subcontractors being paid on a piecework basis and seeing themselves as Levitt employees, communications, process, intent, and quality were easily managed.

Today, planning techniques such as linear scheduling enable a builder to graph ideal start and finish times for each stage of the work and use the same graph to monitor progress in each of the work units. Linear scheduling enables a builder to see problems approaching in time. The builder can either add labor and materials to address the problem or shift the ideal start/finish times for all following work units to accept the delay (Ragolia et al. 1998). When the actual graph of the progress crosses to the left of the ideal production rate line, the builder knows that action to mitigate or acceptance of the delay and rescheduling subsequent work operations is necessary.

OPERATIONS INTEGRATION

Operations integration means running the many parts as one. During performance integration of design and engineering, interactions between the static systems (envelope, structure, insulation) and dynamic systems (lighting, HVAC, power, irrigation, security) are carefully choreographed to provide the highest performance in terms of affordability and durability. The integration of information carries these design decisions—along with physical integration decisions—into the production stage, where subsystems are fabricated, assembled, and installed.

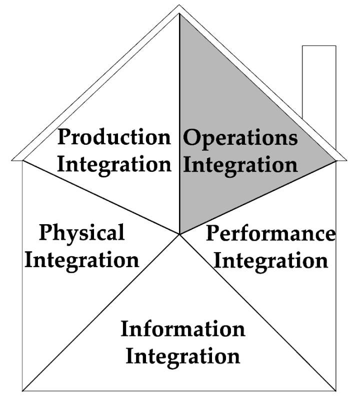

Figure 3.6: Operations integration

Traditionally, design and construction responsibilities stop when the homeowner is handed the keys and a package of manuals covering the care and maintenance of the subsystems and appliances. Some of the more comprehensive packages have maintenance schedules helping the homeowner remember to change furnace filters, purge the hot water heater, lubricate moving parts, open and close crawl space vents, change the washing machine hoses, and vacuum under the clothes dryer on a regular basis. Program settings for setback thermostats, security systems, and irrigation systems might be written on the back of the manual, should the owner be fortunate enough to be able to enter the programming mode.

Today it is possible—and expected in some higher-end market segments—to centralize the control of these subsystems. Home automation systems are becoming more affordable, easier to program, and able to alert the homeowner to complete scheduled maintenance. As home systems and appliances become more numerous, the chances are good that one active system will be operating in conflict with another (e.g., the humidifier causing condensation on window and wall surfaces). More difficult to detect at present, but more important, is the effect these active system conflicts can have on durability and air quality.

Powerline carrier–based systems, also referred to as “X-10,” dominate this growing product market. In the next year, Honeywell Corporation will introduce the “Home Controller,” a home systems operations integrator supporting telephone, home control panel, and World Wide Web interfaces enabling control of appliances, HVAC, telephone, lighting, and security systems. The Home Controller will use electrical wiring as the network backbone, “piggybacking” signals over the electrical current to control devices. This system will also be compatible with Ethernet and CEbus protocols. The system is sold through home improvement centers and computer stores across the United Kingdom. The Home Control system featured in the “future homes” project in Glasgow, Scotland, enables homeowners to remotely control lighting, appliances, and heating and cooling on a timer from a handheld remote or from a home computer. The system is modular, enabling homeowners to upgrade the number of devices controlled or the mode of control as their need and budget allow.

Next steps for these operations integrators will be the development of a whole-house sensor network able to monitor conditions within walls, in attics, and at critical structural connections. This capability will speed assessment of the condition of the structure and insulation and detect environmental conditions within wall/floor/roof assemblies that enhance the development of molds, mildew, fungi, bacteria, and insect pests. Off-the-shelf technologies are currently available to perform many of these functions, but like the operations integrator itself, the cost exceeds perceptions of value in most market segments.

The operations integrator would also include information collected from the production stage on quantities and composition of materials, key subsystem construction, and floor plans, highlighting locations of materials and products which are particularly hazardous or explosive during a fire, post-disaster search and rescue, and recycling of the house and debris at the end of the service life. Properly configured with existing lighting control systems, the operations integrator could also report last known location of occupants to fire or search and rescue personnel.

SYSTEMS INTEGRATION AND HOME BUILDING: CURRENT TECHNOLOGIES

Componentization

Perhaps the most rapidly diffused innovation produced by Operation Breakthrough were roof truss components. These pre-engineered components entered the housing market in the late 1960s and by the middle 1970s were the dominant method for framing gable roofs for single- and multifamily construction. As an engineered truss, these components offered designers longer unsupported spans and offered builders significant timesavings in roof framing and greater dimensional accuracy. The only change to homeowners came in the loss of the attic as a storage and potential expansion space. This disadvantage did not impact the use of roof truss components, as many homebuyers were moving up from a "starter" house. These postwar starter houses frequently were one-story, slab-on-grade construction with a lower roof slope (4:12), which did not offer the storage and expansion possibility, so the builders' switch to trusses and resulting loss of attic space did not impact the market in a negative way.

The component industry began responding to the market's call for greater flexibility in roof and ceiling design by offering trusses with small useable attic spaces carved into them, cathedral ceilings, and steeper roof slopes made possible with stacked or piggyback trusses. Due to longer span possibilities and reduced labor costs for routing plumbing and electrical systems, floor trusses are becoming more common in residential construction, including those specially designed to accept ductwork.

Both floor and roof trusses depend on relatively precise field placement of walls and beams for proper bearing. Based on letters and articles in *Woodwords*, the trade journal of the Wood Truss Council of America (WTCA), the cutting of wood trusses on site to accommodate changes in ceiling, plumbing, or mechanical system is an ongoing concern (Hoover 1999). As these plate trusses become more common, plumbers, electricians, and mechanical contractors become more familiar with what can and cannot be cut or drilled. When field modifications are made to the top, bottom, or intermediate chords of the truss, the truss needs to be reengineered, often by the manufacturer of the metal plate connectors, to be certain the repair will perform as well as unmodified trusses (Hutchins 2000).

Failures of the plate truss components are few and are often related to improper field handling, placing, or bracing of the trusses. The industry is concentrating quality improvement efforts on in-plant quality training and on-site training of labor for proper placement and bracing.

Panelization

Panelization is currently practiced as the assembly of rough framing pieces (plates, studs, sheathing) into 8- to 16-foot-long wall panels in factory settings, shipped to the site, and erected. Plumbing, wiring, insulating, and finishing still take place on site. This method enables assembly to be conducted in dry settings, by trained labor, with regular quality control checks.

Construction of wall panels in factory settings is increasing due to challenges of securing enough qualified on-site labor, rising tipping fees for construction scrap, and competitive forces in the production housing market. Some production builders have tied the purchase of wall panels to the purchase of floor and roof trusses, requiring component manufacturers to begin production of wall panels to keep supplying floor and roof trusses (Edwards 1999). Additionally, complete home packages consisting of wall panels and roof and floor trusses are available from major home improvement retailers.

When comparing panelization to on-site framing of walls, the WTCA found that lumber quantity requirements were comparable, but that panelization achieved a 60 percent reduction in time for the framing crew (Wood Truss Council of America 1996). The framing experiment "Framing the American Dream" was conducted at the 1996 National Association of Home Builders convention site. It involved side-by-side construction of stick-built framing (joists, studs, rafters, with plywood and oriented strand board [OSB] sheathing) and component framing (wall panels, floor and roof trusses, with plywood and OSB sheathing) of identical 2,600-square-foot house plans. The results showed the following advantages of using components rather than stick framing:

- savings of 253 man-hours ($4,560 in 1996 dollars)
- savings of 5,300 board feet of lumber ($1,529)
- reduction of construction scrap from 17 to 4 cubic yards (Waste generation related to the construction of wall panels and floor and roof trusses is handled at the component fabrication plant, where small scraps can be used in other components or as fuel for the plant.)
- cost savings of $3,356 (1996$) on labor, material, and tipping fees

Floor and roof truss framing also speeds installation of electrical, plumbing, and ductwork systems, offering additional savings.

PLANNING AND COORDINATION OF CONSTRUCTION THROUGH CONSTRUCTION MANAGEMENT PRINCIPLES

Managing process versus managing production

In the William Jamerson Professor lecture in Blacksburg, Virginia on December 1,1999, Dr. Ron Wakefield noted that the diffusion of construction management methods and software has led some construction managers to focus on managing the process, and not the production (Beliveau and Wakefield 1999), the difference residing primarily in the dialogue that occurs between field crews and designers. In production management, difficulties in assembling the product are fed back to product and process designers to improve the manufacture of the next product. Process management focuses on meeting timelines through additional labor or incentives, but with little information about construction difficulties fed back to the product/process designers.

Home builders producing large numbers of a single model often invest additional time in the first few models produced to "iron out" conflicts in the complex interrelationships between the many stages of construction, material handling, the design, and production time.

Time- and space-based (linear) scheduling

The traditional bar graph is no longer able to address these complex interrelationships between stages of construction, crew locations, materials handling, and construction progress (Ragolia et al. 1998). Sequencing of starting dates and completion dates for each stage of the work is especially critical in housing production, as the physical spaces being constructed constrict the number of crews able to work in one space simultaneously. Time- and space-based scheduling adds a layer of "where" information to the "who," "what," and "when" information from the bar chart, while retaining the logic of a critical path–sequencing diagram. A decision on the fundamental unit of space becomes the vertical increment of the time and space schedule. This may be a whole house in a larger development or an individual apartment in a multifamily project.

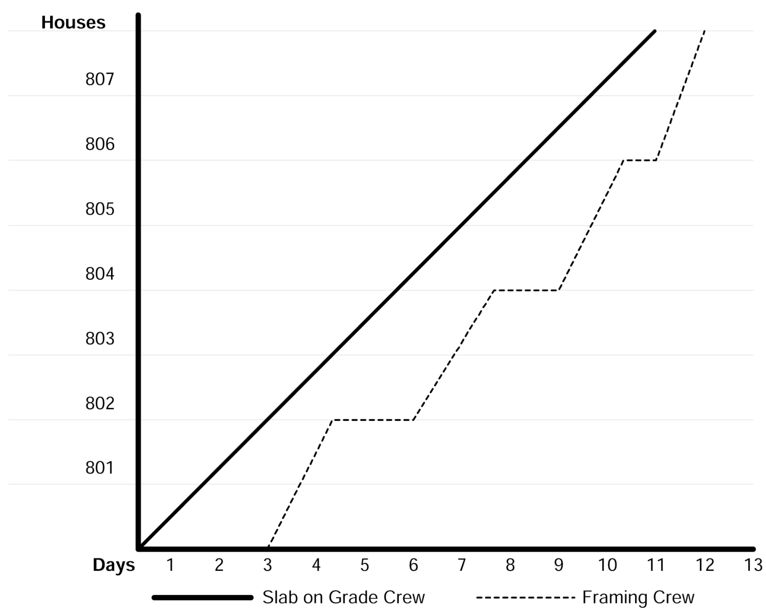

Figure 3.7: Linear scheduling graph of ideal production rate, actual start, and finish dates for framing.

The fundamental principle is that the project manager allocates specific spaces to construction crews in a closely organized sequence along a time line (see Figure 3.6). In this example, the slab-on-grade crew is moving continuously from house #801 to house #815. By day 4, the slab at house #803 is complete. To allow the slab two days to cure, the framing crew does not begin erecting wall panels at house 803 until day 6. The construction manager assigns the degree of continuity or discontinuity of work for each task based on the overall goals for the construction (optimize time, labor, equipment, etc.) and production rates. Time- and space-scheduling supports JIT strategies for material purchases and handling (50 sheets of drywall delivered to a specific house on a specific day), minimizing weather-related material damage, pilfering, and allocation of additional site labor to moving materials multiple times.

This visual integration of information provides a construction manager the ability to schedule and monitor construction activities with greater detail, decreasing space and time conflicts between crews, increasing safety, and increasing production as a whole.

USE OF MATERIALS INCORPORATING THE PERFORMANCE OF MANY DISCRETE PARTS INTO ONE MATERIAL

Structural insulated panel systems

Another strategy for integrating discrete construction and fabrication processes is the replacement of multiple materials with a single product performing the same duties. An example would be a light wood-framed exterior wall assembly (OSB, studs, plates, insulation, gypsum board) being replaced by structural insulated panel (SIP) systems. SIPs are manufactured with structural panel products (OSB, plywood) on one or two faces, with foam plastic insulation bonded to the structural panels. When installed, the two panels are joined along their sides with a variety of spline details (which vary from manufacturer to manufacturer). The bonding process (and subsequent structural capacity) of the foam-plastic insulation also varies among manufacturers. Some manually apply adhesive to preformed foam-plastic sheets, then press the structural panels onto the adhesive; others extrude the foam-plastic insulation in place between the structural panels. Both thermal and structural performance varies according to type of foam plastic (expanded polystyrene [EPS], extruded polystyrene, and polyisocyanurate). Costs and thermal "R" values are less per inch of SIP thickness with EPS and more with polyisocyanurate.

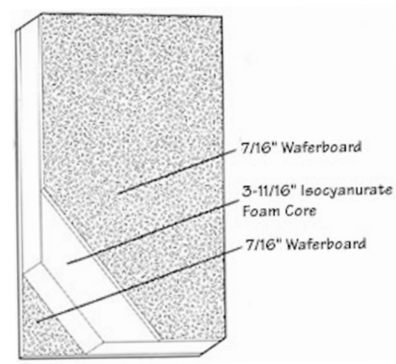

Figure 3.8: Structural insulated panel
Source: Winter Panel Corporation

The SIP primarily reduces on-site labor. Capitalizing the costs of engineering, testing, labor, machinery, marketing, and approvals makes these products slightly more expensive than the on-site fabrication of the discrete pieces. At this time, SIPs represent a small but growing market and are used as both primary structure for houses and as cladding for heavy, timber-framed houses. As on-site costs for labor and materials rise and start-up costs for the SIP industry are amortized, these panels should make steady gains in market share. Recent SIP technological advances include integration of raceway within the foam-plastic core for routing electrical wiring and the development of cam locks between panels to address difficulty in aligning panel splines along the sides of the SIP.

Insulating concrete form systems

Another construction system that assembles functions normally fabricated by a number of discrete pieces and processes into a more simplified process is the insulating concrete form (ICF) system. This system combines the formwork (traditionally constructed of two faces, a steel tie, steel reinforcing, vertical and horizontal ribbing, external bracing), internal insulation, plates, and studs to attach finish materials into one process.

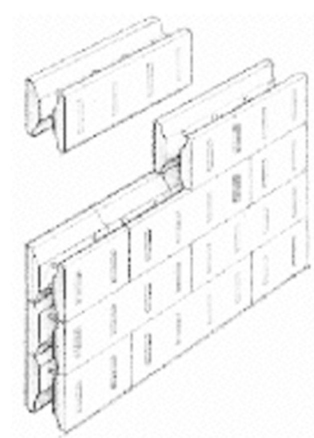

Figure 3.9: Insulated concrete form
Source: Winter Panel Corporation

ICFs have emerged as a construction method addressing thermal performance, shortages of skilled labor, and reduction of construction time. There are over 40 different manufacturers of ICFs (Engel 1999). ICFs can make three different types of reinforced concrete wall: the flat wall, similar to reinforced-concrete walls formed between the faces of wood or metal forms; the grid wall, with vertical and horizontal chambers of reinforced concrete evenly distributed across the foundation; and the post-and-beam wall, having more vertical and fewer reinforced horizontal beams. The post-and-beam wall is used primarily above grade. The ICF itself is made of expanded or extruded polystyrene foam insulation for the most part, with some manufacturers offering cement composite, wood, and plastic ICFs. The forms are shipped as blocks, planks, or panel forms, all requiring some form of exterior bracing during the pouring process.

Problems arising from the use of ICFs are mostly related to layout, aggressive vibration, or inadequate bracing contributing to form shifting and blowouts during concrete placing. Blowouts typically result from use of high-slump concrete or improper placement. Questions about the ability of insect pests to utilize the foam as an easy passage to the wood framing above have led manufacturers to require the foam face above grade to be removed after concrete curing to interrupt a termite or carpenter ant path through the foam. These inspection strips provide homeowners and inspectors the ability to observe termite tubes and paths forming on the inspection strip and take appropriate remedial action (NAHBRC 1997).

Precast foundation systems

With excavation and foundation costs making up 9–12 percent of total construction costs, foundation systems have been closely examined for their potential to contribute to increased affordability. Within the strategy of industrialized systems, which have fewer parts and processes required for installation (simplifying construction), manufacturers of precast concrete products have introduced precast foundation panel products into the residential construction market.

Unlike the simple slab type of precast concrete panels commonly seen on commercial construction sites, these foundation systems make every effort to minimize the amount of concrete in the panel. This efficiency is most often achieved by using more complex formwork to produce a ribbed panel. The resulting elimination of material between the ribbing leaves a stiff panel assembly with lower material costs, but more importantly, a panel of lower weight. The weight reduction enables more panels to be shipped per truck, and consequently fewer trips per home site.

These panels combine the functions of the foundation wall, are preinsulated with EPS foam plastic, have built-in places for electrical wiring, and have integral nailing surfaces for attaching interior finishes. The use of EPS is limited to the interior surface of the panel. This configuration, combined with solid concrete surfaces where the panel attaches to the footing below and wood framing above, minimizes the paths for insect pests from the ground to the wood framing. Being a closed-cell foam, EPS holds minimal moisture and does not appear to develop mold and mildew.

The solid surface of concrete at the base of the panel works with steel connectors between panels to make a rigid concrete wall, eliminating the need for a separate, poured footing and foundation in most soil conditions. High-performance urethane sealant is specified at joints between panels. Combined with the large panel sizes (up to 18 feet long and 8 feet tall), this sealant provides a foundation wall with fewer through joints than a standard masonry block wall and thus higher moisture resistance.

Single truck shipments carry up to 155 linear feet of foundation wall, which is erected on a screeded, compacted, crushed-stone base. Installation includes the preparation, compaction, and leveling of the base (usually one working day) and erection of the panels (usually one-half working day for a building with a simple footprint).

CONCLUSIONS

Each condition of integration requires a complex understanding of residential subsystems, components, behavior, and relationships to the whole house. As housing construction has become more complex and as the production and operation of the house have become more complex, the ability for one person to maintain command of the interrelationships between subsystems has greatly diminished.

A carefully developed data structure and data path—beginning at the design concept and following the house development through analysis, construction, operation, and finally recycling—seems the most likely tool to underpin each condition of integration. This first step, information integration, will be the key enabler to the four other conditions of integration. The next chapter discusses implementation strategies for information integration. From this base, we can develop a prioritized plan for industrialization of the home building industry.

4

Chapter Four: Potential Technologies for Industrialization in the Current Home Building Industry: An Assessment

The industrialization of residential construction requires major strides forward in information management, production processes, organization of production, and use of new materials and technologies. If the housing industry is to make a reasonably rapid transition from its current, craft-based production system to an industrialized production system, participants in the industry need to better understand the relationships among information, labor, resources, and production. This chapter develops strategies for integration and industrialization of the home building industry.

Information integration appears to provide the key to the technological, methodological, and management issues in the industrialization of the home building industry. Information integration is deeply rooted in the four other types of integration discussed in chapter three. To highlight the importance of information integration, this chapter develops overall information schema for bringing integration and industrialization to the residential construction industry. In addition, this chapter develops both an implementation path and plan based upon information integration and management.

Acknowledging that the home building industry is diverse and that strategies for one sector may be inappropriate for other sectors, this chapter continues by classifying the residential construction industry into four different sectors. These sectors aid in not only the discussion of integration and industrialization but also the development of implementation strategies and priorities throughout the chapter.

Strategies for integration and industrialization in the home building industry are needed to make a transition away from current, craft-based production.

AN OVERALL SCHEMA FOR INDUSTRIALIZATION

To create a complete industry model, the overall schema for the residential construction industry must be studied historically. One approach to this task is to focus on improving the performance of the residential construction industry as a whole by developing a cohesive, integrated information system spanning housing design, production, and operation. This seamless flow of information at, to, and from the construction site has been identified in early research as an initial obstacle preventing the industrialization of the residential construction industry. In the end, seamless and integrated information flow will enable change in the current, craft-based concept of housing from an unplanned mixture of components to an “integrated housing system.” The integrated system approach will yield a

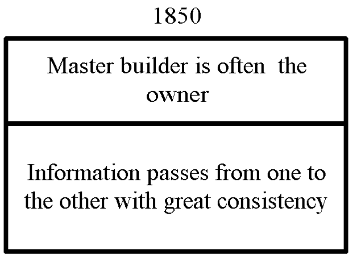

Figure 4.1: Typical information exchange for residential construction in 1850.

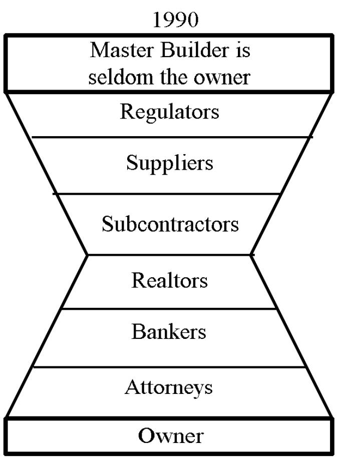

Figure 4.2: Information exchange within the current residential construction industry.

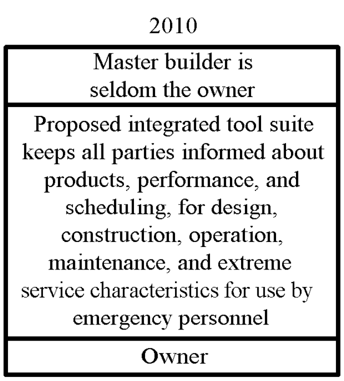

Figure 4.3: Integrated system for information exchange proposed for the residential construction industry.

higher-quality, more cost-effective housing product that, in turn, will increase end-user satisfaction.

Origins of Proposed Concept

The concept of integrated information management is not a new one to the residential construction industry. In 1850, housing design and construction fell within the sole domain of the master builder. Communication between the builder and the owner was as clear as could be between two adults (see Figure 4.1). The model, as illustrated, enabled full information and technology communication to be contained within the house concept of the master builder, and the house performance was considered from the builder's holistic standpoint.

Today, the information exchange model for residential construction often results in the isolation of information within each technical trade or technology involved in the building process, resulting in compartmentalized components and subsystems being optimized without regard to the effects on the overall performance of the house. Conflicts among technologies, subcontractors, and subsystems are inherent to the final product. Figure 4.2 illustrates the current system for information exchange within the residential construction industry.

The proposed model, which helps to create an environment favorable to industrialization of the residential construction industry, returns to a holistic design philosophy. The proposed system is similar to that of the master builder, but with a memory equal to the computing power of the computer server handling the data warehouse. Design, construction, and training tools developed to enable this change will provide a medium for seamless information exchange in a real-time, collaborative environment. This medium would enable the various parties involved in the design, construction, and eventual decommissioning of a house to work together in improving overall quality and end-user satisfaction. These improvements will come via reducing waste, eliminating interference problems and incompatibilities between various subsystems in the building, providing guidance on ramifications of design/construction decisions, reducing the need for a highly specialized and skilled labor force, providing better more usable information to the construction labor force and streamlining the regulatory approval process. These tools will also improve the conceptualization communication among owners, designers, functionality of the home meet all expectations. Figure 4.3 is a proposed diagram of this integrated system.

The proposed model for housing design/construction is an enterprise wide model that considers the multiple issues associated with housing from conceptualization to decommissioning, including the costs associated with all phases of the building's life. Essentially, this model of information flow and integrated tool suite would enable an accurate optimization of the holistic performance of housing from a life cycle cost analysis. These parameters are a significant expansion of those typically associated with optimization of housing design, but they are all included in the costs associated with home ownership. Since the end result of this effort is to provide the homeowner with a better-built, better-performing house at a lower overall cost, all of these pertinent factors should be considered in the work towards industrialization of the residential construction industry as a whole. Figure 4.4 is a graphical version of this systematic, all-inclusive design concept.

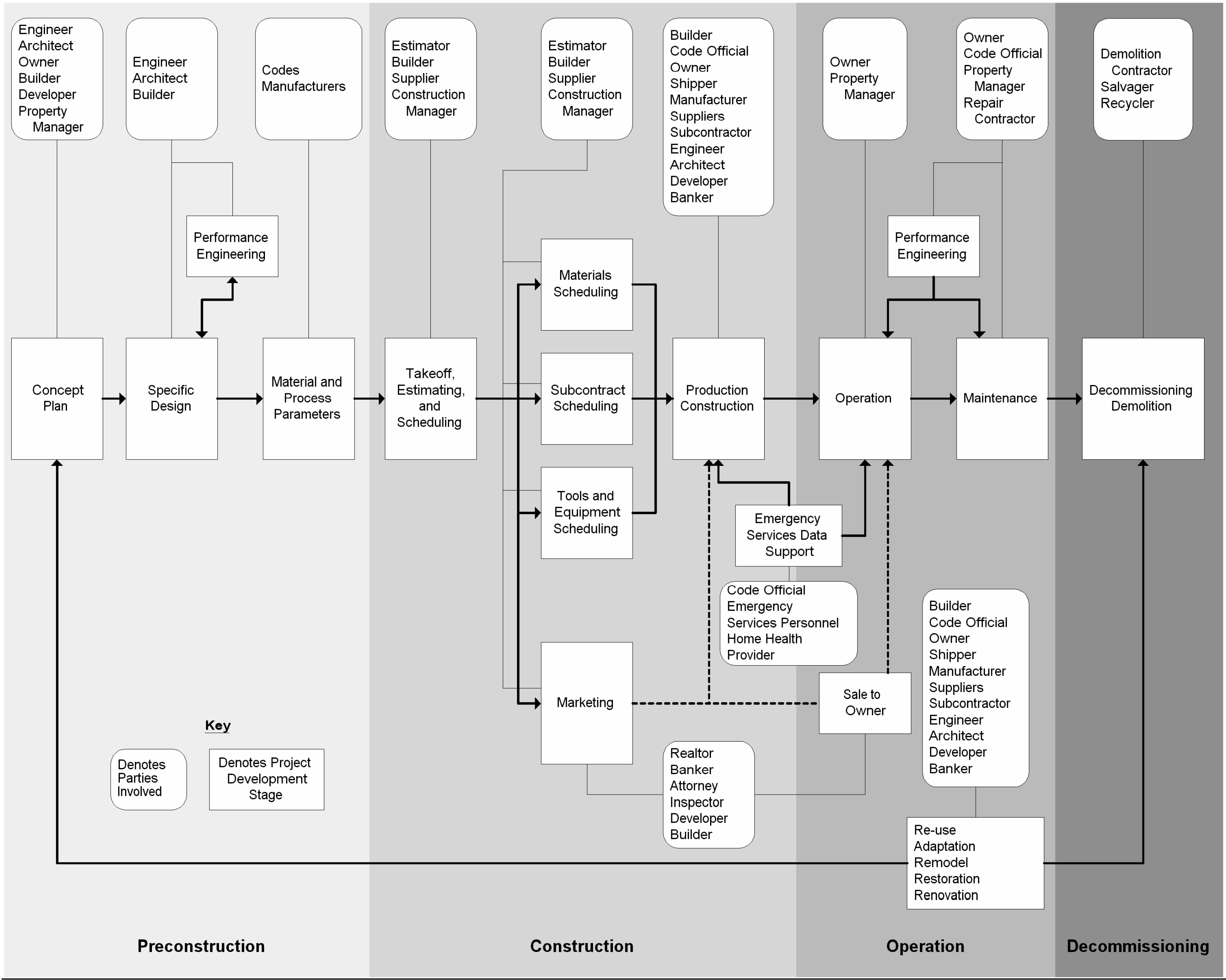

Figure 4.4: Proposed overall design schema.

APPLYING INFORMATION INTEGRATION IN THE CURRENT HOME BUILDING INDUSTRY

The home building industry is far from homogenous. The industry is made up of numerous sectors and markets and the majority of product is built by small volume craft-based builders. Each sector has different structures, different access to capital and capital equipment and different supply chains. Universal implementation of any information integration strategy is likely to be problematic unless the strategy is designed appropriately for the industry sectors in question. For this reason, we divide homebuilders into four groups:

- small-volume residential builders—building fewer than 20 homes per year;
- medium-volume builders—building up to several hundred homes per year in regional markets;
- high-volume builders—building more than 1000 homes per year, utilizing on-site construction methods, with a regional or national presence; and
- production builders—using off-site fabrication including modular, manu-factured (HUD code), and factory-based panelizers, undertaking the majority of their work in a factory environment, and delivering consolidated materials to sites in fewer than 10 deliveries from a single factory.

This grouping will be used in the following sections to develop strategies and priorities that are applicable to each sector of the industry.

Implementation Paths and Plans

The implementation of integration and industrialization in the home building industry rests on the understanding of information flows and usage throughout each of the previously identified home building industry sectors. The first step in developing this understanding is to undertake an information mapping study for each sector of the industry.

Information Mapping and Analysis: The First Step

Information mapping of the industry is an essential first step in implementing an integrated approach to information management in the home building industry. The mapping process needs to look at how information is generated and used in the home building industry sectors. Information use by current industry participants (e.g. customers, designers, builders, subcontractors, subsystem suppliers, materials suppliers, financial institutions, and regulatory authorities) needs to be mapped and understood. This mapping will determine information requirements of current industry participants and currently used construction methods. A comprehensive information model for each industry sector can then be developed that will provide the information requirements for implementation of integration and industrialization strategies.

Small-Volume Home Builders: Appropriate Technologies And Implementation Priorities

Small-volume homebuilders make up a large and important sector of the residential construction industry. The fact that these builders have limited operating finance and capital support represents a considerable challenge for this sector, as many of the integration and industrialization technologies require capital investment that is likely to be beyond their capacity. These builders also lack the supply chain influence that can force a change in the way the industry currently operates. As one of many small customers of large suppliers, small-volume homebuilders often deal with intermediate distributors of building products. For this reason, the adoption of industrial technologies in this sector is likely to be driven by either large suppliers, intermediate distributors, or agents who have an interest in selling product to builders and consumers.

The small-volume builder personally performs the information management of the building task. For example, the builder himself orders materials; schedules subcontractors; supervises the workforce; arranges permits and inspections; and deals with design issues, home purchasers, financing, and accounting. Managing this complex information web is a difficult and nontrivial task. In addition, the manual systems used by small-volume homebuilders perpetuate the fragmented, craft-based approach in this industry sector. The manual systems can also limit productivity and profitability.

Industrialization of this sector could be led by a builders' supply group that provides builders with an integrated information management package that enables input of the design using an object-oriented CAD system and provides for input of the construction schedule. The schedule-linked, object-oriented CAD model would enable the builder to specify the delivery dates of the components to be used in the building. The information management package would then link with the supplier using the World Wide Web or wireless technology and schedule the required materials, subcontractors, payments, and inspections for the construction of the house. Componentization and modularization have made inroads into this sector of the industry with the use roof trusses, wall panels, structural insulated panels (SIPs), windows, and doors, but ordering and delivering are essentially manual processes, as is scheduling of subcontractors and inspectors. A CAD based information system will provide opportunities for further physical and production integration in this sector.

This system would provide for increased predictability and decreased variation in the supply chain. This first stage of industrialization is not as difficult a step as it may seem. Many intermediate distributors and hardware suppliers already use software-based systems supplied by component manufacturers to order kitchen cabinets, doors, and panelized frame components. In addition, the suppliers schedule deliveries of component subsystems using the same systems. This first stage of implementation of an integrated information system requires various systems to be brought together and placed in the hands of the builder. The information management system in this case would enable further parts of the home builder's operation to be industrialized as the system is adopted. For example, increased componentization and modularization would be possible if orders were placed earlier with suppliers. There would also be increased impetus for integration of systems in this case.

It should be emphasized that for industrialization to occur in this sector of the building industry, the capital investment must be provided by some party or coalition other than the builder.

Implementation Priorities for Small-Volume Builders:

- Development of ordering scheduling and site production systems to help reduce fragmentation in this sector

- Introduction of object oriented CAD systems as a linkage between customer orders, suppliers, materials purchasers, subcontractors, payments and inspections, as a stepping stone to physical integration and production integration

Medium-Volume Homebuilders: Appropriate Technologies and Implementation Priorities

Medium-volume builders are generally in a better position than smaller-volume builders to respond to the challenges of industrialization. They generally have access to larger financial resources and can make capital investment in equipment, systems, and training. Medium-volume builders are also likely to have supply chain influence, especially if they are a large regional player. For this reason, it is not uncommon to find builders in this market sector encouraging their suppliers of framing materials to make the step towards providing complete panelized sections of the home rather than individual framing members. This is an initial step in industrialization. Builders in this sector are also likely to have in place a company-wide accounting and procurement system that is familiar to company personnel. This will ease the implementation of an information management tool because people in the organization are familiar with systemized approaches to information management. The challenge in this sector of the industry is to broaden information integration from accounting and cost control to include pre-construction and construction activities.

Integrated providers of information systems, which are now offering linked accounting and procurement systems in a Web-based format, may serve information management needs for this sector of industry. The missing link in these systems is the design, production simulation modeling, and field construction information tools necessary to form an enterprise resource planning (ERP) tool for the builder.

Implementation Priorities for Medium-Volume Builders:

- Introduction of object oriented CAD systems linked to existing purchasing and accounting systems to provide integrated information ERP for customers, suppliers, materials purchasers, subcontrators, payments and inspections. This is a stepping stone to physical integration and production integration

- Use of supply chain influence and ERP to move to Just-In-Time (JIT) operation

- Develop integrated information systems for, resource management, scheduling and construction progress reporting

- Develop tools for field staff for onsite use of the information systems

- Access production modeling and simulation systems for further refinement of existing field processes and development and analysis of new processes.

High-Volume Home Builders: Appropriate Technologies And Implementation Priorities

There are a significant number of national high-volume builders who use predominately on-site construction methods while also utilizing industrialized techniques such as panelization in the form of roof trusses, panelized stud walls, and SIPs. These builders have a significant national presence and considerable supply chain influence, which they use to leverage prices for raw materials and components via long-term, national supply contracts. In general, they have sophisticated information management systems at both the national and regional levels that are used to manage finance, procurement, sales, and marketing.

It is unusual for the sophisticated information management system to extend to the site construction of the house. In fact, in many respects the site construction methods used in this sector do not differ substantially from those used by the medium-volume builder. The scheduling, ordering, and production scheduling are done by a field superintendent, who is responsible for the construction of 10–20 houses. While CAD systems are used in the design, very little use is made of the potentially available embedded information in scheduling, ordering, and supervision phases of the work.

In this production system, the site superintendent can be seen as a missing link in the information chain. Feedback to and from the field is a significant obstacle to further industrialization of the process. An information management tool for superintendents would not only highlight bottlenecks in the process by providing updated schedule information to suppliers, subcontractors, and inspectors but also provide production information to regional offices for sales, ordering, and production planning. The field information would be linked back to the head office for schedule updating as well as cost and financial information. It is anticipated that making this final link in the information chain will have considerable effect on the implementation of other industrial technologies. Once good production information is collected and analyzed, builders will have the opportunity to analyze the field production process similar to other industrialized manufacturers. This analysis is likely to lead to the development of new assembly procedures, use of new materials, and production processes that in turn should yield the long-sought-after benefits of industrialization to the residential construction industry.

Implementation Priorities for High-Volume Builders:

- Extend current use of CAD to embed resource management, scheduling, ordering, and supervision information and link to existing purchasing and accounting systems to provide integrated information ERP for customers, suppliers, materials purchasers, subcontractors, payments and inspections. This is a stepping stone to physical integration, production integration, and operations integration

- Develop tools for superintendents, subcontractors, and other field staff to enable onsite use and appropriate updating of the integrated information (ERP) system data.

- Use design for manufacture (DFMA) and other production modeling, analysis and simulation systems for further refinement of existing field processes

- Develop advanced production methods using new systems and materials

Production Home Builders: Appropriate Technologies And Implementation Priorities

By their very nature, production homebuilders tend to use industrialized production methods in construction of houses or house modules. The builders' off-site factories use assembly-line construction processes with multiple workstations. However, much of the information handling in these organizations is manual. For example, change orders are often processed manually for each house. Exchange of information in the production process uses paper drawings and lists, and very little use is made of numerically controlled production equipment.

Production builders tend to have considerable influence on their supply chain, and several of the production builders visited as part of this study make use of just-in-time (JIT) manufacturing with little inventory of major components held at the plant at any time. These operations are very sophisticated in terms of inventory management, and several of the production builders use materials requirements planning (MRP) systems within the factory environment.

What is surprising about this sector of the industry is that the actual construction methods used in both modular and manufactured housing appear to differ little from those used in site-built construction. Construction is still typically of wood, with some panelization of floor, wall, and roof systems and prefabrication of some home components. It appears that the application of the industrial technique known as "design for assembly" and the increased use of currently available new materials could yield substantial improvements in this sector of the industry.

The sector should consider applying integrated information management throughout the entire design and construction process. This integrated system would include initial design and planning, receipt of orders (including special and change orders), the production process, and delivery of the final product to the site. Establishing such an information chain would enable the enterprise to plan and schedule the resources for production. It would also enable suppliers to look into the information system to move all component supply to a JIT delivery method throughout the production system. This change would result in a reduction of many associated inventory costs.

Implementation Priorities for Production Home Builders

- Extend current use of MRP for factory production to ERP for the whole house production from order to closing. Use the ERP for interaction with customers, suppliers, materials purchasers, factory workers, subcontrac-tors, payments, building code approvals and code officials' inspections.

- Develop tools for superintendents, subcontractors, and other field staff to enable onsite use and appropriate updating of the integrated informa-tion (ERP) system data.

- Implement design for manufacture (DFMA) and other production model-ing and simulation systems for further refinement of existing manufac-turing and field processes

- Develop advanced production methods using new systems and materials

CONCLUSIONS

Information integration provides the key to the industrialization of the home building industry. This chapter develops an overall information schema for integration and industrialization. Four sectors are identified within the housing industry to enable a comprehensive plan for implementation for industrialization and integration to be developed. The first step in implementation requires the mapping and analysis of information flows through the four identified sectors of the home building industry. The results of the information mapping will provide a basis for proceeding to the next stages of integration and industrialization within each sector.

The industrialization of residential construction requires the industry to implement information management, new production processes, better organization of production, and use of new materials and technologies. The characteristics of each industry sector with respect to supply chain influence, currently utilized technologies, information management, and building methods require sector specific implementation plans and priorities for implementation. Implementation of these plans will begin to move the housing industry from its current, craft-based production system to an industrialized production system, resulting in improvements in productivity, efficiency, and quality.

5

Chapter Five: Concluding Remarks on Industrializing the Residential Construction Site

This report examines the means and methods available for integrating and industrializing the housing construction site and industry. Chapter 2 reviews current and past U.S. efforts in industrialization of housing including Building America, PATH, and Operation Breakthrough. International efforts in this area are also discussed. Chapter 2 identifies means and methods of industrialization that have been useful to other industries, mainly in the manufacturing sector, to move to a higher level of industrialization. The techniques identified as most promising are: resource and material planning systems known as enterprise resource planning systems (ERP), object oriented CAD, Just-in-Time supply, design for manufacture and assembly (DFMA), and other prototyping and analysis tools.

Chapter 3 looks at systems integration as an essential element in industrialization. Five types of integrations are identified: information, physical, production, performance, and operation integration. Information integration is identified as the key enabler of the other integrations in the goal of holistic systems integration. Attention to information integration will ensure the availability of key information for all elements of the enterprise. Production integration will result from information integration as participants in the industry become aware of improvements that can be made in componentization and modularization.

The key to industrializing the construction site is to have appropriate information available to each participant.

Chapter 4 sets out plans for bringing integration and industrialization to the home building industry. It begins by developing a strategy for information integration across the industry which is seen as the first essential step in the process. Subsequent plans for implementation are developed as a sector-by-sector basis for the industry. Plans are presented that are appropriate to the degree of capitalization and resources available in each sector. The degree of industrialization already present in each sector was also taken into account in the development of each sector plan.

The plans outlined in this report, when implemented, will begin moving the home building industry from its current fragmented craft-based approach to an industrialized integrated and productive industry. The plans generally use existing technology either already available in other sectors of the construction industry or the manufacturing industry to bring about industrialization. It is envisaged that implementation of the plans will deliver to the industry a platform from which to develop new materials and processes for housing construction. The key to industrializing the industry is to have appropriate information available to each participant. This requires not only collection and capture of the information, but also efficient filtering and representation so that the information is available and accessible. The ability to identify problems and areas from improvement delivered by the information integration will not only help eliminate fragmentation in the construction process but has the potential to deliver a new view of housing performance and operation. Designers will be able to develop design and analysis tools that give comprehensive consideration to life cycle performance issues, in-house design, as well as production performance.

The plans outlined in this report represent a first step in moving the residential construction industry forward using integration industrialized systems to deliver an affordable product with improved performance and operation.

Appendix A: Supply Chain Management Case Examples

SUPPLY CHAIN MANAGEMENT IN THE TEXTILE INDUSTRY

One of the obstacles to supply chain management is enabling different parties to speak the same language. The apparel manufacturing industry has virtually overcome this communication problem. The Textile Apparel Linkage Council (TALC) was formed in May of 1986. Its objectives were to develop industry standards for both the apparel and textile industries. TALC's efforts were widely accepted by virtually all members of the American Textile Manufactures Institute (ATMI) and the American Apparel Manufacturers Association (AAMA) (Hunter 1990). In fact, TALC helped institute several key electronic data interchange (EDI) standards in it first two years of operation. The following is an adapted list from Hunter's (1990) work.

- *EDI Format.* TALC has endorsed the use of ANSI X12 standard formats. ANSI X12 are the American National Standards Institute's standard for the electronic transmission of data for such business transactions as purchase orders and invoices. The communication link between trading partners may take the form either of a direct connection between their computers or via a third party networking service.

- *Roll Identification.* Each roll of fabric shipped by the textile producer will be uniquely identified by means of a 15-character identifier, consisting of a 6-digit producer number followed by a 9-digit alphanumeric produce assigned number. The roll identification number is to be represented in both human and Universal Product Code (UPC) bar code readable forms on a hang tag or pressure sensitive label accompanying the roll. A recommendation has also been approved for the layout of the information on the ticket.

- *Width/Length Measurement.* By obtaining accurate dimensional information in standard form, the apparel manufacturer is in a position to reduce costs and improve efficiency through better fabric utilization, elimination of duplicated measurements, and speeding up the marker making and cutting processes. The standards call for widths to be expressed in ¼" increments, rounded down; the length is to be given in 0.1 yard increments.

- *Shade Measurements.* To eliminate duplicate measurements of fabric shade, the standard calls for each roll to be identified with either delta values or the 5-5-5 shade-sorting convention agreed to by the trading partners.

- *Identification and Flagging of Fabric Defects.* Based upon buyer/seller agreement, defects to be flagged by the producer have been established for four categories: Critical, Denim, Standard, and No Flagging Required. The principal method for flagging defects for automated detection is the use of metallic stick-on devices, but several textile companies are using more sophisticated mappings of defects that record the distance of the fault from the edge of the fabric.

- *Order Status.* The items of information necessary for the seller/buyer interfaces on delivery data relative to order status are provided by this standard. Communications on delivery non-conformance are also being reviewed.

In addition to the items developed by the TALC effort, the committee is also involved in product forecasting. "A committee is examining ways to define the items of information and their timing, to be transmitted by manufacturers to textile supporters projecting future demand. This is a subject of great importance to the textile producer because of long lead times associated with fabric manufacture (Hunter 1990, pg. 71)."

SUPPLY CHAIN MANAGEMENT IN PRODUCT DISTRIBUTION NETWORKS

Examining a supply chain management solution more closely related to the residential construction industry would be the Hardware Wholesalers Inc. case study presented at the 1997 Washington, DC APICS convention (Palevich 1997). Hardware Wholesalers Inc. (HWI) is a distributor of hardware products, building materials, and lumber. With over a 62,000 items stocking list, HWI has combined supply chain management with logistics to create a partnership with their business affiliates. HWI strives to bring distribution, manufacturing, transportation, and customers closer together.

According to Palevich, HWI Inc. had been working in a universe where supply warehouses, transportation companies, and manufacturing plants were not inline with customers' needs. HWI Inc.'s improvement initiative, as a distributor, was to connect vendors and transportation companies directly to the customers. Implementation of a comprehensive computer-based system has allowed inventory control, purchasing, distribution, traffic, accounting, and pricing to be centralized. In addition, HWI Inc.'s supply chain management and logistics system has reduced the company's operating costs, improved asset productivity, and compressed order cycle times (Palevich 1997).

Specific programs that have been reengineered around easing the supply chain process include purchase orders, invoicing, scheduling, credit authorization, advanced shipping notices, electronic pricing, and warehouse management. In fact, one of the most important factors in the success of these programs has been the implementation an electronic data interchange. Order lead times, data entry errors, and vendor based order forecasting have all been positively influenced by the exchange of common electronic data.

Another item of particular interest is HWI Inc.'s certification and compliance program. "Certification allows us [HWI Inc.] to work on common technologies together with our business partners. We are working on verification of bar code quality. Product packaging, type of pallets, and timing of delivery are also part of our certification program (Palevich 1997, pg. 3).” Vendors and suppliers to HWI Inc. must meet these standards or face monetary fines or the potential loss of business. In particular, bar code quality is a critical item of interest because of its application in the warehouse management system.

The warehouse management system (WMS) controls, “the flow of inventory, warehouse operating functions, information processing, transportation decisions, and order placement (Palevich 1997, pg. 4).” Additionally, the WMS works with in-place bar code information labels to allow for information retrieval from many aspects of the warehouse process. First, the receiving process is automated through scanning serial shipping containers. This digitized receiving procedure allows HWI Inc. to

- Verify freight bill piece counts
- Automate the purchase order matching function
- Reduce or eliminate the checking function
- Prioritize receipts for stocking
- Improve the payment process.

Next, forklift operators scan the bar code strip on each stock item in the receiving are and transmit data via radio frequency data communications (RFDC) to the mainframe. Storage stack area data and any additional important information is relayed back to the forklift operators. The materials are then carried to a designated area within the warehouse with the exact location being scanned and sent to the mainframe once the operator has made final placement.

Finally, when shipments are ready to leave the warehouse orders are assembled and scanned once again in the shipping department. The WMS creates a label with important information that includes the part numbers, the MSDS information, and quantities. Additionally, a bill of lading is printed once the final shipment is aboard the truck. All of this information is then passed onto the customer via E.D.I. or paper copies depending on the customer’s sophistication.

At the time of this publication, HWI Inc. had planned to extend this system to the World Wide Web. Customers could then place orders and monitor prices on a real-time basis. Currently, HWI Inc.’s retail Website is http://doitbest.com. Product availability, alternatives, specification, images, and prices can all be found on this Website.

Appendix B: How Many People Make A House?

Number of people	Trade/subcontractor	Task
2	surveyor	lot layout
2	Realtor	lot purchase
1	appraiser	lot appraisal
2	Banker	lot loan process
2	Attorney	title check
2	architect	house design
1	structural engineer	structural design
1	mechanical engineer	plumbing, heating
1	electrical engineer	power lighting
1	civil engineer	storm water
1	town planner	plan review
1	Building inspector	plan review, general
1	plumbing inspector	plan review, plumbing
1	electrical inspector	plan review, electrical
1	contractor estimator	assembles estimates
1	excavation estimator	estimates excavation
1	footing estimator	estimates footing
1	foundation estimator	estimates foundation
1	dampproof estimator	estimates dampproofing
1	Framing estimator	estimates framing
1	insulation estimator	estimates insulation
1	roofing estimator	estimates roofing
1	doors/windows est.	estimates doors/windows
1	siding estimator	estimates siding
1	gutter/downspout est.	estimates gutters/downspouts
1	drywall estimator	estimates drywall
1	Painting estimator	estimates interior paint
1	Cabinets/millwork est.	estimates cabinets/millwork
1	appliances estimator	estimates appliances
1	floor finishes estimator	estimates floor finishes
1	landscape estimator	estimates landscape/irrigation
1	electrical estimator	estimates electrical
1	mechanical estimator	estimates mechanical
1	cable TV installer	cable underground
3	natural gas installer	natural gas underground
3	water installer	water underground
3	sewer installer	sewer underground
3	electrical installer	service underground
2	phone line installer	service underground
1	deliver temporary toilet	
1	deliver temporary dumpster	
2	order/ship stone/gravel	
2	order/ship block	
2	order/ship foundation drains	
2	order/ship concrete	

2	order/ship framing	
2	order/ship plumbing	
2	order/ship mechanical	
2	order/ship electrical	
2	order/ship drywall	
2	order/ship cabinets	
2	order/ship appliances	
2	Surveyor	building layout
2	excavator	footing excavation
3	Concrete subcontractor	footing formwork/pour
3	Masonry subcontractor	foundation
1	dampproofing sub.	installs dampproofing
4	framing crew	framing/sheathing/doors
4	roofing crew	installs roofing
3	insulation crew	installs insulation
2	electrical crew	roughs in electric
2	Plumber	roughs in plumbing
2	mechanical subcontractor	roughs in gas/mechanical
4	drywall installer	installs drywall
2	cabinet installer	installs cabinets
3	flooring installer	installs floor finishes
3	Painter	interior paint
2	gutter/downspout inst.	installs gutter/downspout
2	Millwork and trim installer	installs millwork and trim
3	final grade/landscape inst.	final grading/landscape
1	building inspection dep.	footing inspection
1	building inspection dep.	framing inspection
1	building inspection dep.	electrical inspection
1	building inspection dep.	curb cut/apron inspection
1	building inspection dep.	plumbing inspection
1	building inspection dep.	final inspection
2	Banker	converts to permanent financing
1	appraiser	appraises for permanent financing
1	Attorney	closing
1	insurance agent	insurance

135 TOTAL

Appendix C: School Construction System Design (SCSD)--A Physical Integration Success Story

In a white paper presented to this project's advisory board in August 1999, master's degree candidate Chris Vandenbrock described the open system approach to physical integration promoted by Ezra Ehrenkranz and others. The open system is a "building system whose subsystems are interchangeable with other subsystems. Open systems are usually produced in response to bidding conditions requiring each subsystem to be compatible with two or more subsystems at each interface (thus assuring virtually universal interchangeability)." (Educational Facilities Laboratory 1967) The School Construction Systems Development (SCSD) program, the most successful effort at promoting modularity, allowed diverse manufacturers and suppliers of subsystems such as lighting, ceiling panels, enclosure, and partitions to freely bid and supply product to over 400 schools in California. The open system plays a similar role in Canada and some Scandinavian countries, allowing diverse suppliers while providing contractors with known production rates and owners with known durability. In the wood frame house as currently practiced, the modularity of the sheet panel product is the closest practice to the open system. Insulation, window, and skylight manufacturers also recognize the primacy of the structural panel module, but for the majority of housing subsystems, suppliers (mechanical, plumbing, lighting) make no effort at modular coordination at the scale of the whole system.

A longtime proponent of building systems integration, Ezra Ehrenkranz led a team of school district superintendents, material suppliers, labor unions, builders, sociologists, and financial executives in developing the SCSD, established in 1961. SCSD employed a rigorous systems approach to the design and construction of schools, stressing the need for compatibility, durability, and meeting user-specified performance criteria for the various building components. SCSD components made up approximately half of the cost of the school construction, enabling local designers and school districts to personalize and make regional adjustments to the system. Project specifications required general contractors to utilize the manufacturers of these components (who had previously won competitive bids to produce the components) as subcontractors.

The components were designed for one- and two-story school buildings but were utilized up to three stories. School sizes ranged 30,000–200,000 square feet. Components were designed and specified by the SCSD advisory committee to provide the highest performance in a school setting for the lowest cost. The end result was a system of over 300 components which could be specified by local designers and installed by local contractors.

The SCSD approach stressed end user flexibility. The prime factor for the adoption of this innovation by the school boards was spatial reconfiguration, supported by 70-foot column-free spans, demountable partitions, and reconfigurable air conditioning systems. Performance features such as increased lighting levels, salt air corrosion resistance, and glare-reducing concrete were a standard part of the system.

Another key factor in adoption of the SCSD system was cost competitiveness. At the time of adoption, the system approach was within 6¢ per square foot of traditional school construction having fixed partitions.

Physical integration thinking began with the SCSD planning modules. A 5-foot by 5-foot by 2-foot-deep structural module gave local design architects significant flexibility in customizing the school. All subsystems were required to be able to accommodate the 4-inch by 4-inch partition planning module. This 4-inch module also enabled the incorporation of plumbing within the partition thickness. SCSD's approach to physical systems integration depended on a 36-inch-deep "service sandwich" residing within the depth of the steel trusses making up the roof structure. This space contained structure, mechanical, electrical, lighting, communications, and ceiling finish.

The SCSD approach to performance was tied to a life-cycle cost basis for systems and components. Code minimums were the basis for structural design and life safety design, while the following client-generated performance criteria for the SCSD systems were established to guide manufacturers in the development system components:

sound transmission through assemblies	28 decibels
heat gain through exterior wall	6,000 BTUs per hour per 200 square feet
ventilation air	minimum 8 cubic feet per minute per person
total air supply	minimum 30 cubic feet per minute per person
air velocity at sitting height	20–50 feet per minute
mechanical zoning	minimum 3,600 square feet
mechanical service	minimum bid 5 years
lighting	minimum 70 footcandles
minimum illumination on work plane	within 25 per cent of average illumination level
maximum brightness in direct glare zone	350 footlamberts
lighting module	5 feet by 5 feet
demountble partition facings	must be independently replaceable
demountable partition reconfiguration	must be by school maintenance personnel
demountable partition service integration	must accept vertical and horizontal services

Production integration was considered in the design and specification of demountable partitions, lighting coffers, and the superstructure, which required compatibility with the planning module and flexibility by specifying school district personnel as the maximum skill level necessary to reconfigure. The predominant SCSD superstructure was a steel truss integrated with steel deck as its top chord. This connection was made through a heavy, hinged element, which enabled a higher number of components to be stacked on each truck. These large-scale (up to 70-foot-long and 6-foot-wide) prefabricated structural elements made for quick support and enclosure of the roof plane compared to a series of smaller, site-assembled components.

Glossary of Terms

customer-integrated decision-making (CIDM): a process that enables customer input into many aspects of the manufacturing industry

dependent-demand inventories: those materials whose quantities are directly related to the needs of an independent-demand item and not to the marketplace

design-for-assembly: a method of designing in which a part or series of parts are designed from the point of view of how they will by assembled and manufactured

electronic data interchange: an interchange of structured data according to agreed message standards between computer systems, by electronic means

enterprise resource planning (ERP): a powerful database with broad data format translation capabilities, within which are linked a series of supporting applications specifically addressing the various functions of an enterprise

enterprisewide business support systems: a plan which integrates information management with corporate goals

expert systems: computer programs based on knowledge developed from consulatation with experts on a problem, and the processing and/or formalizing of this knowledge using these programs in such a manner that the problems may be solved

fail-safe design: a design approach in which parts are manufactured that cannot be improperly assembled

floor jacking method: innovative high-rise construction technique which 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.

HUD code housing: also known as "manufactured housing"

independent-demand inventories: those items which are subject to market conditions and are hence independent of operations

information integration: a computing system that seeks to eliminate the traditional linear flow of information and allows all involved a free exchange of information

insulating concrete form (ICF): a concrete form system which combines the formwork, internal insulation, plates, and studs to attach finish materials into one process

just-in-time manufacturing: a manufacturing approach which seeks to eliminate waste by providing the right part, at the right place, and at the right time

knowledge based engineering: a software system that uses relationships and rules developed by manuals, data-sheets, the memories of key engineers, manages, and suppliers to help in the design and analysis of manufacturing products

knowledge based systems: a system which catalogues expert information to advise users

lean manufacturing: a systems-view of an organization that is centered on the notion of customer-defined value. It aims at eliminating all the steps in the production of a good or service that do not add value to the final customer

manufactured housing: 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

manufacturing resourse planning: an information system used to plan and control inventory, capacity, cash, personnel, facilities, and capital equipment. It utilizes a feedback loop between in-process orders and the master schedule to adjust for production capacity availability.

materials requirements planning: an inventory control system which releases manufacturing and purchase orders for the right quantities at the right times to support a master schedule

modular housing: factory built homes of one or more units which typically use platform frame construction

operations integration: making the many subsystems of a building (HVAC, lighting, power, irrigation, security) function together as one

optimum value engineering: a planning technique that seeks to reduce construction material waste by working to modular dimensions of materials and modifying traditional framing practices with engineering based designs for the spacing and dimensions of framing elements

panelized housing: a classification of manufactured housing which consists of factory-built housing components, transported to the site, assembled, and secured to a permanent foundation

performance integration: making the many systems of a building perform as one

performance based specification system: a specification that requires certain standards of performance from the building system in question

physical integration: making the many parts fit together as one

platform framing: evolving from a technique known as "balloon framing", which dates from the 1830's, this construction system uses single-story, wood 2x members connected by wire nails and is constructed by first building a floor system (platform) on which to construct the story walls. Each succeeding story is constructed in the same manner.

production integration: conducting the many operations in the construction or manufacturing process as one

precut housing: a classification of manufactured housing which consists of 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

quality function deployment (QFD): extends integration into the product development phase by bringing together product designers, engineers, process planners, and production planners at the time the customers are being surveyed

structural insulated panels (SIPs): mass produced composite wall panels that are manufactured with structural panel products (OSB, plywood) on one or two faces, with foam plastic insulation bonded to the structural panels

supply chain management: a management system that seeks to monitor and control all aspects of production

systems integration: a process which seeks to incorporate multiple building systems (HVAC, structure, electrical, etc.) into efficienct building design

task characterization: the accurate description of resource and information imputs; inventory of parameters for decision making; documentation of alternative methods for task completion; inventory of resource, product, and information outputs for each task of a larger process

total building commissioning: generally on the commercial scale of construction, this process involves third party certification of building performance, consumption, and maintainability

total quality management: a system-wide strategy for change that focuses on improvement of products, processes and people using tools, techniques, and philosophies to better meet customer requirements

value-engineering: a technique by which a project's value is increased, namely by increasing a project's worth while decreasing a project's cost

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