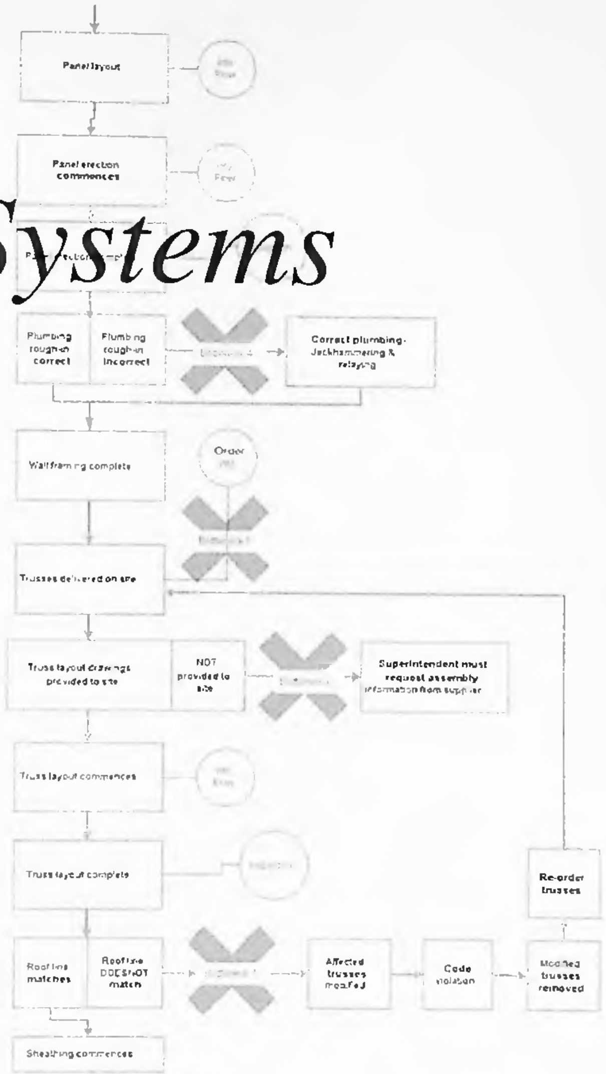
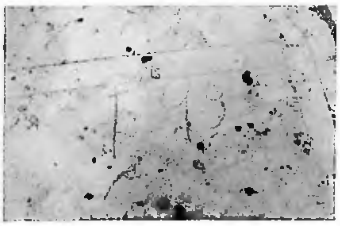
INDUSTRIALIZING
THE
RESIDENTIAL
CONSTRUCTION SITE

Phase III
Production Systems





U.S. Department of Housing and Urban Development
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Industrializing the Residential Construction Site
Phase III: Production Systems

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Foreword

The construction of homes in the United States has reached record highs over the last few years. While the home building industry has made incredible advances in materials and quality, it still lags behind other industries in technological innovation in production—that is, in providing new homes more quickly and more efficiently while still keeping homes affordable and at a high standard. There is much to be done, and there is much that all of the home building industry would like to see done.

Three years ago, HUD began an ongoing research project to address this crisis. While much of HUD's technological research work looks at the building materials, we realized how important construction processes are for homes and homebuilders. Ways to automate home construction processes, to improve construction workflows, and to coordinate construction sites—known as *Industrializing the Residential Construction Site*—became a new research focus. In the first year's effort, *Phase I*, researchers laid out five areas that best contained the possibility of transforming the construction site: production integration, operations integration, performance integration, information integration, and physical integration.

Of these five, HUD first explored "information integration" to see how information exchanges, relationships, and mechanisms shaped construction operations. The resulting document, *Phase II: Information Mapping*, includes an amazing record of the information flows and breaks on construction sites, as well as recommendations for overcoming these breaks. The second project, which is detailed here in *Phase III: Production Systems*, explores the impact of such information breaks on actual workflow. A variety of technical and managerial approaches are studied that will lead to more rapid construction production, with better planning and coordination, and with more efficient material and labor use.

HUD's comprehensive approach to process, the basic building block of any industry's work, will have dramatic consequences for all of housing production. This ongoing exploration opens an entirely new approach to helping homebuilders and building trades understand how their work is structured, and how it can be improved. Ultimately, these improvements will also benefit America's homeowners. Research initiatives and results like those in this series directly support the home building industry's future production capacity and the quality and cost of American homes for years to come. We invite you to read this report and all of the reports in this series, as well as to look out for more advanced research from HUD in this field.

Harold Bunce
Deputy Assistant Secretary for Economic Affairs

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Introduction to Phase III of Industrializing the Residential Construction Site

Executive Summary:

This research examined production systems in residential construction by closely observing framing processes used by four production builders. Three of the builders depend upon field-assembly of pre-manufactured wall panels, floor and roof trusses and one builder uses modular construction methods to assemble framing components in the controlled conditions of a factory.

The study found six categories of error occurring in the builders operations:

- errors of interpretation (misread a drawing/miscounted a quantity of symbols)
- errors of omission in interpretation (didn't see a note or detail, page missing from set)
- errors of representation (drawn or specified incorrectly)
- errors of coordination (incorrect or omission of cross-check for system clearances, incomplete review of plan "handing" or mirroring on details)
- errors of precision related to installation (out of square, out of plumb, misalignments)
- temporal errors (information not up to date)

Five of these types of error can be attributed to the information transmitted through the production process. The sixth, errors of precision are attributed to incompatibility between field and pre-manufactured component tolerances.

Errors of interpretation, omission, representation, coordination and temporal errors all point *away* from field processes and towards the front office processes of the designer, builder, manufacturer and sales agent. There is a significant opportunity to improve quality, profitability and productivity of the homebuilding enterprise if front office processes can capture, integrate, appropriately represent and disseminate the information needed by production crews and their leaders.

Considered as a whole, knowledge capture, design integration, production representation, and information dissemination, will likely produce new highly efficient production systems for residential construction capable of reducing the costs and time needed to construct a house while improving quality without substantial changes to the materials, tools, labor skills, and systems currently used to build a house.

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Industrialization of the Residential Construction Site

This report is the third phase of a multiyear project titled "Industrialization of the Residential Construction Site." The overall goal of this project is to identify, map, and refine the overall process of information transfer between parties engaged in residential construction. Accomplishing this task will lay essential groundwork for the application of fully integrated information and production resource planning systems similar to those in use by the manufacturing sector of the economy. These integrated information/ inventory/production systems have underpinned significant increases in quality while decreasing time-to-market and production costs.

Phase I—Overview and Key Findings

The full report for Phase I of "Industrialization of the Residential Construction Site" can be ordered or downloaded in PDF format from http://www.huduser.org/publications/manufhsg/ircs.html. The report provides an overview of previous and current (year 2000) efforts at industrialization of residential construction. The report also reviews approaches to systems integration; reviews the scope of application for physical integration, performance integration, operations integration, and production integration; and posits information integration as an umbrella form of integration necessary to actually achieve these discrete forms of integration. The report provides an overview of manufacturing sector applications of information integration through the development of Manufacturing Resource Planning (MRPII) and Enterprise Resource Planning (ERP), presenting case studies in productivity and quality gains experienced by manufacturers implementing these integrated information systems.

Phase II—Overview and Key Findings

The full report for Phase II, *Industrialization of the Residential Construction Site—Phase II: Information Mapping*, can be ordered or downloaded in PDF format from http://www.huduser.org/publications/manufhsg/ircs2.html. This report describes overall models of information flow for five production builders. The study identifies areas in the models where information was observed to be interrupted or disconnected from the intended flow, identifies areas in the process flow where complex information filtering occurs, and groups areas of the models into information domains. Finally, the study posits a general information model for residential construction in terms of each domain. The report includes detailed descriptions of the information disconnects and key filtering points of the overall process and proposes areas where information integration could improve productivity of existing production processes. The particular path that information, raw materials, parts, and products follow through the domains of information identified in the Phase II study functions as the production system for the builder.

Historically, houses were the product of a craft-based production system. The knowledge required to select, shape, and assemble the materials used to make a house and the authority to resolve system conflicts was held by the master builder, who assigned tasks to assistants and laborers to accomplish the construction. On the 100th anniversary of the light-wood frame construction method (1933), a typical house took six to nine months to construct. Contemporary production builders are applying bits and pieces of production systems that originated in manufacturing. Mass production, job shop, flexible manufacturing, and "just-in-time" strategies can be seen in parts of the overall production systems in place today. While manufacturing production systems centralize knowledge and control of the overall process to maximize the value of specialized tooling to produce a quality product, production building operates in a decentralized knowledge environment. The site superintendent is no longer the sole source of knowledge and authority on a construction site. Each manufacturer produces its own set of instructions for fabrication and installation based on the documents produced by the production builder for the home buyer.

Information and system conflicts between mass-produced components and site-crafted materials can require superintendents to coordinate up to half-a-dozen specialists to resolve the conflict, losing time, reducing the efficiency of the manufactured component installation, and adding time and cost to the house. Phase II of "Industrialization of the Residential Construction Site" mapped information and construction processes at a general level. In doing so, it discovered some of the points of disconnection in the process related to the conflicts in information and the problem of coordinating updating all the parties involved with the most current information.

Phase III—Purpose

Phase III maps at a fine grain of detail the construction subprocess for four of the production builders who participated in Phase II in the context of production and information systems. During the course of the mapping, problems and opportunities were identified. Alternatives and enhancements to the builders' current production and information systems are suggested.

(Note: The builder identified as Builder Four in *Industrializing the Residential Construction Site—Phase II: Information Mapping* was unable to participate in Phase III of this continuing study.)

Overview of Production Systems 2

Historically, production systems fall along a spectrum from assembly lines to job-shops. The assembly line traces its roots back to the early industrial revolution and came into full form in the early 1920s with the success of Ford Motor Company's production model. The centralization of production control and use of specialized, single-task tools and machines became known as the Ford system. The simplification of worker tasks often attributed to Ford's model traces its origins back to Fredrick Winslow Taylor, who formalized many of the ad hoc methods being used to establish time measurements for discrete work tasks. While Taylor's advocacy for scientific management was simply focused on developing time frames for production tasks, "Taylorism" is often associated with the monotony of production-line life experienced by the employee (Jones and Bryn, 1997).

The assembly-line production model has been particularly well suited to lower-skill labor markets, where extensive training is not financially viable. The assembly-line model is especially well suited for large production runs of a given design and frequently requires that the designs be tailored to the tools, skills, and processes already available on the line. Retooling for new designs comes at considerable cost in time, machinery, and training. The assembly line depends upon management-level intervention to determine the stages of assembly, sequence, and suppliers and to train each worker to complete a specific task or tasks in sequence.

Historically, production systems fall along a spectrum from assembly lines to job-shops.

The job-shop production system traces its origins back to guild workshops of medieval times through the specialty fabricators of the early industrial revolution and continues to make up a large percentage of U.S. manufacturing capacity today. At its core, the job shop is a small concentration of tools capable of being used to accommodate a wide variety of tasks. The employees of a job shop are typically highly skilled, often having been trained in an apprentice/journeyman/master model that also traces its roots to the Middle Ages (Jones and Bryn, 1997). The job shop is well suited for small-quantity production runs and depends upon the broad skill base of the employees to be able to complete several stages of the work on a particular tool or tools. The job shop is able to respond quickly to changes in the product design due to the multipurpose nature of its tooling and the high skill level of its employees (Sabel and Zeitlin, 1985).

Contemporary variations of these historical models focus on improving the production system's responsiveness to change, minimizing inventories, and increasing productivity rates to improve quality while reducing cost. A literature search conducted to capture new manufacturing paradigms for the 21st century identified three new manufacturing concepts: flexible manufacturing, agile manufacturing, and integrated manufacturing, each of which proposes a unique way of approaching change, inventory and supply, tool flexibility, personnel skills, and responsiveness to demand.

Flexible Manufacturing (FM)

The FM concept was first introduced in the mid-1960s, yet it did not catch on until the mid-1980s, when production automation became common practice and tougher global competition in manufacturing and changing customer demands began to push for greater flexibility in manufacturing systems.

The modern FM system is a production facility consisting of computer-controlled machines, or workstations, that are connected by automated material handling and process systems to accommodate greater product variety, shorter product life cycle, lower unit cost, higher product quality, and shorter lead times. Because of this reliance on automation and the short time and low cost involved in the setup to accommodate newly designed components, FM can respond quickly, smoothly, and cheaply to changes in product markets.

The advantages of using FM systems over conventional manufacturing systems can be organized into two categories: scope and speed. Scope flexibility allows for competition based on product mix, volume mix, and customized production. Speed flexibility, on the other hand, emphasizes quick delivery and design responsiveness to changing technologies and customer interests. This improves product innovation, critical to introducing new products into new or existing markets.

Over the years, FM has been adopted by several manufacturing industries, including automotive, aircraft, semiconductor, and textile industries. Most of the applications focused on the use of FM modules rather than FM cells or systems. In the future, this pattern may be reversed. In a survey of manufacturing experts, Mehrabi et al. (2002) found that nearly 75% of all respondents expressed a desire to purchase additional cells or expand existing FM systems.

The experts interviewed agreed that reconfigurable manufacturing (RM) systems are the desirable next step in the evolution of flexible production systems. RM is based on the concept of reconfigurable machines, controllers, and methodologies to facilitate the rapid adjustment of manufacturing production capacity and functionality to new market conditions. RM achieves this goal by using modular machines and open-architecture control systems to produce a variety of parts with family relationships, which can then be processed to produce the desired products. The uniqueness of RM is that by redesigning equipment layout and material flows, an RM system can provide the exact capacity and functionality needed, when it is needed. The end result is an increase in product variety and product quantity.

Placing FM in the context of residential production building, the subcontractor assumes the role of the workcell. Each subcontractor has flexible tooling and skilled labor to complete the same type of task (insulation, drywall) across a variety of product designs. Workcells in manufacturing are dependent upon a combination of information to guide the specific actions of their cell. The production documents instruct them as to the state of the component upon its arrival at their workcell, the materials they will need to add to the component at their workcell, and the completed state of the component as it leaves their workcell. The product itself guides their actions. The parts and materials to be added to the component are designed to minimize ambiguity and misinterpretation through their form and shape. Mating a "D" shaped part to a "D" shaped hole in the component helps minimize assembly error. As a flexible workcell, the subcontractor is dependent upon the project construction documents and the work of the previous subcontractor to provide the information for their subsequent work. An example might be, the framing contractor assembles the stud frame according to the project construction documents, then the insulation subcontractor arrives and if they work from past pattern alone, know that they are to place insulation in the exterior walls, and proceed to do this work. The insulation subcontractor is followed by the drywall installer who often also operates without project documents, knowing their contract is to completely cover the interior side of the stud frame with drywall. It isn't until some months later during the house-warming party that the guests discover that pvc sewer pipe transmits significant sounds of fluids and semi-fluid substances falling from the toilet upstairs through the pipe in the dining room wall. Had the insulation subcontractor worked from the project construction documents, the additional checkbox in the lower corner indicating the owner had purchased an upgrade to acoustically insulate all pipe chases might have been seen and completed prior to the drywall installation. The full implementation of an FM type of production system will have to include the task of changing the culture of some tradespeople to develop a consistent referencing of the project construction documents. To be confident that referencing the documents will add value to the subcontractors work, the project construction documents must contain current, correct and useful project information presented in forms that the tradespeople can understand and apply.

Agile Manufacturing (AM)

AM is characterized by a strategic vision that enables the responsive creation and delivery of customer-valued, high-quality, and mass-customized goods and services and the establishment of relationships facilitated by an information infrastructure that links constituent partners in a unified electronic network. Accordingly, an AM company embraces change and adapts to it rapidly and easily.

Gunasekaran (1998) identified the key enablers of AM to include virtual enterprise formation tools/metrics, physically distributed manufacturing architecture and teams, rapid partnership formation tools/metrics, integrated product/production/business information system, rapid prototyping tools, and electronic commerce. AM accomplishes the goal of producing highly customized products and quick response to customer demands through the efficient use of flexible, programmable machinery and reconfigurable products.

Over the years, AM has attracted an increasing amount of attention. The concept has been implemented by several manufacturing industries, including the microbrewing industry (Stauffer, 1997), the automotive industry (Kirk and Tebaldi, 1997), aircraft industry (Anonymous, 1999), aerospace industry (Mark Phillips Affiliation, 1999), and the semiconductor industry (Tang and Zhou, 2001). Documented benefits of AM include reductions in cycle time, inventory, production floor space, and levels of management. The latter is particularly important as it greatly improves the decision-making process.

With the availability of information and resources via the Internet, a number of Internet-based manufacturing systems have been proposed and developed. These systems share many of the attributes of AM and therefore can be considered variations of AM: holonic manufacturing, virtual manufacturing, and telemanufacturing.

Holonic manufacturing (HM) is a highly decentralized manufacturing system that includes standardized autonomous, cooperative, and intelligent elements. These elements, such as machines, cells, factories, parts, operators and products, are modeled as "holons," i.e., identifiable parts of a system with unique identities.

The strength of the holonic organization is that it enables the construction of complex systems that are efficient in the use of resources, resilient to disturbances, and adaptable to change. HM achieves this goal of "holarchy" through the use of a decentralized information structure, distributed decision-making authority, integrated physical and information framework, and cooperative relationships. The end result is a manufacturing system that can produce a high mix, low volume of highly customized products.

The subcontractor - driven production model common to many production homebuilders could be seen as an example of a Holonic Manufacturing system. Under the contracts from the production builder, subcontractors form a highly decentralized, intelligent, autonomous, cooperative system. Each subcontractor is an identifiable part of the system with a unique identity. The challenge of linking the subcontractor and supplier network into a rational "holarchy" capable of efficient and predictable use of time and labor resources and capable of being modeled as an overall holonic system remains difficult. This is due in part to wide variations in sophistication of business methods, external variations in labor availability, weather and the information technology capability of each subcontractor and supplier.

Virtual manufacturing (VM) can be broadly defined as a concept to replace hardware prototypes by graphical computational systems. VM does so by using information technology and computer simulation to design and evaluate machines, machine cells, parts, and facilities on-screen before actual facilities or products are made.

VM enables the manufacturer to speed up the time to market by integrating product development and production so that the system and parts are tested out in real time on a computer. According to Daly (1999) these simulation tools are so powerful that designers can produce a perfect product on the first try without any scrap and without building a prototype. This level of flexibility in manufacturing has been made possible by advancements in information technology and its ubiquity fueled by the Internet and electronic commerce (Offodile and Abdel-Malek, 2002).

VM is becoming increasingly important since it can respond rapidly to market changes and make resource sharing more efficient among manufacturing partners. In this environment, partners may be located at different geographical locations but can be easily incorporated through the use of Internet and electronic commerce. Virtual cooperation and optimal partner selection are therefore critical to the success of VM.

Virtual manufacturing in construction has been used by Asian and European builders on larger projects in order to evaluate staging, production processes and systems integration. Testing virtual prototypes in a physics-based simulation environment has yielded valuable information on scheduling, safety, structural, thermal, seismic, and fire performance of buildings. Until the widespread availability of three dimensional modeling CAD programs, larger projects had been required to enhance the payback of the investment required to model and test the virtual prototype. Now that three dimensional modeling is available at the scale of the typical desktop computer, virtual prototyping is on the horizon for most production builders. Research is required to discover the costs and frequency of errors in mass-produced production houses in order to better determine the cost effective level of sophistication for the simulation routines.

An area of VM, *telemanufacturing* (TM), or Internet-based manufacturing, is an infrastructure whereby a firm uses the services acquired via communication networks and across information superhighways to perform, in real time, operations and processes necessary for the design and production of items (Abdel-Malek et al., 1998). Three components make up a TM system: a communication medium, a specialized expert center (SEC), and an in-house controller (IHC).

The key element of the communications medium is the Internet, which provides the service channel for the SEC. An SEC is a center that specializes in a particular function, such as product development and design, production control, part programming, etc. The IHC coordinates and oversees all cross-functional activities of the TM system, much like the data link layer of the International Standards Organization/Open System Interconnection architecture in a local area network.

TM enables a company to remain flexible as it enables it to outsource its functions to expert centers. Consequently, the flexibility level of TM enterprises is not affected by the technological obsolescence of its systems' components. Rather, its flexibility depends on the specialized expert centers TM subscribes to.

Telemanufacturing is a similar on-the-horizon activity for production homebuilders. The pre- priced contract agreements with suppliers are very close to the telemanufacturing ideal of purchasing real time production capacity online. The web-based production schedule used by builders two and three could become the enabling step, linking a customer purchase to an automated call for components from pre-authorized suppliers and subcontractors. These subcontractors and suppliers currently operate as SECs controlled by the project managers and superintendents acting as the IHCs.

Integrated Manufacturing (IM)

IM denotes a possible third new manufacturing paradigm. In particular, computer-integrated manufacturing (CIM) has seen widespread use among manufacturing organizations.

CIM uses computers to design products, plan production, control operations, and perform business-related functions. The concept was first introduced in the 1980s and encourages the realignment of fundamental resources, people, and technology into a management philosophy that is aided by modern information technology. The realignment provides the needed integration of the levels of product development and production control as well as shop floor flexibility to enhance synergy and efficiency.

The ultimate goal of CIM is to produce the correct number of parts of acceptable quality at the right time. CIM accomplishes this goal by integrating numerically controlled machines, material requirement planning (MRP), manufacturing resource planning (MRPII), computer-aided design (CAD), computer-aided process planning (CAPP), computer-aided manufacturing (CAM), automated storage, computer-controlled handling, equipment, and robotics into an optimized production planning and control center.

While CIM has seen much application in large enterprises, small and medium-sized enterprises (SMEs) have regarded CIM as only remotely relevant. The perception is that only larger enterprises are affected by the customization frenzy and only they could benefit from using more advanced technologies and from adapting new matching organizational principles (Gunasekaran et al., 2000).

However, research on the adoption of CIM technologies by SMEs has increased in recent years, including both "hard" technologies (such as robotics) and "soft" technologies (such as CAD). It is generally believed that the seamless integration of hard and soft technologies will provide SMEs with easy communication both within their organization and with suppliers, thereby enabling SMEs to improve their potential.

Besides new manufacturing paradigms, the literature search also revealed that 21st century manufacturing requires corporations to generate designs quickly and then rapidly manufacture and launch the product. This finding implies there is little to no room for design changes, prototyping, or debugging the manufacturing line. Integrated product development meets the requirements of modern production strategies to support the next generation of manufacturing through such concepts as design for manufacture (DFM), design for assembly (DFA), design for manufacturing and assembly (DFMA), design for disassembly (DFD), design for x (DFX), and concurrent engineering (CE).

Integrated manufacturing and the substrategies DFM, DFA, DFMA, DFD and DFX are primarily product and process development strategies that "pull" knowledge from manufacturing, assembly, disassembly processes forward to integrate during the design process. Each of the substrategies has a unique focus. In production house building, steps toward integrated manufacturing can be seen in the move away from site fabrication of materials into structural components. The extensive use of pre-engineered structural components manufactured off-site (roof, floor trusses, wall panels) has effectively reduced the number of parts, a primary goal of DFM. For example, one roof truss typically replaces two roof rafters, a collar tie, a ceiling joist and part of the ridge rafter, one part to install instead of five. Production builders seem poised to take the next step, developing the complexity of these parts to speed assembly similar to DFA strategies. The overall integration of assembly optimization and part count reduction common in DFMA has yet to occur on a broad scale. Design for Disassembly, DFD, could have it's construction equivalent in current "un-construction" and "de-construction" research studying recycling of building components and materials.

Design for Manufacture (DFM)

DFM is a systems approach to developing products. The concept was born from the recognition that the delivery of a product to market requires complex interactions among several activities, including product selection, product design, material selection, material purchasing, fabrication technology and tool selection, material handling, process control, assembly, marketing, sales, and distribution.

In the broadest sense, DFM seeks to understand the interactions of all these activities and to leverage this understanding to optimize product development, production, and delivery. More narrowly, DFM focuses on the specific subset of interactions between the product design process and each of the various manufacturing subsystems. Such interactions facilitate easier, faster, and less expensive development of new products while at the same time maintaining all required standards of quality and desired functionalities.

Over the past two decades, DFM has drawn considerable attention. Hundreds of companies, representing more than a dozen different industries, have implemented DFM principles as part of their manufacturing process. Their use has resulted in many companies achieving shorter development times, fewer quality problems, and radically reduced production costs and times (Francis, 1994).

Design for Assembly (DFA)

DFA focuses on the assembly aspect of the manufacturing process as it typically accounts for 40–60 percent of the overall production time. By using DFA, the estimated assembly time can be used as a guideline to find out the design changes that can lead to the reduction of the final cost. DFA is based on the premise that the lowest assembly cost can be achieved by designing a product in such a way that it can be economically assembled by the most appropriate assembly system.

A recognized goal of DFA is part count reduction through part combination. Part combination is the combination of once separate parts into a single piece. As such, part combination decreases the number of parts that compose a product while maintaining the essential functionality of the product. This piece count reduction is considered the most effective means of improving product assembly (Jensen et al., 2000). Fewer parts usually imply fewer operations, less handling, and quicker assembly.

Design for Manufacture and Assembly (DFMA)

DFMA combines elements of both DFM and DFA into a single manufacturing concept. The concept was first developed and marketed by Boothroyd and Dewhurst and, consequently, is also known as the Boothroyd/Dewhurst method. It is based on the realization that approximately 70 percent of a product's cost is established at the design stage.

DFMA is a software and management tool that enables designers to consider a product's material selection, design, manufacturability, and assembly prior to production. In doing so, DFMA facilitates the optimal part design, materials choice, and assembly and fabrication operations to produce an efficient and cost-effective product (Ashley, 1995). The benefits of DFMA have been documented to include simpler product structures, lower product cost, reduced defect rates, higher reliability, and shorter development cycles.

DFMA implementation consists of a two-step process. In the first step, the DFA element of the concept is applied. This facilitates the design of a product that minimizes assembly costs and time. In the second step, the design of the parts identified in the first step is refined. This facilitates the efforts to fabricate the product to be minimized.

Implementation of DFMA is usually accomplished by a multidisciplinary team that includes design engineers, manufacturing engineers, shop floor mechanics, supplier representatives, and specialists in production support, maintainability, and reliability. Under the system, these individuals work together to produce detailed designs of each of the products and individual parts based on requirements of ease of assembly and structural efficiency to select the most feasible manufacturing process at the concept stage and to predict the assembly and manufacturing costs.

The implementation of DFM, DFA, and DFMA has led to enormous benefits to manufacturers, including document and product simplification and manufacturing, assembly, and time-to-market reduction. More recently, mandates on environmental and quality issues have required that manufacturers consider environmental and quality concerns during the design stages as well. This development has led to the creation of the design for disassembly and design for X concepts.

Design for Disassembly (DFD)

The DFD concept was first introduced in the early 1990s, when governments began to mandate that manufacturers be held responsible for their products when they reach the end of their operational lives. DFD was created to comply with the new environmental considerations and to avoid problems with the dismantlement of manufactured products, in particular integrated products.

DFD can be defined as the design of products that enable systematic removal of constituent parts from an assembly without impairment of the parts in the process. DFD extends the useful life of products in several ways: (1) by making them easier to take apart and service, (2) by enabling the removal and reuse of working parts, and (3) by recycling the materials for other uses. In doing so, DFD offers cost savings to manufacturers and benefits to the environment.

In DFD, special consideration is given to such activities as material selection, component fastening and joining methods, specification of recycled materials, and modular design. Fasteners are the heart of DFD, and there are two methods used to disassemble them: reverse assembly and brute force. Often the latter method is the most efficient, but it too requires designed-in pry points, access slots, and locations for grasping.

To date, DFD has been implemented by only a handful of manufacturing companies. These include the electronics and the automotive industries. In the electronics industry, DFD has been used to facilitate the removal of small, yet precious metals. In the automotive industries, DFD has been implemented to improve the recyclability of automobiles, in particular the removal of nonmetallic parts such as plastic.

Design for X (DFX)

DFX is a collective term that incorporates a number of "design for" activities, including design for environment, design for recyclability, design for life cycle, design for quality, design for maintainability, design for reliability, etc. All of these were created to reduce total life-cycle costs for a product through design innovation while complying with promulgated or anticipated legislative mandates.

DFX emphasizes the consideration of all design goals and related constraints derived from existing and/or proposed legislative and customer requirements in the early design stage. By considering all goals and constraints early, companies can produce products that are inherently simpler, better and designed correctly the first time without problems, delays, and change orders.

Although DFX is still in its infancy, the concepts have been embraced by several companies (Kuo et al., 2001). Most of them implemented DFX to integrate product and process into design through business practices, management philosophies, and technology tools. The end result was a more predictable product to better meet customer needs, a quicker and smoother transition to manufacturing, and a lower life-cycle cost.

The primary advantage of the DFX approach to design is the knowledge capture from feed back-loops that allows the design to incorporate lessons learned during the "X" process under scrutiny. The significant distinction between the DFX approaches in industry and construction is primarily one of process knowledge and control. Industry typically has more detailed knowledge of its processes as carefully mapped sequences of events occurring over specific time periods. To date construction, particularly housing construction has little data on the specific maps of processes used, and the time required to complete each process. Time and process data are required to determine which processes should be the focus of DFX product and process developments.

Concurrent Engineering (CE)

In CE, the focus is on developing a team approach to the simultaneous design of products and related processes. The team includes representatives from all applicable disciplines and functional groups that contribute to the successful translation of product concepts into ready-to-manufacture goods. Most often the team consists of a program manager supported by representatives from sales, marketing, finance, suppliers, subcontractors, manufacturing, and engineering. Oftentimes, also customers are represented on the CE team.

By integrating the various individuals into a cohesive unit, an integrated product design and development team is created that ensures that everyone is working in synchrony. This multidisciplinary, cross-sectional team participates in the design and development of products and related process simultaneously to obtain common objectives: design and manufacturing of a cost-effective product that meets customers' needs and satisfaction. The end result is a process that shortens lead times, reduces cost, and increases product quality.

As one can imagine, the success of the finished product largely depends on how well the team is integrated. Published information on concurrent engineering team integration suggests that four core elements normally dictate successful team integration: management support, information sharing, intelligent planning, and correct implementation. For building construction purposes, the information sharing and implementation elements are of particular interest.

In the concept of CE, "information sharing" refers to the mechanism whereby all necessary pieces of information used in the design and development of products are made accessible to the concurrent engineering team on a server. Through the use of common software (groupware) drawings and organization, product and process data files are freely transferred, thereby enabling effective work and efficient communication between all parties. A value added of working from the same data files is that changes in drawings, plans, and schedules can be easily managed and controlled.

The literature search further identified three business strategies to support 21st century manufacturing: enterprise resource planning, manufacturing execution systems, and business intelligence.

Enterprise Resource Planning (ERP)

Watson and Schneider (1999) describe ERP as a generic term for an integrated enterprise computing system for planning. They define it as an integrated, customized software-based system that handles the majority of an enterprise's system requirements in all functional areas, including sales, marketing, finance, manufacturing, and human resources.

A key to ERP is using information technology to achieve a capability to plan and integrate enterprise resources by integrating the applications and processes of various functions such as design, production, purchasing, marketing, and finance. Enterprisewide integration goes beyond physical computer integration. It also incorporates business integration (understanding the way business processes and enterprise policies are structured) and system integration (building integrated systems based on shared data, exchange format, and common architecture).

ERP systems that are currently available belong to the client server era (Rao, 2000). These systems are built with a clear separation of functional components. The graphical user interface is deployed on client machines. Power server machines host the databases and business logic written as server procedures. The databases are built using relational database technology. With suitable communication infrastructure, these systems can be deployed in a distributed process, meaning that software and information can be shared irrespective of the location of the user.

The objectives of ERP systems are threefold: first, to provide support for all variations of best business practices; second, to enable implementation of these practices with a view to enhancing productivity; and third, to empower customers to modify the implemented business processes to suit their needs. The challenge to ERP systems is to set up and integrate information resources across business units while at the same time enabling optimization across the organization.

Manufacturing Execution Systems (MESs)

The MES concept was developed in the early 1990s to create a real-time link between corporate-level resource planning systems and the automated systems that control machinery and equipment on the plant floor. Three characteristics define an MES: it tracks products on the plant floor, managing the workload and reporting on transactions to resource planning systems; it electronically dispatches order or product requirements to shop floor personnel, enabling the schedule to change quickly in response to unexpected demands or breakdowns; and it provides other data services to the shop floor, such as quality tracking and electronic work instructions. Core functions of an MES system include operations scheduling, resource allocation, document control, product tracking, performance analysis, labor management, maintenance management, process management, quality management and data collection/acquisition.

ERP and MES systems are both methods of integrating data across the corporate enterprise. They differ in degree with the ERP providing up-to-date information, primarily in text forms and numeric tables, and the MES integrating numeric data to drive manufacturing machinery, track production, inventory and shipping. In construction, the ERP could be considered as the office management functions, updating the project manager on costs, and orders while the MES would be similar to the project management functions, receiving inputs from field personnel on project progress, and disseminating updates to the project documents. In production building there are no fully integrated ERP - MES systems operating.

Business Intelligence (BI)

The BI concept was developed during the early 1990s when companies began to realize that to reap the full benefits of e-business, it is essential not only to feed data across a supply chain but also to collect, manage, and use data effectively. By tying together various data sources and presenting everything within a unified interface, BI was designed to do just that.

The Data Warehousing Institute defines BI as "the process of turning data into knowledge and knowledge into action for business gain. It is an end-user activity facilitated by a number of analytical and collaborative tools and applications." As such, BI is a decision support system delivered through a wide selection of specific reports accessing a centralized database of information. Tools and technologies that must be deployed target data acquisition, enterprise memory, exploitation, integration, and business process management.

A key element of successful BI implementation is ensuring that people have access to the information in the system whenever and wherever they need it. By linking islands of automation and providing tools and technologies to extract, transform, and load data into formats suitable for analysis and reporting, BI can deliver continuous information in near real time. Companies use this information to bolster an array of business tasks, including order taking, purchasing, inventory management, design collaboration, and production scheduling.

Some of today's BI systems are modular in nature. As such, they can be integrated as required by a company to address a specific business performance area. For example, there are BI modules for manufacturing performance management, customer relationship management, procurement performance management, sales performance management, e-business analysis, etc. However, it is believed (Hobbs, 2000) that the greatest asset rests with comprehensive BI systems empowering the entire workforce with access to the critical information it needs to support business decisions.

BI hasn't established a large footprint yet. It is still an emerging concept. However, based on the number of articles written on the subject since the beginning of the 21st century, it would seem that the concept has relevance for any manufacturing company seeking to maximize the value of information. With the Internet providing unparalleled access to data and generating unprecedented demand for information, BI may be the most critical factor in competitive advantage. Knowing when, where, and how products are moving from start to finish through the supply chain can become the difference between success and failure.

In the context of building construction, BI systems are used at higher management levels to discern buying trends and profitability in regional divisions. The data-mining strengths of BI systems are seldom applied to trend analysis of productivity, errors, bottlenecks, on-time performance and repeat buyers.

Production Strategies	Orientation	Tooling Characteristics	Process Control	Change Characteristics	Product Characteristics
Flexible Manufacturing	Process	Flexible, reprogrammable	Centralized	Designed for change	Highly variable - Shorter life
Reconfigurable Manufacturing	cycle Process	Flexible, reconfigurable	Centralized	Rapid adjustment	Highly variable
Agile Manufacturing	Product	Distributed, Flexible	Virtual partnerships	Rapid adjustment through partner selection	Mass Customized - Short cycle
Holonic Manufacturing	Product	Intelligent, Decentralized	Decentralized	Rapid adjustment through holon selection	Highly variable - Low Volume
Virtual Manufacturing	Product Process Dev.	None, tooling simulation only	Centralized	Rapid adjustment through web-partner selection	Simulation of product and production processes only
Telemanufacturing	Product	Decentralized, Outsourced	Web based IHC	Rapid adjustment through choice of SEC	Highly variable High or low volume
Integrated Manufacturing	Product Dev. Process Dev.				
Computer Integrated Manufacturing	Process Dev.	Varies Usually reprogrammable	Centralized MRP	Fast relative to large enterprise timeframes	High volume - Low variability
Design for Manufacture	Product Dev. Process	Varies	Focused on part count reduction	Fewer errors during product changeover	Reduced part count, higher part complexity to speed assembly
Design for Assembly	Product Dev. Process	Varies	Focused on time reduction	Fewer errors during product changeover	Part design for rapid assembly
Design for Manufacture Assembly	Product Dev. Process	Varies	Team integrates DMA, DFA	Maximize existing production capability	Low part count, high part complexity for rapid assembly
Design for Disassembly	Product Dev. Process	Varies	Team focused on Disassembly, recycling	Focus on recycled content integration	Focus on fastening of parts for rapid cost-effective disassembly
Design for X	Product Dev. Process	Varies	Team focused on "X" (a variable concern)	Knowledge integration for "X" optimization	Design optimized to facilitate action on "X"
Concurrent Engineering	Product Dev. Process Dev.	Varies	Centralized MRP / ERP	Speed a function of team size, focus	Highly Integrated
Enterprise Resource Planning	Process	Varies	Centralized data allows decentralized controls	Allows for rapid adjustment to change during production	Variable within a product "family."
Manufacturing Execution Systems	Process	Intelligent, Networked	Centralized	Rapid	Varies
Business Intelligence	Process	Varies	Centralized data mining	Real-time updates to functionality	Variable within a product "family."

3

Study of Production Builders

Recent developments in manufacturing systems have increased their similarity with production homebuilding. Similarities in speed of product development cycles, small production runs, assembly by outside partners at remote sites using off-the-shelf and specially made parts to produce user customizable product families in highly regulated environments make compelling reasons to consider the production homebuilding process in the context of contemporary manufacturing strategies. This chapter will present the study of four production builders and consider process bottlenecks that reduce overall speed, productivity or quality.

In the previous study, *Industrialization of the Residential Construction Site—Phase II: Information Mapping*, the framing of walls, floors, and the roof was identified as potential information and production bottlenecks in the overall production process. Based on this finding and consultation with the builders, a more detailed study of the framing of walls, floors, or the roof was undertaken.

Framing and assembly of prefabricated framing components are some of the most challenging processes for most of the builders in this study. Timely communication and precise execution are required to accommodate variations in floor plans and buyer customization. The interfacing of prefabricated and site-fabricated components on site is also problematic. Observations of current systems and practices reveals frequent time-consuming manual adjustments or rework to successfully join the prefabricated components to the site-fabricated components. The study also found that the builders who did not fully utilize existing information and production systems consequently failed to realize the complete potential of prefabricated components in the production of houses.

The information systems and production practices observed in this study were seldom capable of extracting the full potential of prefabricated components in production houses

Case Study Methodology

Each builder study is developed using a case study methodology. Data were collected by interview, observation, and samples of production documentation during a two-day field study conducted by two research assistants.

Initial Contact with Builders

The principal investigator (PI) initially contacted a corporate officer for each builder. During this initial contact, the PI described the project and goals in general terms and requested the builder to recommend a specific subcomponent process for study. The PI also requested that the builder coordinate the field study with the supervisory personnel involved in the subcomponent process.

Introductory Visit

The PI and research assistants met with the builders' supervisory personnel to discuss the following aspects of the production process of constructing the house frame:

- stages of the process
- personnel involved
- materials handling
- documentation
- internal and external communications
- quality controls

With these observations, the PI and the research assistants further refined data collection methods to prepare for the field study.

Field Study

The field studies were conducted in two-day periods at each builder's production site. The research assistants operated as independent observers, each recording the following:

- information inputs and outputs at each process stage
- material inputs and outputs at each process stage
- physical environment/staging unprocessed and processed materials
- task stages
- level of task complexity, unchanging vs changing information
- personnel assignments
- related/competing activities for workers at each stage
- personnel comments regarding error, difficulty, or quality concerns
- approximate task duration at each stage
- quality control methods
- task completion indicators

The research assistants followed the subcomponent production process through each of the tasks required to complete its production, paying special attention to the following:

- job initiation orders
- materials/information passing through each process stage
- time, competing activities, level of information in/out
- personnel perceptions (obtained through interview) of complexity, nature of typical error, compatibility between capacity at each station, and capacity of preceding/following stations
- record quality control measures

Samples of the formal production documentation provided to the subcomponent supervisor were copied for subsequent analysis. Also, informal production documentation and communications used by supervisors and personnel to complete tasks were recorded, along with information supplied by the subcomponent supervisor to subsequent stage and coordinating supervisors.

Data Assembly

After the field study, the research assistants began a joint process of data assembly. During this process, particular attention was paid to differences between the observations of the assistants. Field notes, diagrams, digital images of tasks, and sampled documentation were assembled into a process map and process narrative. The process of data assembly was performed by two research assistants who conducted the field study. A third research assistant identified gaps in the collected data for follow-up study.

The following tasks were undertaken in the data assembly phase:

- tag and file documents, image file names, and diagrams provided by the builder
- construct process diagram
- construct information flow diagram
- construct narrative description of production flow
- construct material flow diagram
- scan images/link to diagrams
- identify gaps in data for follow-up study

Follow-Up Study

Research assistants conducted follow-up studies by either revisiting the production site or contacting a task supervisor for clarification of data identified within the assembly stage. The clarifications made during the follow-up stage were integrated into the assembled data to complete the data collection phase for the builder.

Data Analysis

Explanation of error, productivity bottlenecks, quality problems, and the relationship between information disconnects and information filtering were sought during the data analysis phase. An underlying assumption was that personnel involved in completing the subcomponent assembly were given the right information, in the right format, with a proper amount of time, material, and tools to produce a high-quality, error-free subcomponent.

The PI and research assistants conducted the data analysis in two stages. First, the assembled data for each builder was analyzed discretely in the following terms:

- points in the subcomponent production where errors were observed or noted by builder personnel
- points where the tools, facilities, or material handling processes limited productivity
- points of excessive complexity in formal production documents
- points where informal production documents were produced
- points where the data collectors noted excessive personnel inputs to complete a task

Second, the data analysis sought larger patterns of error, productivity loss, or quality deficiencies:

- information errors in the formal production documentation (content errors)

- errors in interpretation of information contained within formal production documentation (filtering errors)
- errors in interpretation of the information contained in the informal production documentation and communication (representation errors)
- productivity losses attributed to a lack of timely distribution of production information (information disconnect)
- quality deficiencies attributed to facilities, tools, materials quality, materials handling, or staging practices (specification or process errors)
- quality deficiencies attributed to lack of training or task description matched to personnel skill level (process or information representation error)

Production bottlenecks were identified from the following:

- the comments of workers
- observations of shortages or backlogs
- typical sources of identified error
- observations of rework piles or discarded assemblies
- identified causes of error: incorrect/conflicting information, material quality, tool/infrastructure, worker operation.

Finally, excessive information filtering locations were identified based on the following:

- presence of informal communications/instructions
- number of information sources
- clarity of information source

Builder One

Builder One, a modular homebuilder with production facilities in two states, produces over 700 homes per year from Florida to Pennsylvania. Builder One employs in-house architectural services to offer predesigned home plans with custom options to home buyers. Unlike many builders today, Builder One uses no subcontractors, employing all necessary trades to produce a modular home. The builder has two types of production facilities: a component plant that manufactures housing components and a modular plant that assembles components into house modules.

This case study focuses on the portion of the production line housed in one of the modular plants and on the component assembly plant housed in a separate building. In consultation with Builder One, it was decided to study the fabrication and assembly of the roof components which are later mated to the wall/floor assembly at the "start" of the modular production line.

Subcomponents of the roof assembly are produced in a separate building from the production line. The component plant operates as a series of work cells linked by the daily production schedule produced by the component plant manager and communicated to the work cells as detailed "cut sheets" describing the type, quantity, and dimensions for each roof subcomponent.

Fig. 3.1 Process map for Builder One (See Fold-out Process map)

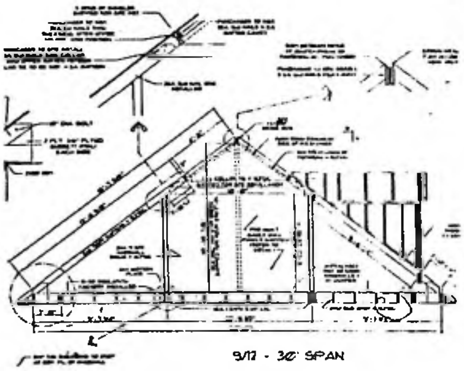


Fig. 3.2 Details for folding roof assembly

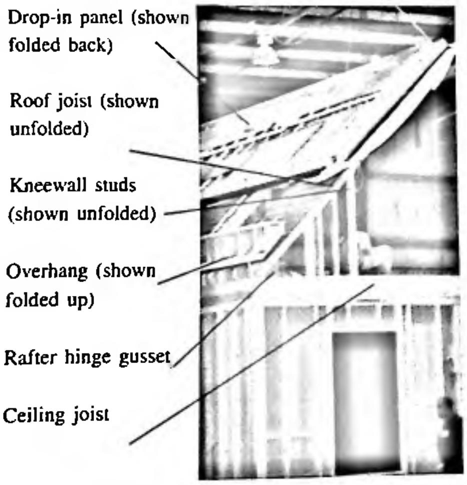
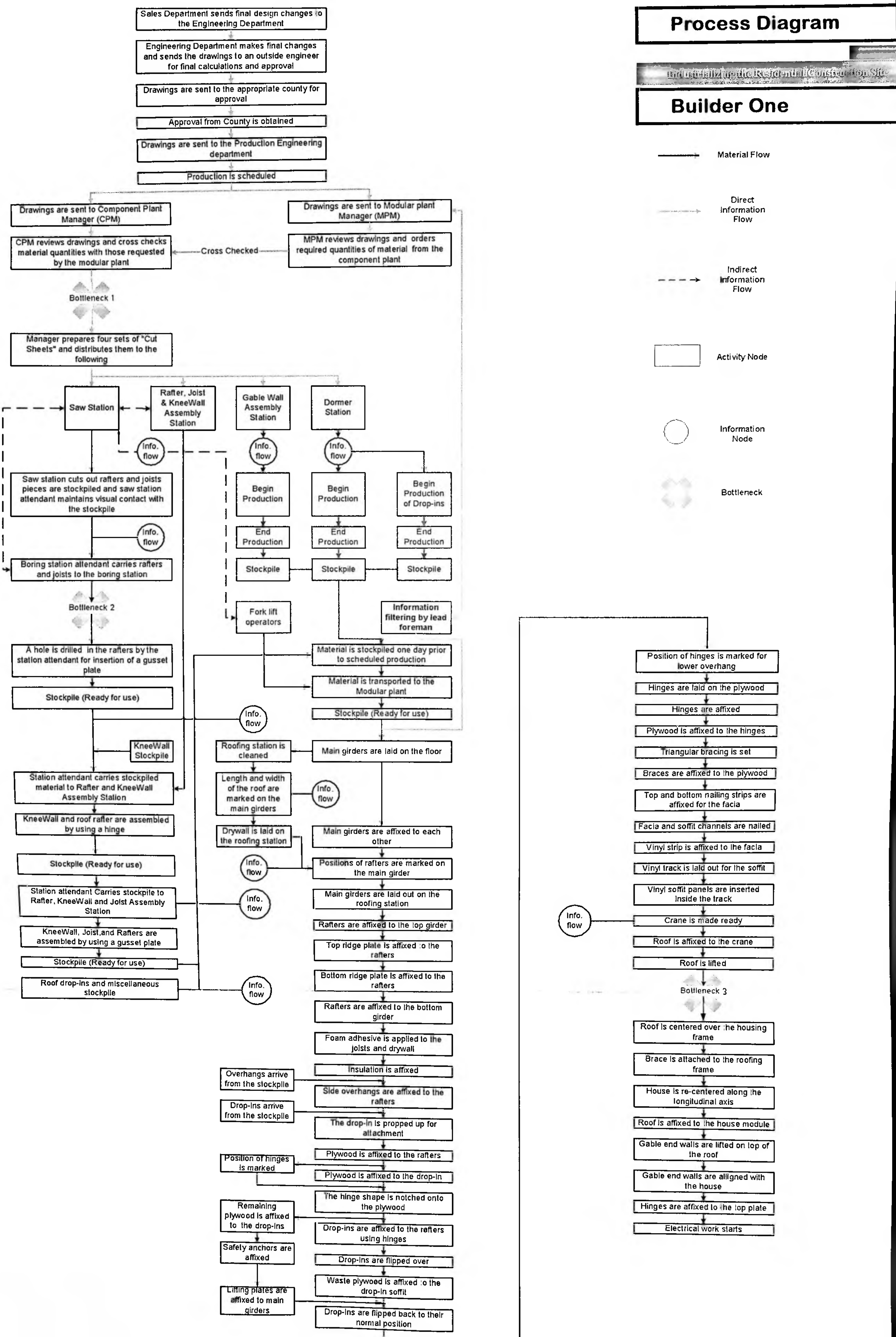


Fig. 3.3 Folding roof components

Process Diagram

Industrializing the Residential Construction Site

Builder One



Process Narrative (Read in Conjunction with the Foldout Process Map)

Introduction to a folding modular roof

Builder One produces a complex folding roof and gable wall assembly which allows most of the roof construction to be completed in the plant. The roof can be folded down to meet transportation regulations and quickly unfolded after delivery to minimize the possible rain damage to interior finishes, cabinets, and appliances.

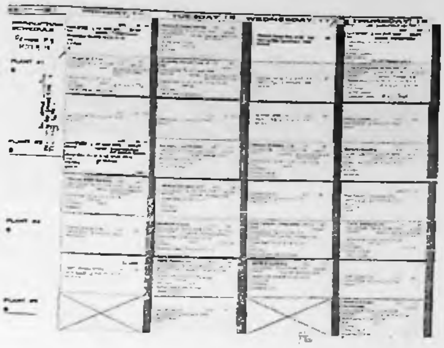


Fig. 3.4 Production schedule for modular and component plants

A folding roof has the following components:

- a roof rafter that is hinged to the ceiling joist
- a kneewall hinged below each rafter to "self-unfold" and support the rafter on the ceiling joist as the roof unfolds
- an overhang hinged to the roof sheathing that is flipped down into position after the roof is unfolded
- a "drop-in panel," which is a short section of roof framing with sheathing, inserted to close a small gap between unfolded roof sections
- a gable end closure wall, folded down over the wall assembly during shipping and flipped up into position to enclose the gable end/attic

The precision cutting and hinging of rafter/joist/kneewall studs takes place in the component plant. The completed and hinged rafter joists are shipped as subcomponents on palettes to the modular plant, where they are laid out on an assembly table. The assembly is then joined together with perimeter box beams and sheathed with oriented strand board (OSB). Gypsum ceiling board is installed. Anchorage for roofing safety rigs and final overhangs are attached to complete the roof assembly. This assembly is then transported by overhead crane to be attached to the wall and floor framing assembly.

Fig. 3.5 Saw station

Fig. 3.6 Boring station

Fig. 3.7 Rafter stockpile

Fig. 3.8 Rafter/ kneewall station

Fig. 3.9 Dormer station

Fig. 3.10 Drop-in panel station

Detailed fabrication process of constructing a folding modular roof

The roof fabrication process occurs in two stages: the component plant and the modular plant. The component plant fabricates all the material required for the fabrication of the roof. The Production Engineering Department reproduces the required drawings and specifications for the fabrication of the roof as part of the "production packet" and sends copies of the packet to the component and the modular plant managers. The modular plant manager studies the drawings and determines the exact quantities of materials required for the roof and the date on which they are required. He faxes this information to the component plant manager who schedules the production of roofing components. The component plant manager receives the fax and crosschecks the quantity takeoff with his own count. Raw materials for the roofing components are kept in stock and are continuously refilled by the respective supplier without notification by the builder. The roofing process starts with the fabrication of the required subcomponents in the component plant and is completed by the subsequent assembly of the subcomponents into the roof subassembly in the modular plant.

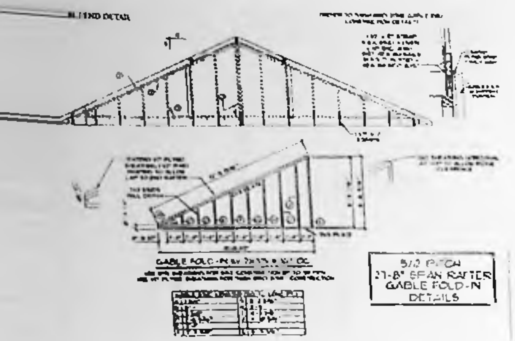


Fig. 3.11 Gable end detail from production packet

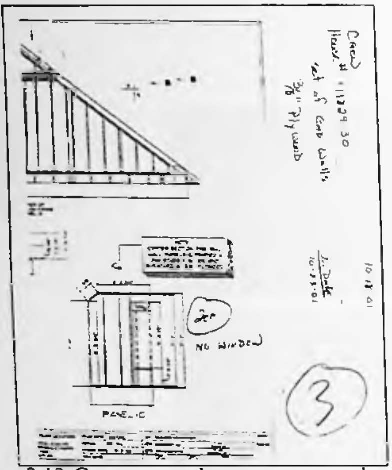


Fig. 3.12 Component plant manager markup "cut sheet" (1)

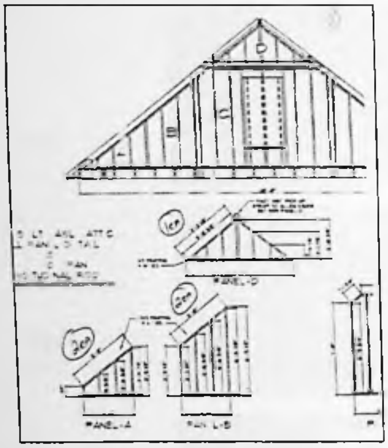


Fig. 3.13 Component plant manager markup "cut sheet" (2)

Fig. 3.14 Dormer panels fabricated from "cut sheets"

Component plant

The component plant always works off the time frame faxed from the modular plant manager to the component plant manager. This time frame requires that all the subcomponents required for roof fabrication have to be ready to be shipped to the modular plant, at least one day prior to the day when the modular plant commences the assembly process. The component plant usually requires three days to fabricate all the necessary components for any roof. The component plant manager studies the drawings, filters required information, and prepares necessary cut sheets. A cut sheet is a precise instruction to a workstation regarding type and quantity of material required. The component plant manager prepares four cut sheets and distributes them manually to the following work stations:

- automated saw station—a programmable saw that cuts rafters, joists, dormer frames, overhang, and gable end components
- rafter, kneewall, and joist assembly station—a layout table with jigs/fixtures for assembly of various roof lengths, joist depths, and roof slopes
- dormer window station—an area of the component plant floor where dormers are framed, sheathed, roofed, sided, and glazed
- gable wall assembly station—where flip-up gable end closure panels are framed, sheathed, and stockpiled

Saw station

The saw station is responsible for initial processing of the raw framing materials into precut joists, rafters, and wall framing. Builder One uses standard roof types (span and pitch). Based on these types, the material required for fabrication of the roofs is also standard. The saw station attendant is responsible for maintaining a minimum inventory of standard rafters and joists. Thus, unless there is a special roof requiring nonstandard material, the saw station attendant mass produces the full range of stock rafters and joists. The attendant stockpiles this material and maintains visual contact with other stockpiles. The rafter, kneewall, and joist assembly; dormer window; and gable wall assembly workstations pull material directed by the cut sheets from the stockpiles. When a stockpile of joists, dormer framing, or rafters falls below a designated quantity, the saw station replenishes that material inventory. From the stockpile, a stack of rafters is taken to the drill station, and a hole is bored into them at one end for the insertion of the folding roof assembly hinge bolt. After the hole is drilled in each rafter, the stack is stockpiled near the rafter-joist assembly station location.

Forklift operators play a very important role in the communication process by moving material from stockpiles to subcomponent assembly stations and moving completed subcomponents stockpiles to the modular plant. It is apparent that the saw station is one of the most important constituents in the roof production process, as it matches the stockpile level to the production quantity. It is very important for this station to know the exact status of subcomponent stockpiles in the modular plant and also in the component plant. The forklift drivers relay stockpile status information between the modular plant stations (which are out of the visual range of the saw station attendant) and the saw station.

Kneewall, rafter, and joist assembly station

The bored rafters are taken to the rafter and kneewall assembly station. The station attendant sets up the jig which complies with rafter and joist depths and roof slopes specified on the cut sheets. The kneewall stud is attached to the rafter with a hinge. The pitch of the roof determines the position of the kneewall stud. This is a very important step in the fabrication of the roof. Any mistakes may result in the roof not matching specifications. This procedure is repeated for the whole stockpile of rafters and kneewalls and produces a ready stockpile.

This stockpile is taken to a different table in the same workstation. This workstation also takes the required size of rafters from the saw station stockpile. Here, the kneewall, rafters, and joists are assembled to produce a single component. This process is repeated for the pile, and the ready material is stacked in the storage area for delivery to the modular plant.

Dormer station

The dormer window station mass produces the standard type of dormer window. Like the saw station, this station maintains a designated quantity of dormers. When the stock falls below a given quantity, more dormers are produced to maintain the inventory. If a nonstandard type of dormer is required, it can be constructed according to the cut sheet and production schedule.

Gable wall assembly station

This station works off the master production schedule. Based on the cut sheet provided by the component plant manager, this station produces the required gable end walls and stockpiles them.

Miscellaneous assembly

The small triangular frame used for the roof overhang is produced in the component plant from the waste resulting from different operations. A cutting station is dedicated to such miscellaneous activities, mass produces the triangular overhang frame, and attaches plywood sheathing to the overhang assembly. Other miscellaneous items, including the longitudinal roof overhang frame, roof drop-in panel frame, kneewall bracing plate, and central connection joist, are fabricated in the temporary storage space in the component plant and stockpiled. Upon fabricating their designated material, individual workstations pack and transport assemblies to the storage area. Forklift operators transport the material to the modular plant for further processing.

Modular plant

After all the required subassemblies are fabricated in the component plant, they are transported to the modular plant for further assembly. The roof assembly process takes place on two or sometimes three stations, depending on the availability of space. Laborers check the subassemblies for any defects or mistakes. The roofing station is cleaned, and the perimeter box girders are laid out on the floor. These girders are attached to each other temporarily by means of pins. The roofing foreman studies the rafter layout drawings and the electrical layout to reconfirm that there are no conflicts between the rafter and light fixture locations.


Fig. 3.15 Drywall layout on roof table


Fig. 3.16 Joist spacing layout on perimeter box girder


Fig. 3.17 Overall view of box girder with layout marks


Fig. 3.18 Installation of ceiling joist/ kneewall/roof rafter assembly


Fig. 3.19 Kneewall between ceiling joist and roof rafter (shown folded down)


Fig. 3.20 Overall view of roof rafter folded down on ceiling joist


Fig. 3.21 Overall view of crane rigged to unfold roof rafters


Fig. 3.22 Unfolded roof rafters showing attic insulation


Fig. 3.23 Routing roof sheathing to accept hinges for drop-in panel


Fig. 3.24 Drop-in panel ready for sheathing


Fig. 3.25 Hinge layout for attaching folding overhang


Fig. 3.26 Attaching folding overhang

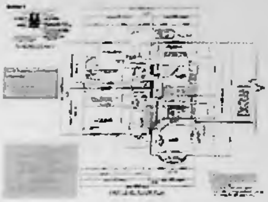
Based on the layout, the foreman marks the positions of these rafters on the box girders. Drywall sheets are laid out on the cleaned roofing table and taped. The box girders are laid around the drywall, with its edge resting on the drywall. The basic roofing framework comprising of the joist, rafter, and kneewall is laid out inside the box girders. The joist assemblies are attached to the top box girder. After all joist assemblies are attached, the upper ends of the rafters are connected using a top ridge plate. This connection is checked, and the bottoms of the kneewall studs are connected using a bottom ridge plate. After these connections are made, the position of the joist assemblies is checked again for accuracy, and they are attached to the bottom box girder.

An adhesive is sprayed in the gap between the bottom of the ceiling joist and the drywall. This adhesive secures the drywall to the joists. Insulation material is packed into the spaces between joists. Overhang assemblies are then attached to the lower end of the rafters. The roof is unfolded and propped onto the kneewall for attachment of hinges for the drop-in panel. The drop-in is attached to the top ridge plate. Plywood is attached onto the rafters. The position of the hinges for the drop-in is marked on the plywood to ensure that hinges are located exactly over a rafter for secure attachment. Plywood sheathing is then attached to the drop-in framing after the shape of the hinge is routed into the plywood and hinges are attached. Once the drop-in and rafters are securely attached to each other, the drop-in is flipped over to continue work on the roof. At this point, safety anchors and lifting plates are attached to the rafters and box girders respectively. Scrap plywood is attached to the drop-in panel, and the basic roof assembly is complete.

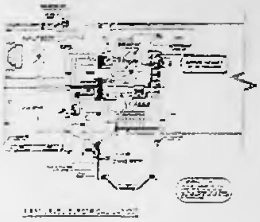
After this process, the roof is transported to another station for further work depending on the production schedule. Position of hinges for the lower overhang is marked on the plywood, and the hinges are fixed. Plywood is attached to these hinges and is flipped over. Top and bottom nailing strips for the facia are fixed to the overhang frame. Facia and soffit channels are nailed to these strips. Vinyl strips are attached as facia. Vinyl tracks are laid out on the bracing. These tracks are fixed, and soffit boards, which are precut vinyl pieces, are inserted inside the tracks. The roof is now ready for installation on the wall/floor subassembly.

The roof is attached to the overhead crane and transported to the drywall station, where the wall/floor subassembly module is ready for the roof installation. The roof is aligned over the module, and a wooden block is attached to the outside of the wall assembly as a fixed reference point. The flexibility of the tops of the walls requires that the walls be manually realigned using pry bars, hammers, and muscle so that all wall corners match perfectly to the roof assembly. Once alignment is achieved, the roof is the attached to the wall/floor module. This exacting process consumes as much time as the production of the roof assembly itself. Gable end walls are manually lifted on top of the roof and aligned with the roof and walls.

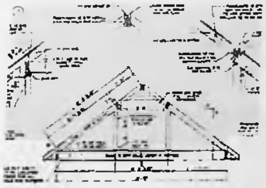
Depending on the span and type of roof, these gable ends may be extremely heavy and require the use of the overhead crane. The gable ends are attached to the frame by using heavy-duty hinges. The gable end is then folded and kept on top of the roof. The roof is propped up, and the completed wall-roof module is transported via floor rollers to the rough-in station for electrical, HVAC, and plumbing rough-in. After rough-in is completed, tar paper, vapor barrier, and asphalt shingles are attached to the roof. This process happens farther down the assembly line and is treated as part of the finishing process.



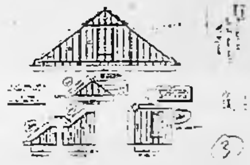
(A) Architectural floor plan



(B) Electrical floor plan



(C) Folding roof detail sheet



(D) Gable end detail sheet

Fig. 3.27 Production packet excerpts filtered by component plant manager to produce cut sheets for production stations

Results of Analysis

The results of the functional analysis mapping revealed places in the workflow where errors and production bottlenecks had occurred or were likely to occur. For the purpose of this study, "error" was defined as an incorrect piece of information transferred through one or more production stations, while "bottleneck" was defined as a place where production work ceased or slowed below the normal production rate. Errors and bottlenecks fell into six categories:

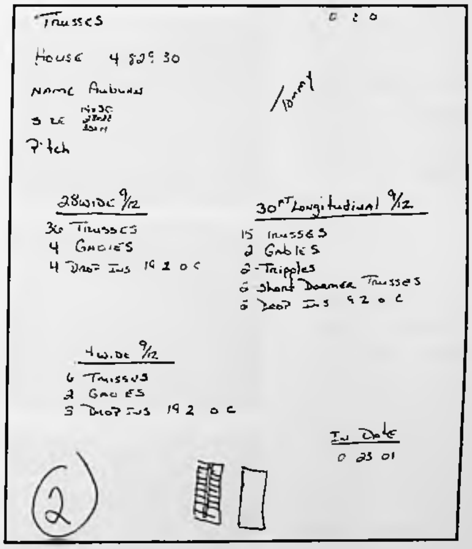
- errors in the information supplied to the production floor
- errors in the interpretation (filtering) of information supplied to the production floor
- errors in the generation or interpretation of informal production documents (referred to as "cut sheets" in this study)
- bottlenecks caused by facility limitations such as overhead clearances, crane capacity, dimension, layout, and distances between facilities/stations
- bottlenecks caused by mismatched production capacity between adjacent stations in the workflow
- bottlenecks caused by errors in coordination of the design documents

Points in the subcomponent production where errors were observed or noted by builder personnel

During data collection, one of the managers of the component process noted that his most likely error was in the filtering of information from several drawings to generate the cut sheets for the saw and roof component assembly stations. Managers in the assembly plant noted that coordination errors resulting from conflicting information provided in the drawings and specifications was their most likely error.

Points where the tools, facilities, or material handling processes limited productivity

A close study of material and subassembly staging areas and movement paths revealed numerous conflicts in material movement caused by adaptation of an existing building to the subcomponent assembly process (Fig. 3.32). Builder One has combined automated tools with manually operated tools in the subcomponent plant. In this plant, the automated saw frequently produces material faster than the subsequent boring operation can process material. The manual setup and operating boring station were observed to be unable to keep up with the materials supplied by the automated saw or to match the production rate of the subsequent rafter assembly operation. This production bottleneck is avoided by the automated saw operator, who reprograms the saw to produce components for the drop-in roof panels, gable end walls, overhangs, and dormers, so no production time is wasted. The personnel at the rafter assembly station had to reduce their production rate so as not to run out of bored materials. This bottleneck may be simply addressed by having an additional



Trusses

House 4 829 30

Name Auburn

Size [illegible]

Pitch

28wide 9/12
30 Trusses
4 Gables
4 Drop Ins 19 2 o c

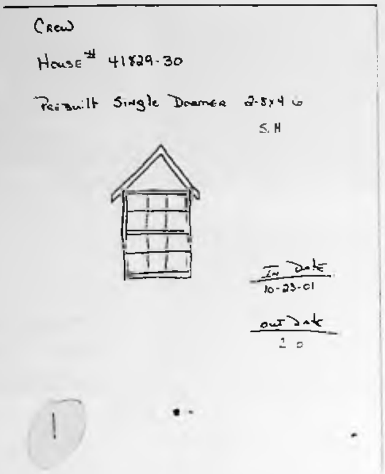
30FT Longitudinal 9/12
15 Trusses
2 Gables
2-Tripples
6 Short Dormer Trusses
6 Drop Ins 19 2 o c

4wide 9/12
6 Trusses
2 Gables
3 Drop Ins 19 2 o c

In Date
0 23 01

(2)

Fig. 3.28 Roof framing component cut sheet filtered from production packet by component plant manager



Crew

House # 41829-30

Prebuilt Single Dormer 2-5x4 6

S. H

In Date
10-23-01

Out Date

Fig. 3.29 Component plant manager cut sheet, filtered from four sheets of drawings

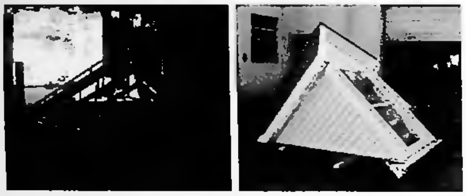


Fig. 3.30 Framed and completed dormer

(A) Overhead crane positions roof over wall assembly

(B) Locating block attached to wall to stop roof near final position

(C) Worker uses hammer and pry bar to adjust wall top to roof

(D) Roof assembly in final position over walls

Fig. 3.31 Mating roof assembly to wall assembly

boring machine that could be operated by the rafter assembly personnel when inventory of bored materials is depleted.

Points of excessive complexity in formal production documents

The field observations recorded the component manager having to consult and cross-check up to nine separate drawing sheets to prepare cut sheets identifying type, quantity, and dimensions of subcomponents for production by the saw, boring, rafter/kneewall, and dormer workstations. The drawings in use by this builder closely resemble typical architectural drawings for buildings. They serve the typical building bid process reasonably well because organizational and representational conventions are necessary given the large number of suppliers and bidders, which are typically independent businesses. Builder One has the unique opportunity to "prefilter" the drawings and specifications for the information necessary for a workstation to produce its component.

Points where informal production documents were produced

In this study of the roof subassembly process, the most informal production documentation is produced by the component plant manager. After receiving the drawing packet from the Production Engineering Department, the component plant manager reviews the sheets containing information used in the production of the roof components. These are the floor plan, roof framing plan, exterior elevations, and gable and end wall details.

Points where the data collectors noted excessive personnel inputs to complete a task

Overall, personnel observed in this segment of the building process seemed well matched in number and skill level to carry out the operations required to complete the construction of roof assembly subcomponents, assemble those subcomponents into the roof subassembly, and mate the subassembly to the wall assembly for subsequent finishing operations.

The physical characteristics of this particular assembly line required the rigging of chains and cables to lift the roof assembly with a traveling overhead crane and carry it to a production station, where it was joined to the wall/floor subassembly. The assembly of the roof components into a completed roof subassembly took "X" amount of time. Rigging, lifting, and joining the roof subassembly to the wall floor subassembly took an equal amount of time due to the absence of precision controls for the traveling crane and extensive hand fitting (prying out, hammering back) of the top of the walls to the roof perimeter. It should be noted that this extended time period for joining the roof to the walls provides a time buffer that is well matched to the time required for the concurrent production of the next roof subassembly and next wall/floor subassembly.

The flexible nature of the framed walls contributes to the need for extensive manual adjustment. The potential for improved productivity in this joining process lies in the development of temporary fixtures to hold the top plates square and precision crane controls for locating the roof subassembly over the wall/floor subassembly.

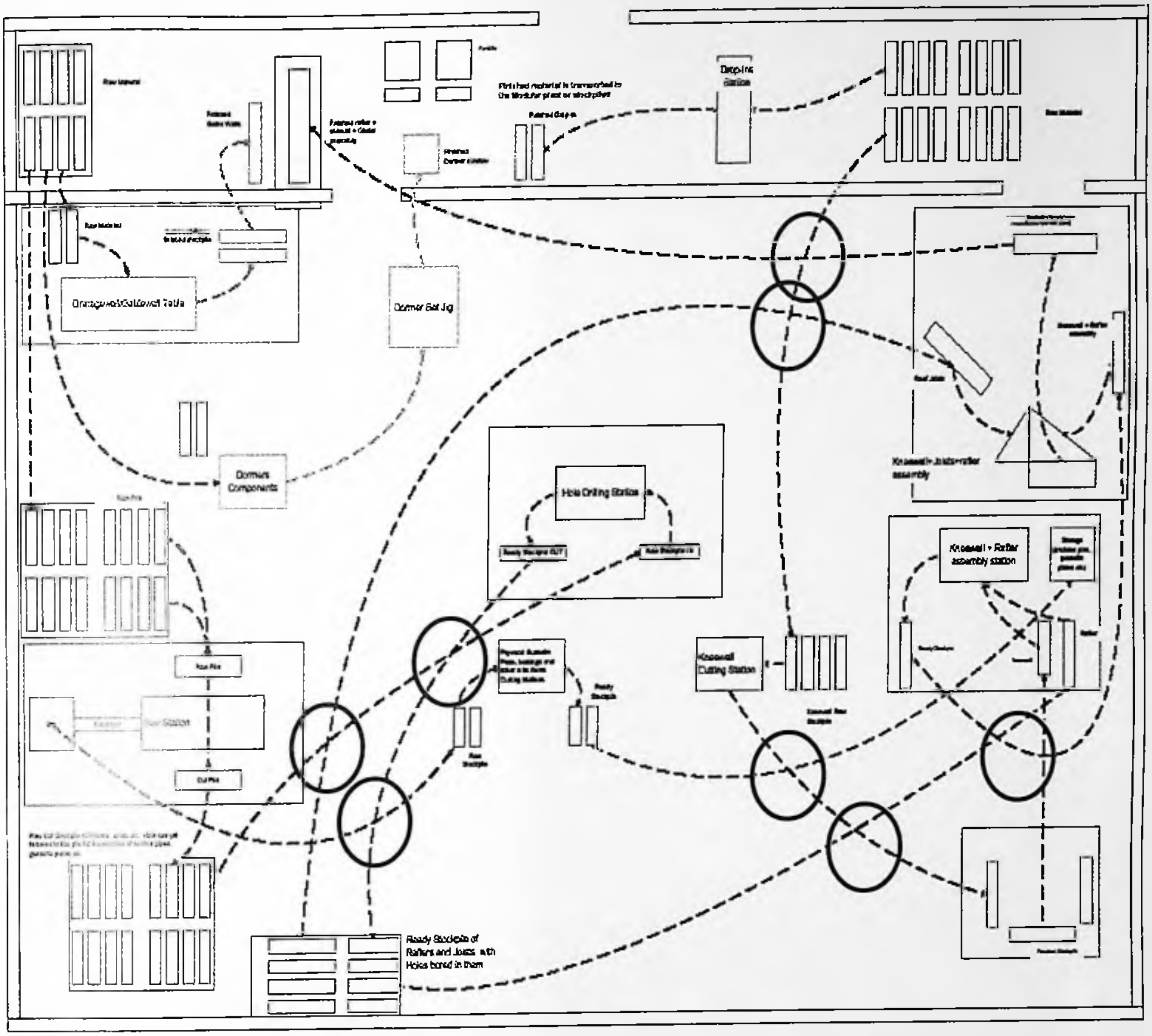


Fig. 3.32 Component plant layout diagram highlighting conflicts in material movement paths

Builder Two

Builder Two is a medium- to high-volume production builder and a regional division of an international homebuilder. Builder Two has in-house architectural services and offers predesigned plans for single-family detached houses and townhouses with custom options to buyers. Upon purchase, the home is produced making extensive use of subcontractors under the direction of an on-site superintendent, who uses a Web-based responsive schedule to coordinate the project. This study will focuses on the regional division operating in the mid-Atlantic portion of the United States.

The previous study of information flows through the Builder Two production process identified the framing of walls, floors, and roof as a potential bottleneck in the overall production process. Based on this finding and consultation with Builder Two, a more detailed study of the framing of the walls, floors, and roof trusses was undertaken.

Process Narrative (Read in Conjunction with the Foldout Process Map)

Fig. 3.33 Process map for Builder Two (See Fold-out Process map)

Preconstruction

Builder Two clients select from home designs provided for each respective community. Clients are offered options to the standard design model to customize their homes. The options listed by the Corporate Sales Office for selection by customers include amenities such as fireplaces, wood floors, and additional square footage. Once the design parameters are selected, they are placed in the builder's Housing Information System, which informs the departments and trades responsible for the home completion. Initially, preconstruction contractors, such as foundation and manufactured building system suppliers, use this information to augment their standard home production plans. Later, downstream trades can be scheduled using the same information.

The Corporate Sales Office processes a Job Initiation Order (JIO) once the Operations Committee has approved a contract. This committee meets weekly. The Vice President of Construction calls a superintendent with a project start date. Upon notification, superintendents begin a house foundation survey (staking out) and preconstruction preparations. The contract release also starts the local permitting process. Permits for a construction start typically arrive prior to the start of the foundation. Foundation footings can be dug and poured prior to obtaining a permit but may not be inspected without one.

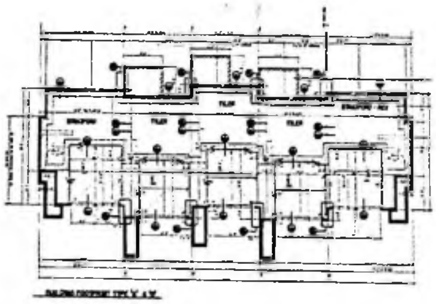


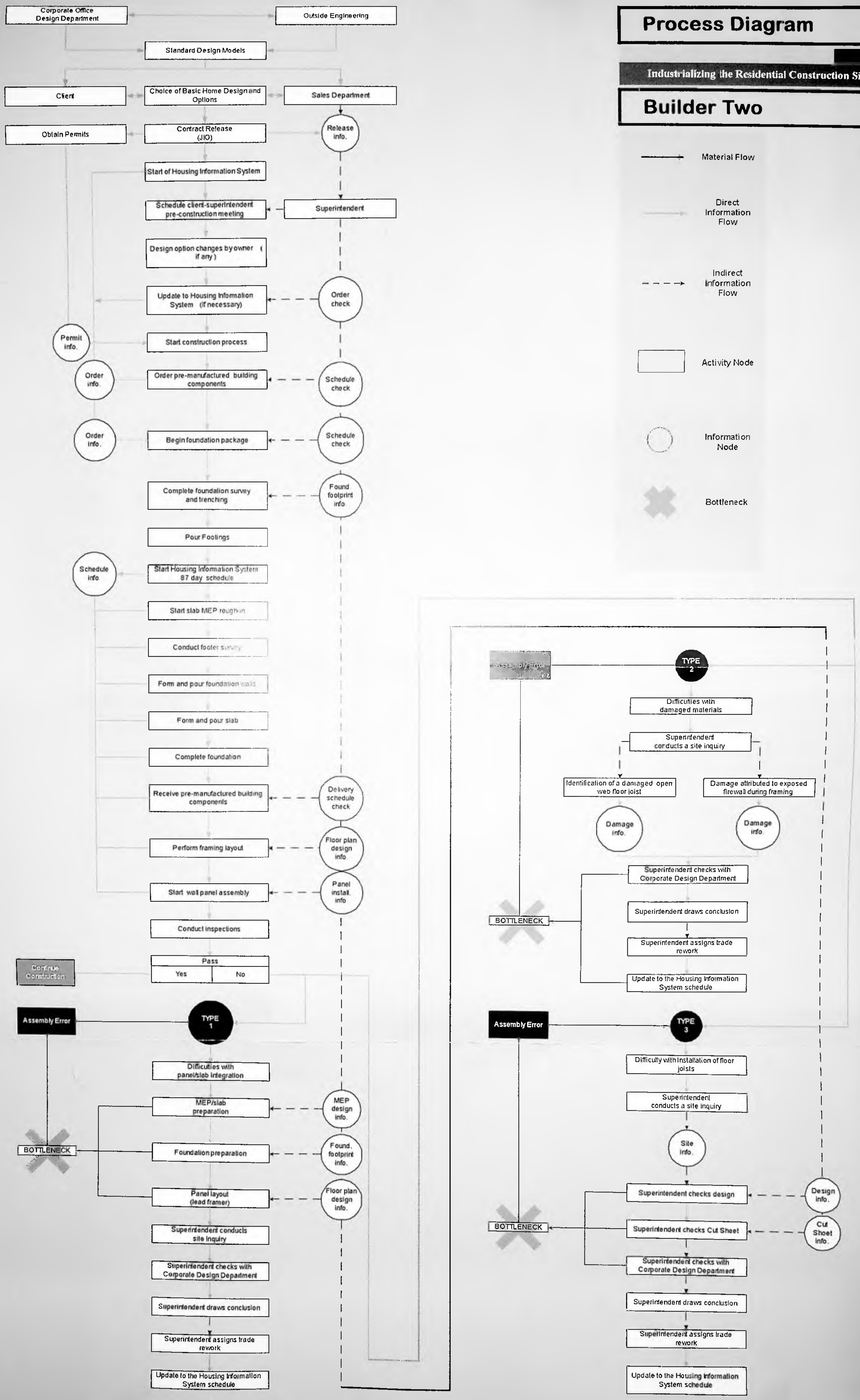
Fig. 3.34 Builder Two foundation plan information

Upon initiation of the Housing Information System, preselected building component suppliers such as wall panel, floor truss, and roof truss manufacturers are notified to begin production. These preapproved contractors are supplied with appropriate architectural drawings identifying wall layouts, floor and roofing requirements, as well as mechanical, electrical and plumbing (MEP) locations. Similarly, preselected foundation contractors for surveying, trenching, MEP, and slab preparation are notified to begin production. Preapproved contractors are supplied with appropriate drawings identifying site layouts, foundation footprints, and MEP rough-in

Process Diagram

Industrializing the Residential Construction Site

Builder Two



locations.

During the permit and building material supply period, a meeting is held between the client and the superintendent to inform both parties as to project delivery expectations. At this meeting, design options can be reviewed and minor changes can be ordered upon superintendent review and approval. Generally, superintendents allow home owners a three-week time period from the date of the preconstruction meeting for possible home option changes. Any change to the home is typically limited to a selection of predetermined design options. Ultimately, what can be changed is determined by the timing of this meeting in relation to the construction process. The earlier this meeting occurs in the process, the more flexibility is afforded for the possibility of a change.

The superintendent must approve all design option changes, as he or she is the single authority bridging corporate design and engineering departments with the on-site construction trades. The superintendent submits acceptable design options to the sales department for update to the Web-based Housing Information System. Late or radical option changes may require upper-management approval. Finally, the Corporate Sales Office updates the Housing Information System based on changes or option substitutions agreed upon at the client preconstruction meeting.

While the JIO informs the premanufactured building system component production and foundation work start-ups, superintendents verbally cross-check these activated material orders and scheduled component production with the individual suppliers and subcontractors. Late option changes may require supply or component modification/clarification to the suppliers from the superintendent. Additionally, on-site work compression or delay may require delivery rescheduling by the superintendent. Similarly, site restrictions may require material staging or delivery rescheduling. The project superintendent may call or fax manufacturers to verify order processing and delivery schedules.

Foundation system

Foundation subcontractors begin on-site foundation work with footprint plans given to each affected trade. Foundations observed were slab-on-grade type. For single-family homes, an owner's model selection defines which preapproved schematics are to be used by the foundation contractors. In townhome construction, the homebuilder can construct a complete multiunit slab foundation in advance of full-phase purchase commitments.

Foundation survey and trenching begins on the selected site. Slab control points are pinned and the slab footprint outlines are chalked. Footer placement is achieved with a laser level and backhoe operation. When trenching has been completed, the concrete slab perimeter strip footings are poured.

Upon completion of footings, the Housing Information System Web-based schedule commences. Subcontracting trades can expect to perform ordered activities based on projected two-week schedules. These work increments are typically updated daily by the superintendent to match actual on-site production levels. The

(A) Underslab services placed prior to backfill and gravel

(B) Underslab services at foundation offsets

(C) Underslab services in completed slab

Fig. 3.35 Underslab plumbing and finished slab

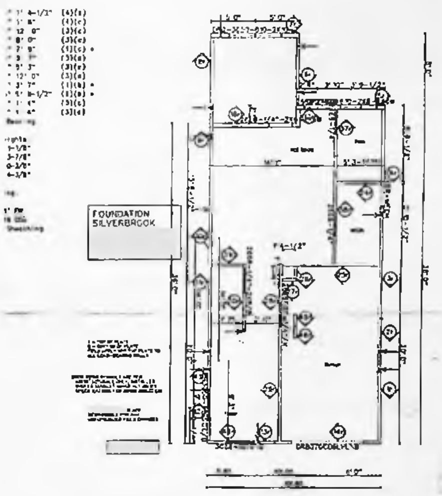


Fig. 3.36 Wall panel installation sheet

Fig. 3.37 Wall panels as delivered and installed

Fig. 3.38 Wall panels and out-of-square foundation

Fig. 3.39 Preengineered component handling

Fig. 3.40 Preengineered component damage

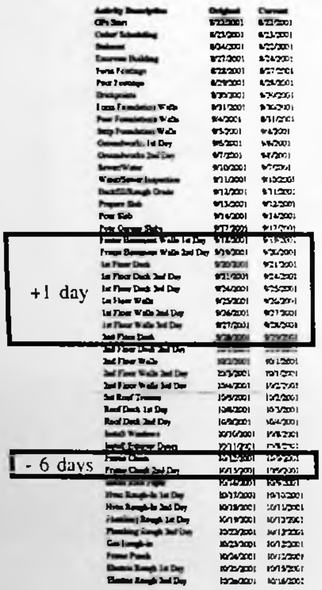


Fig. 3.41 Online Housing Information System update, Column 1—Initial schedule, Column 2—Revised dates; schedule buffers coordination with additional time

complete home production takes approximately 120 calendar days or 87 working days.

After footer placement, plumbing and electrical runs are sited, trenched, and prepared for the slab pour. The in-ground strip footings are resurveyed upon completion. The surveyor identifies exterior foundation wall points (brick points) along which the concrete foundation wall forms will align. The concrete foundation wall forms are placed and poured. The forms used produce flat finish or rusticated exterior wall patterns.

Wall panel layout

The wall panels are delivered on site around the time of slab completion. Framing layout by the lead wall panel foreman begins once the slab has cured and wall panels have arrived. Typically, chalk line layout begins along the highest rear corner of the slab. With the slab's front face typically containing foundation offsets for garage framing, the foreman pulls a line inset the dimensional width of the exterior wall panel system, from the rear corner to the center of the first shared partition firewall. Individual townhouse unit dimensions are noted on the drawings with an outside frame-to-frame measurement. The foreman pulls this distance and then subtracts the width of the firewall, its framing gap, and interior wall panel width to determine an inside wall line mark. As many townhome slab foundations step down in elevation per unit, some foremen attempt to use a longer single measurement pull from the rear start-dimension corner point. Perpendicular layout lines are then squared using a 3-4-5 measure and snapped to the front of the house.

The process of squaring layout lines becomes more difficult when foundations deviate from square. The manufactured wall system's overall dimensions are factory set and must be adjusted to fit evenly and squarely upon the available slab dimensions. This task requires particular skill and experience from the layout foreman. Production tolerances (related to firewall installation and its framing gap) matched with vertically stepping layout points further frustrates the end-wall panel installation to a foundation dimensional match.

Wall panel assembly starts once layout has been completed. On-site staging of wall panels brings palletized panels close to the work area. Panels are packaged for shipping economy, not layout efficiency, and must be broken out once staged. However, interior and exterior walls are typically separated by pallet. Workers match a panel layout drawing with identification numbers affixed to each panel. Superintendents sometimes mark corresponding panel numbers along the slab line layout to assist workers in wall identification and placement.

Workers have two options in placement procedure. Panels are typically taken from the pallet and set at the exterior corner wall positions first. Workers then move from these corners to the center wall panel. This method allows for a single dimensional alteration (if necessary) of the final panel in the center of the wall. Some crews pull panels off as received, with placement occurring in a piecemeal manner. Before panels are placed on the slab, a weather seal foam strip is attached to the slab. Once the wall panel is placed, installers attach the panels to the slab with concrete nails through the base plate of the panel. Temporary bracing is attached as necessary. Upon completion of the exterior walls, interior walls are placed, with work commencing from squaring. With all wall panels set, horizontal alignment and vertical plumbing of the top of the panels are completed by nailing the top (splicing) plate in place.

Fig. 3.42 Underslab pipe falls in firewall plan; field modification damages firewall

Results of Analysis

Three types of problems were discovered in the analysis of the construction process: precision problems, damaged components and materials, and problems with interpretation of information.

Precision problems

Assembly anomalies are potentially caused by information inconsistencies (dimensional and precision errors) spread across the slab survey, foundation production, and wall panel framing layout processes. While precision survey techniques typically employ the smallest dimensional tolerances of all of the on-site production processes, subsequent trade activities can disturb survey control points, contributing to dimensional errors propagating throughout remaining processes. Slab accuracy and tolerances vary with the layout/forming/placing processes employed. Foundation walls projecting above grade are discontinuous and difficult to keep square with the rest of the foundation. Panel layout and placing efficiency is significantly affected by slab deviations from square and the layout foreman's ability to compensate for out-of-square foundations/slabs. Major out-of-square errors in the exterior walls that cause the wall panels to overhang the foundation often require installation of additional foundation wall supports. Major out-of-square errors on interior walls may require the on-site crafting of tapering framing to bring the finished interior space back into square prior to drywall installation.

Plumbing and electrical underslab runs are set before the slab pour. Because they are loosely set in place prior to the leveling of foundation fill, they can be physically displaced from their original intended position. Resulting location errors are difficult to correct due to their embedment in the slab. Rework to correct these types of precision error requires breaking through the slab, relocating the underslab run, and repouring the slab.

Damaged components and materials

Damage of preengineered structural components (floor or roof trusses) was observed with a superintendent, whose inquiry could not determine whether the damage occurred at time of manufacture, delivery, or installation. The precise quantity of preengineered components shown on the drawings is delivered to the project site; no additional components are provided as replacements in case of damage. Truss installers may have installed the damaged component to meet production goals. Damage to preengineered components can cause significant delays to the project schedule. It requires the superintendent to coordinate the possibility of a repair with the builder's engineers and representatives of the component manufacturer. If repair is not possible, a replacement truss must be manufactured, shipped, and installed prior to the next phase of construction.

The drywall firewall system is the most fragile building component on the site during wall panel and floor and roof truss installation. Punctures, ruptures, and other damage to the firewall can require its extraction and replacement to meet regulatory requirements. Firewall punctures are often caused by errors in placement or location of MEP pipe risers and collisions between bulky interior wall panels and the firewall surface during panel placement.

Interpretation problems

The superintendent noted additional floor trusses present on site and a missing floor truss from a truss-girder assembly (Fig. 3.43). The superintendent checked the suppliers' installation sheet and observed that the designation for a truss girder constructed of multiple trusses was to be indicated with an asterisk. The asterisk notation did not indicate the number of trusses required for this member (Fig. 3.45). Workers installing the trusses were not able to determine the correct installation from a review of previously constructed units. Direct contact with the supplier was required, and rework to install the omitted truss was assigned. This error began on the project documentation that showed multiple lines close together to indicate a truss girder constructed from multiple trusses (Fig. 3.44). The required number of trusses and their relationship to each other (laminated or spaced apart) could not be determined from the drawings. As the truss lines were poorly represented, it was difficult to discern the design intent from the reproduced on-site drawings.

Major framing errors observed by the superintendent may require contacting the Corporate Design Office for corrective alternatives. The superintendent then notifies all affected trades of the necessary rework and accepted techniques for repair. Small changes are handled directly by the superintendent in conjunction with the component manufacturer and affected trades. Upon successful completion of the rework, the superintendent updates the Housing Information System so that affected downstream subcontractors and suppliers can adjust their schedules.

Fig. 3.43 Superintendent's observation of missing truss

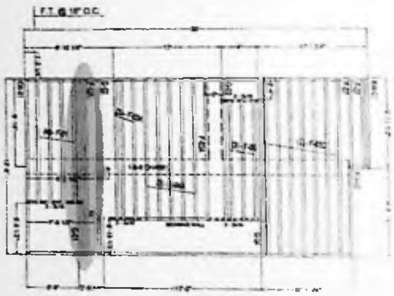


Fig. 3.44 Builder's framing plan, multi-ply trusses highlighted

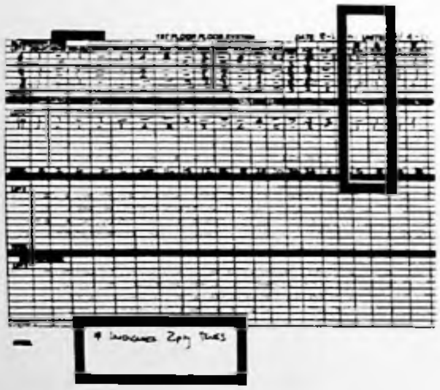


Fig. 3.45 Manufacturer's component list, highlights over special two-ply notation

Builder Three

Builder Three is a medium- to high-volume production builder and a regional division of an international homebuilder. Builder Three has in-house architectural services and offers predesigned plans for single-family detached houses and townhomes with custom options to buyers. Upon purchase, the home is produced, making extensive use of subcontractors under the direction of an on-site superintendent who uses a Web-based responsive schedule to coordinate the project. This case study focuses on the regional division operating in the mid-Atlantic portion of the United States.

The previous study of information flows through the Builder Three production process in *Industrialization of the Residential Construction Site—Phase II: Information Mapping* identified the framing of walls, floors, and the roof as a potential bottleneck in the overall production process. Based on this finding and consultation with Builder Three, a more detailed study of the framing of the walls, floors, and roof trusses was undertaken.

Process Narrative (Read in Conjunction with Foldout Process Map)

Fig. 3.46 Process map for Builder Three (See Fold-out Process map)

Preconstruction

Builder Three's clients select from home models available for each respective community. Clients are offered options to the standard design model to customize their homes. The options listed by the Corporate Sales Office for selection by customers include amenities such as fireplaces, wood floors, and additional square footage.

Once the design parameters are selected, they are placed in the builder's Housing Information System, which informs the departments and trades responsible for the home completion. Initially, preconstruction contractors such as foundation and manufactured building system suppliers use this information to augment their standard home production plans. Later, downstream trades can be scheduled using the same information. Once a contract has been signed between a client and the corporate office, a copy is sent to the corresponding community superintendent. This is known as the Job Initiation Order (JIO). It contains all selected options and a copy of the contract agreement.

Upon receipt of the JIO, the superintendent seeks a permit from the county in which the community is located. Depending on the county office, this request may take one day or multiple weeks. After receiving the permit, a Housing Information System sheet is generated and distributed to all subcontractors. Upon initiation of the Housing Information System, preselected building component suppliers such as wall panel and truss work manufacturers are notified to begin production. These preapproved contractors have a copy of the standard design models.

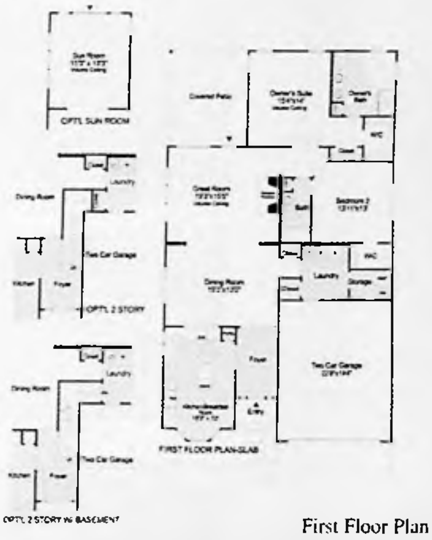


Fig. 3.47 Typical model design with options shown at right

Fig. 3.48 Typical model elevation options

The corporate office informs these manufacturers about the model and the options chosen by the client. Based on this information, they fabricate the components to be shipped to the construction site. Similarly, preselected foundation contractors for surveying, trenching,

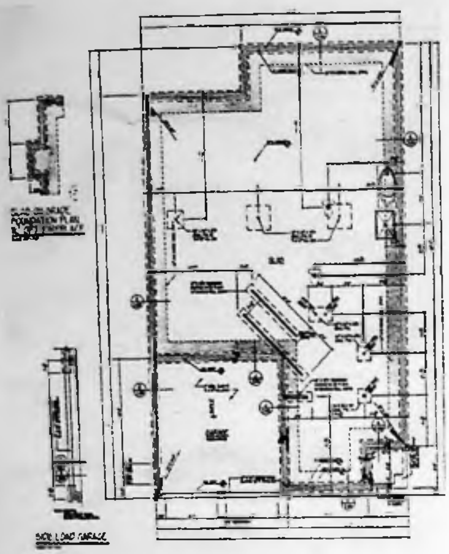


Fig. 3.49 Typical model foundation plan

Fig. 3.50 Chalk outline of excavation

Fig. 3.51 Slab pour

Fig. 3.52 Slab cured, complete

Fig. 3.53 Panel layout from longest side

MEP, and slab preparation are notified to begin production. Preapproved contractors are supplied with appropriate drawings identifying site layouts, foundation footprints, and MEP rough-in locations.

During the permit application and building material supply time periods, a meeting is held between the client and superintendent to inform both parties on project delivery expectations. At this meeting design options can be reviewed, and minor changes can be ordered upon superintendent review. Generally, superintendents allow home owners a time period from the date of the preconstruction meeting for possible home option changes. Any change to the home is typically limited to a selection of predetermined design options. Ultimately, what can be changed is determined by the timing of this meeting in relation to the construction process. The earlier this meeting occurs, the greater the possibility for a production change is. The superintendent must approve all design option changes, as he or she is the single authority bridging corporate design and engineering departments with on-site construction trades. The superintendent submits acceptable option changes to the sales department for update to the Web-based Housing Information System.

Builder Three has an off-site design center which sells additional options to the clients. The design center professionals' salary is dictated by the number and price of options they sell. When the off-site design center sells options to the clients, a spreadsheet summary is sent to the on-site sales department. This summary is presented to the superintendent, who consults his subcontractors and his documents to evaluate the possibility of the change. The result is communicated to the client and the corporate office, which is responsible for updating the Housing Information System to reflect the change.

Usually there is a two-week lag between an approved change and the update of the Housing Information System. Due to this lag, the superintendent has to call the subcontractors and instruct them to ignore the Housing Information System and follow his instructions instead. The whole process is time-consuming and prone to errors resulting in production errors and bottlenecks. While the initial JIO informs manufactured building system production and foundation work start-up, superintendents verbally cross-check activated material orders and scheduled component production with individual suppliers and contractors. Late option changes may require supply or component modification/clarification to the suppliers from the superintendent. Additionally, on-site work compression or delay may require delivery rescheduling by the superintendent. Similarly, site restrictions may require material staging or delivery rescheduling. The project superintendent may call or fax manufacturers to verify order processing and delivery schedules.

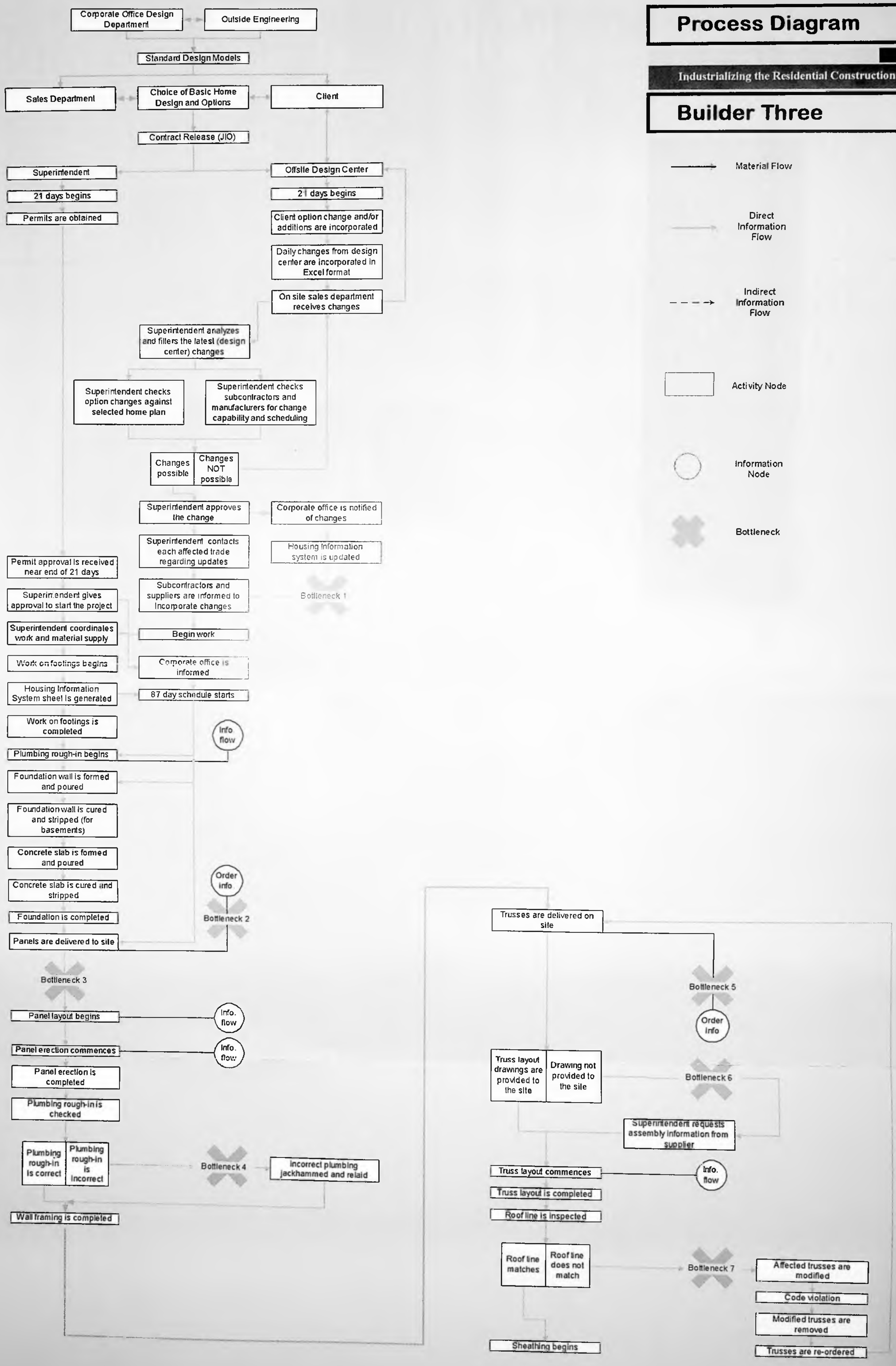
Construction Process

The foundation subcontractor refers to the Housing Information System and starts work. A survey team draws the house footprint into the soil. Based on this footprint, the foundation subcontractor excavates the soil and places forms for the footing pour. The plumbing subcontractor refers to the plumbing rough-in layout and

Process Diagram

Industrializing the Residential Construction Site

Builder Three



lays the underslab pipes. The superintendent cross-checks the position of the plumbing rough-ins for consistency with the drawings. The concrete subcontractor places the necessary foundation wall forms, underslab fill, gravel, and the slab. The walls and slab are poured, cured, and stripped. Once the concrete slab is ready, the superintendent instructs the panel manufacturing company to ship the corresponding panels to the site.

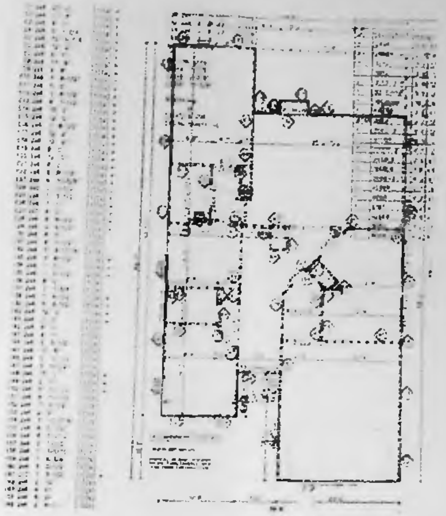


Fig. 3.54 Wall panel layout from panel supplier

When a client purchases a new home and finalizes the options, a JIO is generated and sent to the panel manufacturing company. The panel company has a copy of the panel drawings for all possible options for a house. The model options purchased by the client are standard but, depending on the orientation of the house on the site, there can be considerable changes in the panel design. If a house model is reversed, i.e., if the standard model has a garage on the right and the model selected by the client has a garage on the left, panel designs change. If the panel manufacturing company fabricates panels for the standard right-sided garage but the buyer has opted for a garage on the left side, the OSB sheathing panel will be attached to the inside instead of the outside of the wall panel. In such a case, the workers have to remove the OSB and resheath the panel.

The framing foreman refers to the panel layout drawings and draws layout lines on the concrete slab. These lines are actually the position of the wall panels on the concrete slab. The framing crew make their layout lines to account for the thickness variations of the finishing material of the each wall (vinyl siding or brick veneer). The plumbing crew, on the other hand, always lay their pipes with respect to the reference point given to them by the surveyor. The inconsistency between panel and plumbing layout reference points results in potential problems in the accurate positioning of the plumbing rough-in locations in the slab.

Fig. 3.55 Panel number on slab

Fig. 3.56 Panel delivery

Fig. 3.57 Panel identification mark

Fig. 3.58 Manual sorting of panels

After the panel layout has been drawn on the concrete slab, the framing team write the panel numbers on the concrete slab corresponding to their location on the slab. This step enables the framing crew to lay the panels without referring to the panel layout drawing. The framing crew unload the panels from the delivery truck using a forklift. The panels are stacked close to the concrete slab. The crew then take each panel from the stack and place it according to its number on the slab. The panels are then connected to the slab with anchor straps. This process is repeated for the whole stack of wall panels. The exterior panels are connected, and then the internal panels are positioned and squared to the exterior panels. After all the panels set, the framing foreman climbs on top of the panels and squares them to the concrete slab and each other using a hammer and a spirit level. A top plate is fixed to the panels, which ties the panels together.

After the framing process is complete, mistakes in the plumbing rough-in become evident. The plumber has to come back and correct the underslab plumbing rough-in locations. Since the pipes are already cast into the slab, the plumber has to use a jackhammer to remove the concrete. He then lays out his pipes again to correspond to the correct wall locations. During this process, the wall panels are also in place, further frustrating the re-laying of rough-ins.

Fig. 3.59 Interior and exterior panels set and braced plumb

Fig. 3.60 Exterior panels set and braced plumb

Fig. 3.61 Panels aligned by nailing to top plate

Fig. 3.62 Plumbing misalignment discovered after panel installation (1)

Fig. 3.63 Plumbing misalignment discovered after panel installation (2)

Fig. 3.64 Plumbing misalignment observable during panel layout

Mistakes in the underslab plumbing rough-in locations are evident when the panel layout is drawn on the concrete slab by the framing crew. It would be much easier to correct mistakes in plumbing at this stage, but would delay the panel assembly crew. It would also ensure higher overall quality and time savings.

After the framing process is complete, the truss manufacturing company delivers floor and roof trusses to the construction site. The truss manufacturing company has to provide a truss layout drawing with the trusses, which communicates the installed location of each truss in the overall layout. Sometimes this document is not prepared or provided by the truss manufacturing company. In this case, the truss installation procedure cannot proceed, and the superintendent has to request this document from the truss manufacturing company and wait for it to arrive.

The framing crew installs the trusses referencing the truss layout drawings. The trusses are delivered to the site stacked on pallets. During unloading, the trusses are often dropped onto the ground, sometimes causing damage. After the trusses are installed, there is an inspection to examine the consistency and continuity of the roof line. Occasionally, due to either errors in the panel layout or damage to the trusses, the roof line does not align with the adjacent and adjoining trusses. In this case, the workers try to adjust the height of the trusses by trimming or shimming the trusses. Material removed from the truss can reduce its load capacity, and such field-modified trusses are considered damaged and need to be replaced. This process involves removing trusses that have been modified and installing new ones after they have been fabricated and shipped. After the trusses have been installed on the house frame, the sheathing process commences.

Results of Analysis

The Builder Three process diagram illustrates the information flow needed to get the construction under way. Once the site superintendent has distributed the proper information to the subcontractors and the purchase order has been released, the 80-day construction schedule begins.

Builder Three is in the early stages of integrating an off-site design center into the sales and production process. At the time of the data collection visits, the design center was allocated a 21-day period commencing after the signing of the sales contract to receive commissions for options sold to the home buyer. Because of time lags in updating the on-line Housing Information System, the production process is complicated when the design center sells options to the home buyer after the 21-day period. The options purchased are communicated to the on-site superintendent in spreadsheet format. On this site, five to six significant changes per house are typical. Each feature of the change is listed on a spreadsheet and transmitted to the superintendent for review, coordination with ordering, and scheduling. With changes approved, the superintendent manually updates the on-site drawings, notifies each subcontractor by phone or fax, and then sends the change to the corporate office for eventual update of the Housing Information System.

The combination of the time lag in updating the Housing Information System and frequency of changes throughout the production process result in reduced accuracy and diminish the effectiveness of the Housing Information System. The superintendent has to perform additional coordination with suppliers and subcontractors to validate the correctness of the on-line housing information. Most of the changes involve exterior door or window location or sizes. The superintendent manually incorporates these changes into the field documents. The superintendent also makes design changes to floor plans to accommodate buyer needs. No process was observed for forwarding error correction on the plans and design changes to the engineering and design department, contributing to the propagation of error when the house design is purchased by another home buyer.


Fig. 3.65 Staples remain after moving OSB from inside of panel to outside


Fig. 3.66 OSB partially removed from outside of wall panel

The plumber receives a foundation plan, which shows the position of plumbing rough-ins. The plumber lays his pipes in the ground with reference to a fixed stake provided by the surveyor team. These positions are cross-checked by the superintendent for accuracy. The plumbing team always do their layout from a fixed point, but the framing crew do their layout depending upon the nature of the finishing material for the house (vinyl siding or brick veneer). Due to this inconsistency, there are potential problems in the position of the plumbing rough-in.

The Builder Three corporate office has a contract with a panel manufacturing company. When a client purchases a new home and finalizes the options, the JIO is issued. The panel company has a copy of the panel drawings for all possible options for a house. Builder Three corporate office sends the JIO to the panel manufacturing company. The model options purchased by the client are standard, but depending on the orientation of the house on the site, there can be considerable changes in the panel design. If a house model is reversed, i.e., if the standard model has a garage on the opposite side, the panel designs must change. The panel manufacturing company fabricates panels for a certain sided home; in the reversed plans that OSB sheathing is fixed to the wrong side of the panel. This problem was observed on site in a home model under construction. Workers removed the OSB and resheathed the panels. Apart from the time taken for resheathing the panels, the foreman must check each panel for correctness. In some cases, the workers remove the OSB from panels that are correct, assuming them to be wrong. To address this problem, Builder Three now provides house orientation information to the panel company. Even with this information, there are still problems regarding manufacture of reversed interior wall panels within the panel set.

When the framers do their panel layout, mistakes in the plumbing rough-in become visible. In some cases, the plumbing pipes fall outside the wall panel. In places like a kitchen that has a dishwasher adjacent to a sink, mistakes in the plumbing rough-in can be extremely costly. The framers erect their panels and, after the exact location of plumbing is determined with reference to the wall panels, the plumber is notified. The plumber has to remove the concrete slab using a jackhammer and replace the underslab plumbing pipes.

When a new model house design is launched for production, the superintendent has to filter information from architectural drawings regarding room heights. In a new product, it is not unusual for the architectural drawings to have errors. The superintendent has to consult the architects and relay this information to the wall panel and truss producers. In the event of a filtering error, the trusses or wall panels are incorrectly fabricated, shipped, and occasionally installed. The resulting verification, removal, remanufacture, reshipping, and reinstallation produce a production bottleneck, slowing project progress.

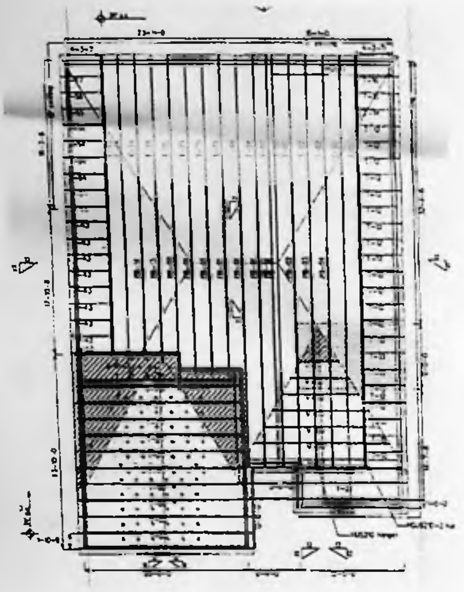


Fig. 3.67 Truss installation plan from supplier

Fig. 3.68 Truss framing plan from builder

Fig. 3.69 Truss top chord misalignment and field modification

Fig. 3.70 Truss end misalignment and field modification

Builder Five

Builder Five is a medium- to high-volume production builder and a regional division of a national homebuilder. Builder Five has in-house architectural services and offers clients predesigned single family homes with customized building options. Upon purchase, the home is produced, making extensive use of subcontractors under the direction of an on-site superintendent, who uses a Web-based responsive schedule to coordinate the project. This study will focus on the regional division operating in the southern mid-Atlantic portion of the United States.

Industrializing the Residential Construction Site—Phase II: Information Mapping identified the framing of walls, floors, and roof as a potential bottleneck area for Builder Five. Based on this finding and consultation with Builder Five, a detailed case study of the framing of the walls, floors, and roof trusses was undertaken.

Process Narrative (Read in Conjunction with Foldout Process Map)

Fig. 3.71 Process map for Builder Five (See Fold-out Process map)

To define the areas where errors, information disconnects, and production bottlenecks are located in the framing process for Builder Five, construction operations affecting the panelized construction process were observed. Observations were made during the following stages of construction:

- lot preparation
- panelization process (panel line layout and panel assembly)
- sheathing of panels

Three techniques for capturing the information were used to identify areas where bottlenecks occur within each stage: conversation with the site superintendent, notetaking on site to log the steps of each stage, and capturing information through digital photos.

Preconstruction

The information flow needed to begin construction is illustrated in Builder Five's process diagram. Once the site superintendent has distributed the proper information to the subcontractors and the purchase order has been released, an 80-day construction schedule begins.

Lot preparation

To begin the preparation of the lot, the concrete subcontractor indicates the corners for the slab pour by placing wooden stakes, using information from a full set of drawings, which includes a 1/8 inch = 1 foot foundation/slab drawing. A nylon string connects these stakes to identify the footprint of the house and also indicate the location for footing excavation. The formwork for the slab is established by staking 2X6 dimensional lumber around the perimeter. The dimensions used to mark the slab pour are slightly larger than the drawing dimensions to compensate for shrinkage during the curing process of the slab, but this approach can create squaring issues once the foundation has cured. The loose, sandy soil contributes to errors in panel alignment as it is not firm enough to hold an edge or sufficiently brace the formwork straight, square, and level with standard stakes.

Fig. 3.72 Formwork, stakes, hand-dug foundation trench

Fig. 3.73 Hand-digging foundation trench


Fig. 3.74
Completed slab with utility risers


Fig. 3.75 Step 1:
Wall panel is removed from pile


Fig. 3.76 Step 2:
With panel positioned, anchor bolt locations are scribed to bottom plate


Fig. 3.77 Step 3:
Anchor bolt location is transferred and plate is drilled


Fig. 3.78 Step 4:
Panel is placed over anchor bolts


Fig. 3.79 Step 5:
Panels are temporarily pinned to slab with cut nail


Fig. 3.80 Step 6:
Panels are plumbed and braced

Once the underground plumbing has been installed, it is inspected for proper slope, trap, and venting considerations, and the digging of the footers commences. This process begins by manually digging 1 foot by 2 foot continuous exterior footing trenches along the perimeter marked during the forming of the slab. The hand-dug excavation contributes to precision errors with both the squaring and the bulging of the foundation due to the combination of manual digging of the footers occasionally undermining or impacting the formwork. A solution to this issue could be to provide forms extending the full depth of the footers to help control the inaccuracies from manual digging.

Upon the completion of the footer excavation, the foundation is leveled, and a second plumbing inspection takes place. To ensure that the foundation is suitable for the slab pour, a soil hydration and compaction test is administered. The time taken for both the compaction test and any natural occurrences caused by the weather (rain/swelling) during this time all impact the schedule for the framing process.

This seven- to nine-day process to set and pour the slab ends once the slab has been leveled and cured and the anchor bolts have been placed according to code (21 inches on center).

Panelization process

The panel companies are responsible for deciding the panel breaks and the panel lengths. This information is gathered from the set of company drawings provided to the panel manufacturing company. Builder Five has established a standard specification and detail requiring the flush alignment of the OSB sheathing and the face of the slab. To meet this specification, the drawings provide dimensions for the proper setback of the wall panels to achieve the flush finish between OSB and slab face after panel installation. These dimensions do not account for the dimensional modifications made by the slab subcontractor, nor do they allow any tolerance for the wall panel installers to "lose" slab errors incrementally across the wall panels.

If the slab formwork is square, then the slab, wall panels, and consequently the building will also be square, and wall panel installers tend to set the first panels flush to the slab, assuming it to be square. Subsequent efforts to compensate for an out-of-square slab often result in wall panels and OSB sheathing overhanging the slab edge. The company specification requiring flush alignment of OSB sheathing and slab edge depends on the slab being square.

Panel line layout

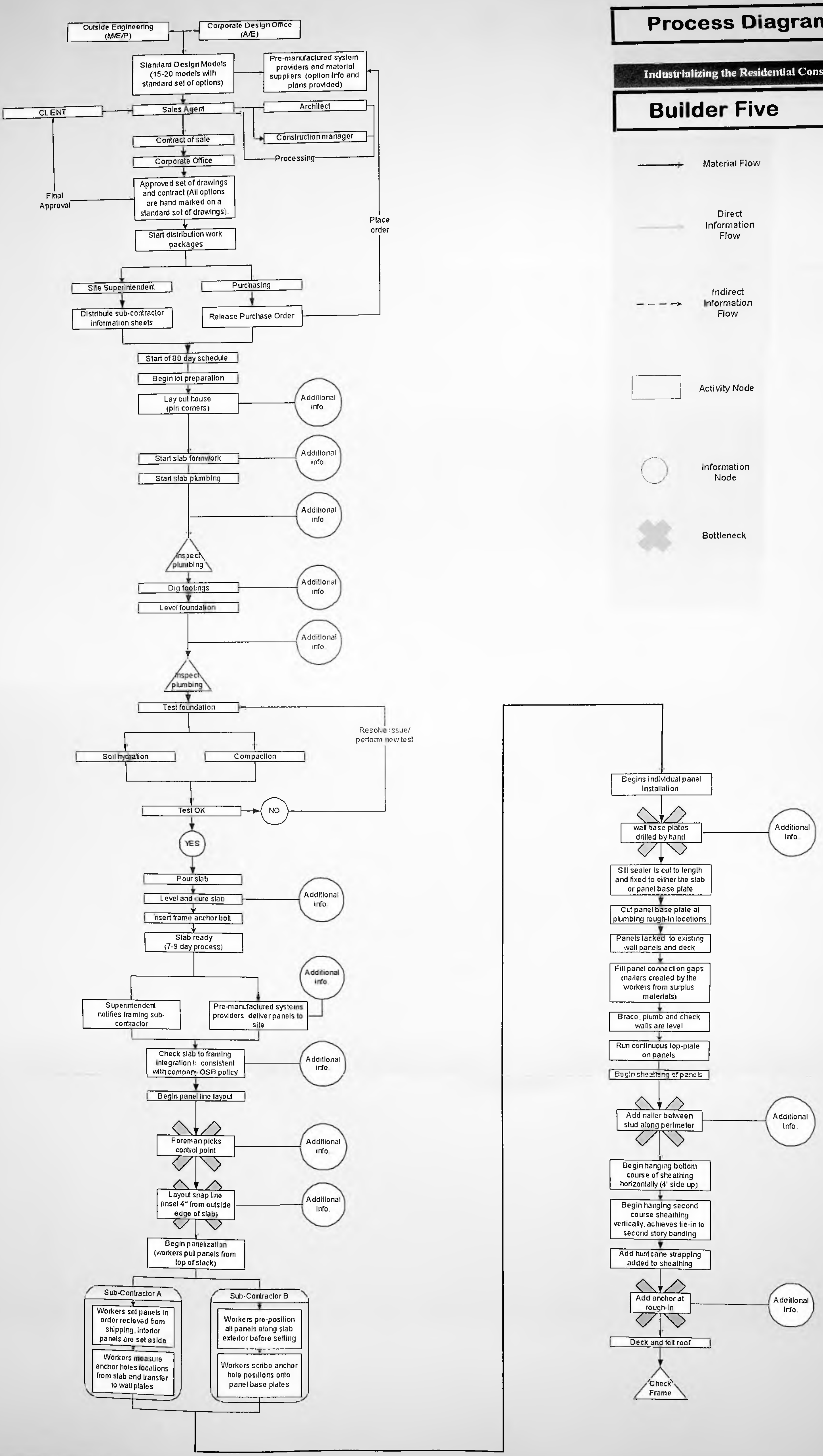
When the slab is cured, the panel company and the framing subs are notified that the site is prepared for their work. The unsheathed panels arrive on site marked with both lot address and panel assembly according to the accompanying plans provided by the panel company.

To begin the wall panel assembly process, the exterior wall lines must be marked on the slab. To do so, the panel foreman picks a point from one corner of the slab and squares the entire layout from that point (usually starting along longest unbroken slab perimeter

Process Diagram

Industrializing the Residential Construction Site

Builder Five



line). The foreman usually uses the panel layout or the site's architectural drawings to make his decision. Neither set of drawings shows the relationship of the walls to the foundation or indicated control points.

When snapped, the lines are inset four inches from the edge of the slab's face to enable the exterior stud walls (2X4s) and OSB to sit fully flush to the slab surface with no overhang to company specification.

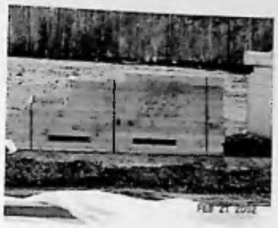


Fig. 3.81 Wall panels delivered to site

Panel assembly

During the site visit, two different subcontractors were assembling wall panels for the two houses observed. Subcontractor A begins the process by pulling the top panel from the stack and placing it on the slab. Subcontractor B prepositions the panels along the slab exterior before setting them. The absence of control points or panel layout on the architectural drawings limits the panel fabricators' ability to load the trucks so panels are unloaded at the site in the order of use. This shortcoming requires that the panels be handled two to three times prior to installation.


Fig. 3.82 Panel numbering

The two subcontractors techniques also varied when measuring the anchor bolt holes for placement on the panels. Subcontractor A pulls the measurement off the panel while another worker measures the placement space on the slab. They call out bolt distances and mark. They then measure the bolt distance from the panel layout line to find the short dimension distance of the hole. The panel measurer then marks the short dimension on the panel.


Fig. 3.83 Panel end, chalkline, and anchor bolt

Subcontractor B prepositions all panels around the slab before assembly. The panels are laid on the slab flush with the anchor bolts. Workers then trace the elevation of the bolts onto the base plates of each panel. A measurement is taken from the slab layout to establish the short dimension distance. This distance is then marked within the premarked bolt outline.


Fig. 3.84 Installing OSB spacers to make up for differences between panels and foundation

Holes are then drilled in the wall panel base plates. Strips of sill sealer are cut to the length of the panel and affixed directly to the slab or to the panel. There are no standard methods preestablished by the company for this process. Depending on the wall panel length and weight, the exterior panels are set in place over the anchor bolts by two to three workers.


Fig. 3.85 Panels arranged for scribing anchor bolt locations


Fig. 3.86 Exterior panels braced plumb, interior panels being set

Interference errors significantly impact the production efficiency of wall panel systems, requiring extensive panel handling and field modification. When there is a form of interference (e.g., anchor bolts in direct alignment with wall studs), the stud is driven to one side of the bolt with a hammer, the bolts are countersunk and tightened, and the stud is nailed back in place. In the case of plumbing-run interference, the base plate of the panels is fully cut away to allow for the pipe penetration. Two 3/4-inch-high steel plates are then placed across this break to protect the interior pipes from being penetrated by base molding nails. Additional anchor bolts are necessary on both sides of this panel break (perimeter only). When additional anchor bolts must be installed, the workers must come back and drill through the bottom panel plate and concrete. This process requires the setting of bolts and grout before anchoring the


Fig. 3.87 Aligning panel top plates

Fig. 3.88 Field installation of blocking for horizontal OSB pattern

Fig. 3.89 Horizontal OSB sheathing installation

Fig. 3.9 Sheathing nailers cut back for electrical box installation

Fig. 3.91 Hurricane tie anchor installed; OSB and tight stud spacing make impact wrench difficult to use

panel.

With the panels in place, they are tacked to adjacent panels and braced to the slab for stability. Where the slab dimensions are longer than the panel dimensions, the void spaces between panels are filled with shims cut from OSB. All walls are then squared, plumbed, and aligned. The steps for aligning ("worming") the top of the wall panels are as follows:

- panels are braced and straightened with top plate
- workers level outside corners and then apply a "straight" 2X4 to the top corner panel
- a worker walks along the top of wall panels and hammers panels in or out to meet the top plate edge
- when the panel and top plate align, the assembly is nailed in place

Panel sheathing

The sheathing for the exterior is added after all walls have been squared, anchored, nailed, plumbed, and aligned. There are two options for the application of exterior sheathing:

Option One - Plywood or OSB is laid horizontally. A second sheet is then nailed above and oriented vertically to overlap and connect the first and second floor framing. This horizontal-to-vertical pattern requires a field-installed nailer between each stud in the first-floor panels.

Option Two - Nine-foot plywood or OSB panels are oriented vertically to extend from slab to bottom plate of second-floor framing panels.

The cutting and installation of field-installed nailers required for the first option was observed to be both labor-intensive and time-consuming. This nailer could have been installed by the wall panel company if the dimensions and the sheathing patterns for each model were communicated clearly.

After perimeter walls are up and hurricane strapping is added, one worker goes around the exterior panels to tighten the anchor bolts with an air wrench. Because this process typically occurs after the panel sheathing process, there is insufficient space in the sheathed stud cavity for efficient constructability.

Results of Analysis

The following potential problems exist in the framing process for Builder Five:

- Different subcontractors are operating on different directions. Builder requirements are not reaching field crews in a uniform manner
- There is a lack of precision in layout, excavation, and construction of footings that has the potential to cause problems for downstream processes
- The foreman for each subcontractor is at liberty to pick his own control points for layout
- If the subcontractor is not aware of the builder's specification for alignment of sheathing and slab, the interior dimensioning

will be affected, causing further field adjustment modification of interior partition panels that could affect cabinet, millwork, and appliance installation

- The framing crew adds nailers to the prefabricated wall panels, slowing production. This step could be undertaken as part of panel production
- Anchor bolts, plumbing, and electrical risers are often in conflict with panels, requiring field adjustment and loss of panel integrity

Fig. 3.92 Panel rough-in conflict

Fig. 3.93 Panel misalignment at stair opening

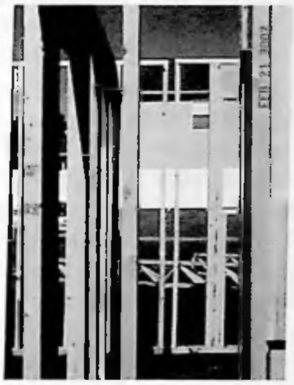


Fig. 3.94 Dimensional mismatch between panels and foundation

4

Generalized Findings from Field Data and Categories of Error

General Categories of Error

Production bottlenecks observed in this study were generally information-related errors, but a smaller group of resource-related causes of production bottlenecks were also observed. Limitations of a physical plant, tool, or workstation (taken in the context of the time required for preceding and following workstations needed to conduct an operation) may be the cause of a slowdown in the production process but are not productively attributed as errors. Weather and material or labor shortages are other examples of factors that can contribute to production bottlenecks but cannot be directly attributed to error. This report will focus on the opportunities to reduce information-related bottlenecks rather than weather- or facility-related bottlenecks.

In this study errors can be grouped according to the following categories:

- errors of interpretation (misread a drawing/miscounted a quantity of symbols)
- errors of omission in interpretation (didn't see a note or detail, page missing from set)
- errors of representation (drawn or specified incorrectly)
- errors of coordination (incorrect or omission of cross-check for system clearances, incomplete review of plan "handing" or mirroring on details)
- errors of precision related to installation (out of square, out of plumb, misalignments)
- temporal errors (information not up to date)

Potential Solutions for Categories of Error

These categories of error, with the exception of errors of precision, may be addressed with applications of existing information technology and principles of representation:

- errors of interpretation may be best addressed by producing project documents that incorporate both line and tone. Contemporary plotters and laser printers, as well as CAD programs are capable of producing tone or hatching patterns with no substantial cost increase. Where quantities are critical, as in built-up structural members, quantities should be indicated either on the drawn symbol or keyed to a table on the same page
- errors of omission in interpretation may be addressed by graphically highlighting the information used by a specific party.

> ***In addition to decision making, personnel coordination, production planning, and scheduling, managers, superintendents, and crew leaders observed in this study are required to extract and categorize information contained in drawings, updates, and specifications and then communicate this information with verbal instructions, hand-drawn diagrams, or hand-drawn lists to the appropriate labor crews.***

This would require knowledge of information filtered from each drawing, by each user of the drawing and writing a script for each user that would highlight the appropriate information on the printed, plotted or pdf page distributed to each user

- errors of representation would require a significant transition from the current approach to CAD drawings as simple lines and symbols to seeing the drawing as an assembly of objects. Each object would have to be developed, its attributes assigned, and its associated components scripted to include themselves whenever the object was placed in a drawing. The object scripts would include specification attributes for extraction into the text specification document accompanying the drawings
- errors of coordination could be addressed by a single architect/ designer/engineer who carefully checks for physical interference between elements and systems, adjusts plans to show proper plan "handing" or mirroring and incorporates only the options purchased. Alternatively the intelligent-object-oriented-CAD-drawing described above could become the basis for applying existing interference checking software. Plan objects could be scripted to respond to a filled checkbox on an e-sales form for "left handed" or plan mirroring to provide proper orientation for plan, elevation and associated details
- temporal errors, combined with great distances (physical or organizational) between the party holding the updated information and the party needing the updated information are being overcome using centralized databases. These databases, also referred to as Enterprise Resource Planning (ERP) tools and their precursors, MRP, and MRPII index data held by each organizational domain. The domain, sales, purchasing, production, customer service, etc. "shares" it's data through a central data warehouse to the other domains. A last-minute kitchen upgrade can be communicated to the superintendent this way, and the superintendents daily progress updates can let the sales domain know that the kitchen is half complete and they will need to include demolition and restocking costs in pricing the upgrade. Constructing an ERP with customized forms and scripted business logic for each domain is a daunting task for most small to mid-sized businesses
- Errors of precision are unique in this grouping as their potential solutions lie outside of manufacturing systems information technology tools, but are closely related to manufacturing systems precision control tools and strategies. Precision control tools fall in the family of jigs, fixtures, and self-aligning parts. Jigs and fixtures are special purpose devices specifically designed to assist a single stage in the production process. An example of a simple fixture is the vertical board builder one uses to locate and stop the roof assembly as it is being mated to the wall assembly. A development of this simple board, might be a jig or fixture bracket that is rapidly attached to (and detached from) the wall assembly which would square the top edge of the wall assembly and provide a tapering drop zone that would automatically align the roof assembly to the squared walls as the roof is lowered onto the walls. Industry has developed many special purpose jigs, fixtures, tools and processes to aid in the rapid location of parts prior to assembly. A detailed survey of manufacturers tools for precision should be conducted to identify

those most likely to increase productivity for production homebuilding.

Production Bottlenecks Related to Interpretation and Representation

In addition to decision making, personnel coordination, production planning, and scheduling, managers, superintendents, and crew leaders observed in this study are required to extract and categorize information contained in drawings, updates, and specifications and then communicate this information with verbal instructions, hand-drawn diagrams, or hand-drawn lists to the appropriate labor crews. This activity is referred to as information filtering, i.e., the process of providing just the information needed, in a form the labor crew understands, and at the time the labor crew commences the work. Eliminating filtering work that can be automated and removed from a manager's, superintendent's, or crew leader's daily responsibilities could increase system productivity.

Often, contemporary design and documentation processes do not address the growing need for increased precision and accuracy in field documents. Information contained in traditional construction documents was developed to generally guide the master builder, who had hands-on responsibility for coordinating systems and shaping materials to make one house. Architectural and engineering drawings for residential construction generally reflect their responsibility under the contract, i.e., a general description of the products and locations of completed walls, windows, floors, appliances, etc. Construction drawings in use today consciously omit information related to "means and methods," a subject traditionally left up to the builder to best handle on the site. However, in the context of an assembly process where semiautonomous suppliers, manufacturers, and subcontractors conduct their own work with little knowledge of the role their subsystems play in the whole house, the construction documents need to formalize the information to attain this general description of completion. As economic and labor issues continue to favor the use of components manufactured off site, tolerance of imprecision and ambiguity in the project documents approaches zero.

An example of a "means and method" needed to attain the design, but not included in the documentation, is the simple task of layout. Each leader of a work crew has to instruct the crew where and how materials are to be installed to complete the subcontract. While the design drawing may show two parallel lines to indicate a wall, the individual studs are rarely shown, leaving the layout of the studs to the crew leader, or in the case of preengineered wall panels, to the engineer making the "shop" drawing. The design drawing also shows a sink centered below a window on the model plan, but does not dimension its location. Convention or specification instructs the wall panel engineer to space the studs 16 inches on center, but the wall, as dimensioned on the drawings, does not quite work out to even modules of 16 inches. The engineer makes a decision to lay out the wall from left to right when facing the exterior. On site, the plumbing crew leader needs to locate the sink to place a drain pipe in the slab before it is poured. The plumbing crew leader knows the studs will be 16 inches on center and lays out the underslab piping and risers assuming the stud spacing will be laid out left to right facing the interior and proceeds to install the pipe. Ideally, the pipe riser will fall between two studs. When the wall panel crew arrive and set the wall panels, they cut out the bottom plate to let the pipe pass through. The cut in the bottom plate requires additional anchor bolts within 12 inches of both sides of the cut to meet building regulations.

The concrete crew arrive to pour the floor slab. They look at the specifications and place anchor bolts 48 inches on center. The crew leader decides the anchor bolt layout will go from right to left facing the exterior of the house. It turns out the plumbing riser falls about halfway between anchor bolts. The slab is poured and as it cures, the wall panels are delivered. The wall panel crew arrive on site and begin unloading and installing the stacked panels according to their engineer's plan. They measure the location of the anchor bolts, transfer the measurements to the bottom plates of the wall panels, and drill the holes. The laborer drilling the holes notices that a few holes fall at studs instead of between them, but there are lots of bolts to hold the panel in place. The panels are set and bolted to the slab. It turns out the plumbing riser falls right under a stud, the installers hammer the stud slightly to the left to make room for the riser. Additional anchor bolts need to be drilled into the slab, but the sheathing, installed when the panels were prefabricated, doesn't leave enough room for the hammer drill to get a vertical angle to drill the holes. One hole goes almost vertically in the foundation and an anchor bolt is placed. The second hole is a little more angled and punches through the face of the foundation wall and cracks the top corner of the wall. The crew finishes installing the remaining panels and leaves.

The preinspection review by the superintendent turns up the cracked foundation wall and some extra washers and nuts. The leftovers raise some question in the superintendent's mind. Close inspection shows that every third anchor bolt isn't visible through the plate but lines up with a stud. The superintendent calls the panel manufacturer, the panel installer, the concrete subcontractor, and the project engineer. None of the people called are in; phone messages are left for each. The next day the superintendent gets returned calls from each party. The problems are described in each of the phone calls, and an on-site meeting time arranged.

With all the parties on site, the project engineer tells the concrete subcontractor that the broken corner of the foundation has to be repoured and pinned to the remaining foundation wall with reinforcing bars. The concrete subcontractor explains that a crew will be available in a few days and asks whom to bill for the work. The discussion shifts to the panel manufacturer who insists that the wall panels were made to meet the contract and looks over at the panel installer. The panel installer explains that the anchor bolts were poorly laid out (the project engineer nods) and that the crew did the best they could, but agrees to have a crew relocate the studs that fall over anchor bolts. The project engineer points out that additional studs will have to be installed as the stud spacing will be too great if studs are relocated. The concrete subcontractor looks to the project engineer and asks why the anchor bolt layout is wrong. The engineer says because they fell under the stud locations, not between studs.

After an hour or so it becomes apparent that the layout of the studs from left to right from the exterior and the anchor bolts and plumbing right to left from the exterior is the root cause of this problem. Everyone present agrees the designer (not present) should have specified how the layout should be done. The project engineer relays this conclusion to the designer when they return to the office. The designer tells the engineer that layout falls under "means and methods" and is outside of the design contract. A week later, an engineer for a different wall panel supplier makes a decision that the studs should be laid out left to right and the process begins again.

Manufacturers design the parts, tooling, and processes used to make production documentation with exacting precision and extensive detail to maintain a level of precision which minimizes rework (zero defects) to increase production efficiency and decrease cost. This documentation is often developed after constructing and carefully studying physical and virtual prototypes to minimize problems during assembly. While production homes are often documented with dozens of pages of drawings and perhaps hundreds of pages of specification, there are significant disconnects between what the designer expects is necessary to understand and execute the work and what the crew leaders and laborers actually need to successfully complete their contract.

Compared to automobiles and aircraft, houses remain relatively simple products to construct. Given enough time, most of the field personnel involved in residential construction could coordinate their way out of the system conflicts encountered. "Time" is the key term here. In the context of productivity, on-site time is the most expensive time to correct coordination and interpretation errors due to hourly cost of the number of laborers rendered inactive by the error and costs of the crew leaders, superintendents, managers, designers, and manufacturers needed to resolve the error. These categories of error must be addressed and documented in the design/engineering stages. The site is the wrong place to fix a problem related to coordination or interpretation.

The key is providing up-to-date information (with current changes), just the right amount of information (to minimize filtering-related errors), in just the right form of representation (to minimize interpretation errors), and at just the right times (during estimating and ordering and in the field).

Production Bottlenecks Related to Precision

The idea of manufacturing building components (such as wall panels, trusses, and windows) off site is that specialized design, tools, and labor can be combined in a climate-controlled facility to construct consistent-quality components to a high level of precision and repeatability that on-site processes can seldom attain. Historians believe this practice began when preglazed window sash was imported to America from England as early as the middle 1700s. The practice accelerated in the 1970s and '80s when plywood structural panels, drywall panels, and prefabricated wood roof trusses became standard elements in house construction. The addition of prefabricated floor trusses and wall panels is a natural extension of the component approach for most production builders in this study. The only primary part of the structure and enclosure in homes in this study that is not premanufactured is the foundation/slab on grade. Prior to the use of premanufactured (both panelized and modular) components, the foundation/slab was primarily a support for the wood frame. Foundations were made as square, plumb and level as practical, but the walls installed above were independently squared and deviations from square, plumb and level could be accommodated by shaping individual sticks of wood to "build" precision from a coarse tolerance in the foundation to fine tolerances in finishes, millwork, windows, and appliances. The use of premanufactured (both panelized and modular) components places a new demand for higher precision on this foundation, the last remaining site-crafted part of the structure/enclosure. Instead of being able to "lose" error in small increments, the larger wall panels can be adjusted for deviations from square, plumb, and level only at their edges.

Coping with inaccurate foundations and minimal coordination between panel layouts, joints, and related systems dramatically reduces the efficiency of panel use from a simple unload, place, bolt down, and nail tight to an extensive on-site adaptation process of unload, layout, drill, cut, splice, place, bolt down, drill, bolt down, hammer into line, and nail tight. The extensive on-site adaptation requires additional labor and time buffers in the project schedule or causes delays.

Individuals with specialized knowledge of these components design them for manufacture and make them available in regional and national markets. Fundamentally, the use of manufactured components diffuses building knowledge across a variety specialists in a number of off-site locations.

General Categories of Productivity and Quality Enhancement Opportunities

The opportunities to increase production system productivity and product quality can be seen in two categories:

- Full employment of CAD capabilities to minimize field modification caused by
  - being uninformed about specific work processes
  - not coordinating structure, mechanical, electrical, plumbing systems
  - providing too much information for rapid understanding and application by crew leaders and laborers
  - providing too little information on dimensional locations of rough-in runs and fasteners
  - misreading of the "conventions" of two-dimensional drawings
- Development of field processes capable of meeting the precision required by manufactured components to
  - standardize site and building layout methods—identify layout control points on plans

- develop alternative payment/reward contracts for subcontractors based on the quality of the installed work versus the quantity of material installed
- develop standardized approaches / best practices for labelling, stacking, shipping, unloading and installing panelized wall components
- develop/deploy precision formwork systems for concrete processes to include placement of anchors and system risers
- develop/deploy spatial position tools to enable rapid inspection of formwork, anchors, and system risers; this tool could also be used to guide the crew unloading the wall panel to the proper location of the panel on the house

If the form, accuracy, and timeliness of information can be successfully addressed, layout and installation times—and with them, rework—should decrease.

As production housing continues to employ higher percentages of manufacturing practices, conflicts with craft-based practices will increase. At some time in the future, the cost of these conflicts will provoke a decision to either return to the craft-based master builder model or fully optimize both on- and off-site practices and gain full control over the process as manufacturers have done. Development of a work force fully trained in craft techniques and practices is an unlikely action for production builders as they exist today. A more realistic path for today's production builders is the development of a strategy to fully leverage the capabilities of their existing information systems with a production goal based on a fully coordinated set of documents, fully and individually filtered for each subcontract, for each house model offered.

Suggested Process/Information Technology Enhancements

BUILDER ONE

Builder One essentially employs all its subcontractors under one or two roofs. Because of the level of process control, Builder One is best positioned among the builders in this study to benefit from implementation of an enterprisewide information system. Such a system would link a decentralized sales office to the central management/design/engineering office and to both of production facilities.

Implementation of a full-scale ERP system would require an intensive study of in-house business practices and development of a physical information technology (IT) infrastructure prior to deployment of the system and thus should be considered a long-term project. In the short term, this builder could immediately reduce filtering-related errors by using existing software designed to extract additional information from CAD files and present that information in the various forms (graphic, text, tabular) required by the component and modular plants.

The changes required to implement this software would be the conversion of graphic CAD objects to more intelligent objects by encoding dimensional and quantity data with the graphic objects used to represent building components on the CAD files. A further benefit of intelligent CAD objects is that they enable the use of interference-checking software that could detect conflicts between electrical, mechanical, plumbing, and structural system elements during the more appropriate design and documentation phase, rather than during the production process.

BUILDER TWO

The Corporate Design Office does not typically document superintendents' "requests for information" or trade rework. This omission suggests that most on-site errors may be repeated as they are neither recognized nor integrated into the project's documents database or the Housing Information System. Superintendents must maintain hard-copy, on-site design updates for multiple house types and rotating subcontractors.

Subcontractors are paid based on timely completion of their subcontract. The "reward-for-quantity-installed" model may be encouraging installation of damaged or incorrectly detailed components to avoid delays in completion of the subcontracts. Due to the rotating nature of subcontractors and the diverse languages found among them, more intensive training or more explicit documents may need to be produced to shift the focus from quantity to quality.

The precision of the concrete foundation, slab-on-grade, and underslab utilities is a source of significant production efficiency loss in the subsequent wall panel and truss installations. A small investment in additional formwork setting time, formwork upgrades, or quality control inspections may be justified, considering the adjustments required by the subsequent trades: panel installers, truss framers, drywall subcontractors, and millwork and cabinet installers.

BUILDER THREE

Many of the errors and bottlenecks observed on the Builder Three site are related to the interface between systems and components originating in a manufacturing environment and those originating in a site-craft environment.

There are some advantages to the components originating in a manufacturing environment:

- less material waste
- less material damage due to weather
- decreased construction time due to concurrent manufacturing of components
- decreased dependence on skilled craftsmen for manufacturing and installation of components

Components originating in a manufactured environment have disadvantages as well:

- less redundancy in structural capacity
- prone to damage in packing, shipping, unloading, and handling
- less adaptable to dimensional variations
- longer time period required to remove, remanufacture, reship,

and replace if damaged
- more precise information required for manufacture, packing, shipping, unloading, and installation

The increased use of building components manufactured off site requires a higher level of design coordination, precision, and specificity in the construction documents. The increased use of manufactured components uncovers fundamental mismatches in precision tolerances between the systems that require additional quality assurance inspections of preceding systems to realize the full efficiency of the manufactured component system.

Other process enhancements that may be required are substantial improvements relating to the underslab plumbing. The drawings showing underslab plumbing rough-ins and wall panel placement should be dimensioned from the same control points during the design phase. The layout for wall panels should be coordinated with underslab plumbing, and the drawings showing underslab plumbing and wall placement should be dimensioned from the same control points. These steps would reduce the field conflicts. On-site inspection of underslab placement of plumbing rough-ins should occur later in the process, immediately prior to the slab pour, to ensure that pipes have not been moved during gravel and backfill placement. Similarly, a plumbing check should be performed before wall panel placement so that detected problems can be fixed prior to panel placement.

Substantial process efficiency improvements could be realized in the coordination of other design documents before field production. "Virtual prototyping" of wall panel heights, truss designs, structural supports, and MEP equipment locations prior to field assembly offers the possibility of detecting and correcting conflicting design information.

The on-line Housing Information System should be updated on a more frequent basis, perhaps on each owner transaction, to provide up-to-date information to subcontractors and suppliers. The on-line Housing Information System should be enhanced to
- enable suppliers to upload installation drawings
- give field installation crews access to the system to download best practices guides to component installation
- enable site progress to be recorded to support accurate pricing and feasibility analysis of option purchases between the design center and site superintendent
- automate filtering of changes to highlight the most recent change, affected parts of the work, and affected subcontractors
- establish "feedback loops" between the design center, superintendent, suppliers, and the design/engineering office to prevent propagation of errors in standard designs

BUILDER FIVE

The use of prefabricated wall panels has the potential to substantially accelerate the framing process while reducing material waste. However, the slab and underslab foundation services need to be coordinated with the panel layout to realize the full benefits of panelization. The field construction process would benefit greatly from coordination of these subsystems at the design stage to avoid spatial conflict resolution in the field.

The design documents could include more information to identify panel locations, control points for layout, and the sequence of panel erection. This change would provide better information for framing, footing, and underslab service subcontractors; increase the precision of the footings; and reduce the need for panel modifications in the field.

Consideration should be given to increasing the amount of work undertaken in the panel manufacturing stage. The nailers for OSB attachment could be added in the factory, and anchor bolt holes could be drilled in the bottom plate. This alteration would increase field precision and efficiency but would require improvements in design documentation to be successful.

5

Alternative Production System Generation

The recommendations for process modification and/or the implementation of information technology enhancements to the IT systems currently used by the builders are based upon the nature of the conclusions drawn from the data analysis. In discussion with the project advisory board members, two general classes of solution emerged: quality assurance process revisions and IT-related process revision alternatives.

Quality Assurance Process Revisions

The foundation and framing study revealed that Builders Two, Three, and Five were similar in the use of premanufactured wall panels anchored to cast-in-place concrete slabs and foundations. The study documented precision, coordination, and interpretation problems that were intensified because they occurred at the interface between the site-crafted concrete and the manufactured panels. Close examination of the process map shows that Builder Five's quality assurance inspections of the underslab plumbing occur twice before the slab is poured. This precaution corresponds to fewer plumbing/framing problems observed in the Builder Five study. The Builders Two and Three studies did not document plumbing rough-in inspections occurring until after the slab was poured and wall panels were placed. The study of these two builders documented several underslab plumbing location errors.

Quality assurance process revisions emerged as a potential remedy in discussions following presentation of the process maps. The process maps made it possible to observe a pattern of production bottlenecks occurring during framing operations that were related to preceding construction processes. Some examples are the discovery of the foundation being out of square or the plumbing riser not falling within the wall panel. The inference was that the layout process used by a following subcontractor frequently revealed errors of precision, interpretation, coordination, or omission in the work of a preceding subcontractor.

The discussion of quality assurance process revisions occurred in the context of mismatched precision tolerances between site-fabricated foundation/underslab utilities and manufactured wall panels. Here it seemed that a quality assurance inspection of the slab formwork, anchor bolt locations, and underslab utilities conducted prior to pouring the concrete foundation and slab could detect errors before they disrupt and complicate subsequent subcontractor operations.

An intensive dialogue with all parties involved in the actual construction—superintendents, production managers, subcontractors, component manufacturers, and crew leaders—is necessary to capture detailed knowledge

Implementing this quality assurance process revision would likely require additional buffer time in the overall process schedule. The time buffer would have to take into account potential rework time for the excavator, formwork/reinforcing subcontractor, plumber, and electrician, but is most likely to make the largest positive impact on the foundation and framing process for the least initial investment.

Housing Production System Development and Manufacturing Systems

The innovative approaches to manufacturing systems described in Chapter Two can be divided into three categories:

- product design and development, DFA, DFM, DFMA, DFD, DFX and CE
- data management and distribution, ERP, BI
- production systems, FM, AM, HM, TM, CIM, and MES

To some extent, each category will be a necessary part of an alternative housing production system.

The product (house) design and documentation needs to be continuously infused with knowledge from subcontractors, in-house tradespeople, suppliers and other field personnel. The information gathered from the field becomes part of the product (house) design and documentation, the same approach that is the foundation of Design for Assembly (DFA,) Design for Manufacturing (DFM,) and Design for Manufacturing Assembly (DFMA.) The continuous aspect of knowledge infusion from field to design and documentation depends upon a field feedback channel and is especially critical to prevent error propagation within a product line (pre-designed house plan, its options and upgrades.)

To maintain confidence in and dependence on the design documentation, the document set must be kept current, with up-to-date information on buyer options, changes and schedules. The documents also must be kept relevant to the user, the information must be filtered and represented in forms that are specifically developed for each user. Form development of this type is a common characteristic of the Business Intelligence (BI) approach to implementing Enterprise Resource Planning (ERP) systems in manufacturing industries. Accountants, inventory control, and personnel departments often use the same data, but in forms specifically developed to support the productivity of the user. The goal is to supply each information user the right (most current) information in the right (user specific) form at the right (not too early or late) time.

Production itself will likely continue to develop as an adaptation of a Flexible or Agile Manufacturing system (FM or AM.) The subcontractors / tradespeople, their specialized skills and flexible tools will continue in the role of the manufacturing cell and the builder will add or subtract cells to match sales / production demands. The web based schedule has allowed some suppliers to receive notice to proceed to manufacture components, set up the necessary fixtures and jigs to produce the components, order the material for the components, assemble the components and ship the components at the specified time and location without ready to communicate directly with the production builder. This semi-autonomous production is facilitated by the use of pre-designed plans that are pre-bid by suppliers, allowing them to operate in ways very similar to the autonomous Manufacture Execution Systems (MES) used in the automotive and electronics industries.

Enhancing the sophistication of business and production practices for all parties involved in the homebuilding enterprise is the key to continuing the development of advanced housing production systems.

Information Technology Alternatives and Enhancements

The general categories of information technology alternatives/ enhancements to the production systems are as follow:

- process simulation (numerical and graphic models and animation), particularly useful in understanding issues related to capacity of facilities, tools, materials handling, inventory and component interferences
- scripted filtering (e.g. color, highlighting, screening information to make only that which applies to the task visually prominent on formal production documents), applicable when error or productivity loss is attributed to excessive information superfluous to the subcomponent production tasks
- scripted representation (process pictograms), applicable when error or productivity loss is attributed to inadequate training or absence of task instruction in a form and language understandable to the personnel assigned to the task
- integration of data (ERP, MRPII), applicable when error or productivity loss is attributed to production information that is inaccurate or out of date

Placed in the context of the foundation and framing processes studied for this project, process simulation, a primary characteristic of Virtual Manufacturing (VM,) most likely would have uncovered conflicts between structural system components observed with Builder Two. Currently, the time needed to construct a three-dimensional (3-D) model of the building with a component level of detail is a strong disincentive to the use of process models in residential construction. Arguments citing the relatively low quantities of any design as a basis for minimizing the investment in design and documentation must be quantified against the frequency of interference errors and related rework costs compared to model and simulation costs in future research. At the present frequency of interference, errors and related rework costs are difficult to determine because costing and feedback loops are not common between field construction and design and rework costs tend to be absorbed into the construction process. Costs for the initial construction of the 3-D prototype will likely decline as the production building industry adopts 3-D models as a means of integrating sales, marketing, design, and production in a Concurrent Engineering (CE) model.

Scripted filtering is a strategy to automate the process of highlighting information for a targeted user or user group. An example is a proposed set of drawings given to the component manager for Builder One. The current production packet transmitted to the manager includes many pages of text and drawings not used by the manager to prepare the detailed "cut sheet" instructions for the workstations producing a modular folding roof assembly. Out of the dozens of pages, the manager is seeking a few bits of information, including roof slope, location of dormers, framing member dimensions, overhang length, rake overhang length, and the quantity of rafters, overhang frames, and gable end walls needed to construct the house. In the current process, the manager reviews six to nine pages of drawings and multiple text pages to extract the information needed by the component plant personnel. If the manager misreads, overlooks, or misinterprets the information, a set of roof components will be incorrectly fabricated.

Existing CAD and third-party software can be used to make a script that automatically extracts just the information needed by the component plant personnel and presents it as lists, diagrams, or text required by each workstation. Automation of the filtering step would require formalizing, in the case of this example, the component plant manager's existing information filtering process, evaluating that process, and writing a script to produce the same extracted information. Given that Builder One operates as a modular producer in a relatively controlled production environment, there are possibly dozens of workstations that manually repeat the same information filtering processes each day on each house. This change would potentially enable the component manager to focus on production rather than instruction, thereby enhancing productivity and reliability.

Each of these strategies is dependent on enhancing the level of knowledge encoded in the production documents and requires an intensive dialogue with all parties involved in the actual construction. In-depth discussions with superintendents, production managers, subcontractors, component manufacturers, and crew leaders are necessary to capture detailed knowledge related to the following:

- detailed work and decision making processes
- perceptions of the information forms and content required for parties and their workforces to conduct their work
- perception of the information currently provided, its effectiveness with their workforce, and its accuracy and completeness
- recollection of the types of situations that cause delay, problems, rework, or back-charges

Manufacturers implementing Design for Manufacture (DFM,) Design for Assembly (DFA,) or Design for Manufacture Assembly (DFMA) have proven that for effective production, the people conducting the work should be at the center of a dialogue with design, engineering and production planning. It is not yet clear if the most effective direction is to tailor the documents and process to the current sophistication of the workforce or to address the skills and sophistication of the workforce itself on a national scale.

Taken in aggregate, residential construction's shift away from handmade parts crafted in the field by a single master craftsman towards mass-produced components and materials assembled in the field by dozens of different independent subcontractors can be seen as the early stage of adoption (with adaptation) of production systems developed in the context of high-volume manufacturers. The errors and related production bottlenecks cited in these case studies demonstrate the need for extending the manufacturing production system model further into the field by developing the information systems, design processes, and field production techniques necessary to bring the precision of manufacturing to field installation of the components.

Process Modeling of Integrated Design/Construction Strategies

One of the most significant advances in new product design and production processes used by manufacturers is virtual prototyping. A virtual prototype is distinguished from a simple computer model in that the objects that make up the model carry additional attributes that enable simulation programs to accurately model the assembly process, highlighting occurrences of physical conflict, excessive installation time, and the likelihood of installation error. Applying virtual prototyping to model-specific areas of production studied in Phase III would enable development and testing of production system innovations without disrupting the business cycles of the production builders. These innovations would be simulated/modeled according to Phase III's recommended revisions to the design/ production system to provide production builders a graphical and numerical demonstration of viability of each recommended revision.

We anticipate this work to include to the following:

- process modeling of the specific production system details studied in Phase III to establish baseline data
- process modeling of alternatives/improvements to the system details studied in Phase III to develop and demonstrate viability
- integration of DFSA principles into the model design process and information systems to minimize production error and increase production rates
- application of information filters to customize information supplied to specific production stations with the goal of reductions in production error and bottlenecks
- introduction of integrated two-way information communication to provide production progress updates and revisions "upstream" as a feedback mechanism to refine scheduling processes and reduce systematic errors in information provided between the production domain and the engineering, marketing, and customer service domains

Summary of Conclusions

6

Purpose of the Study

The purpose of this Phase III report is to map, at a finer grain in the context of production and information systems, the construction subprocesses for four of the production builders who participated in Phase II. During the course of the mapping, problems and opportunities are identified. Alternatives and enhancements to the builders' current production and information systems are suggested.

Identification of the Areas of Detailed Study

Builders One, Two, Three and Five studied in *Industrialization of the Residential Construction Site—Phase II: Information Mapping* participated in this Phase III study by giving access to key personnel and construction sites to the research team. Each of the production builders participating in Phase III selected a construction subprocess for detailed study. In each case, the builder selected a process related to the assembly of the structural framing for the house:

- Builder One: Roof subassembly construction
- Builder Two: Wall panel assembly in townhomes
- Builder Three: Wall panel assembly in single-family, detached houses
- Builder Five: Wall panel assembly in slab-on-grade, single-family, detached houses

> ***In each case, the builder selected a process related to the assembly of the structural framing for the house***

Data Types/Quantities Collected

The field studies were conducted in two-day periods at each builder's production site. The data was collected in hundreds of pages of interview notes, observation notes, digital images, builder forms, and builder drawings. The research assistants operated as independent observers, each recording the following:

- information inputs and outputs at each process stage
- material inputs and outputs at each process stage
- physical environment/staging unprocessed and processed materials
- task stages
- level of task complexity, unchanging versus changing information
- personnel assignments
- related/competing activities for workers at each stage
- personnel comments regarding error, difficulty, or quality concerns

- approximate task duration at each stage
- quality control methods
- task completion indicators

Analytical Findings

The small number of builders represented in this study precludes the establishment of a verifiable rule capable of predictive use. However, the builders in this study are fairly representative of production builders, giving the generalizations formed in the conclusion a broader applicability in the U.S. market.

The result of this finer-grained mapping identified errors and production bottlenecks related to the piecemeal adoption of production strategies. This finding was most evident in the observations of the panelization projects but could also be seen in the assembly line production of the roof assembly.

In the panelization studies (Builders Two, Three, and Five), the shift from site crafting of individual pieces of materials, cut to fit in place, to the installation of modular wall panels constructed off site at a manufacturing site should be considered an early effort at a design for manufacture and assembly (DFMA) strategy. Implementing a DFMA strategy with only one system (wall panels) is a piecemeal approach, where the full benefits of the panelization effort will seldom be realized. The production strategy must be applied to the whole house design and construction—or at a minimum to the assemblies and systems adjacent to the wall panel—to avoid productivity problems, quality problems, and their associated costs.

One of the challenges of interjecting a manufacturing process into residential construction is precision. The layout tables, jigs, and fixtures used in the manufacturing plant allow a high level of precision in the flatness and trueness of the component. In the case of wall panels, the conflicts between manufactured precision and site-crafted precision become visibly clear at wall panel connections. Where the site-crafted wall might be adapted to the imprecision of the foundation on a plate-by-plate or stud-by-stud basis, the worker installing a wall panel has a much larger dimensional increment with which to compensate. The resulting gaps between panels are large enough to have to be filled with multiple layers of 1/2-inch material in a time-intensive, hand-crafted process.

In the roof assembly study with Builder One, moving the construction process indoors with a production line system and employing all necessary trades under one roof yields a workforce with extraordinary pride and loyalty, lower training costs due to low employee turnover, increased quality due to employees completing a high number of repetitions in the familiar surroundings of their workstation, and cross-training of personnel in workstations related to their own to understand the preconditions for quality.

Given these advantages of modular construction under roof, building under roof itself poses limitations, particularly when the production facility has been adapted to fit modular production. In both the component manufacturing plant and the modular plant, the physical limitations of the site and buildings causes traffic pattern conflicts, requires exterior storage of subassemblies, and slows production when workstations have to wait their turn for crane access. The employees of Builder One have worked around these limitations to a large degree but could achieve even higher levels of productivity given a physical production environment planned and designed for the production of modular homes.

Employing all the construction trades on the same site with engineering, purchasing, and management gives Builder One a distinct advantage in overcoming many of the information-related disconnects and their associated production bottlenecks. One way to understand this potential is to consider that the organizational focus of Builder One has been on "making it work" using the ingenuity and dedication of the employees to effectively adapt the traditional separation of design and construction to the modular building process. The next step towards a manufacturing approach for Builder One is a fuller integration of design and construction. Because of the stability of the workforce, Builder One is not adapting to a new set of subcontractors on each house. This stability makes it possible to establish a two-way dialogue between members of the design/engineering and production domains, leading to production documents optimized for each workstation or groups of related workstations.

The information filtering conducted by the modular and component plant managers to determine counts of joists and rafters and checking for electrical, mechanical, or plumbing system interference is an example of production personnel coordinating and compensating for information that could easily be included in the production documents.

Alternative Strategies and Implementation

Builder One

The next steps towards a full manufacturing approach to modular homes should begin in the design/engineering department in close conjunction with the production and purchasing departments.

These next steps may be approached through the following strategies:

- Careful examination of the business practices of the organization as a whole as a first step towards implementing an enterprisewide information system. This is a large step to take, costly in terms of personnel hours—development of an information system infrastructure connecting sales offices with purchasing and inventory, design and engineering, production, transportation, and customer services departments. Although this strategy will take the greatest reinvestment and commitment on the part of the company, it may become a necessity within the next decade to effectively leverage the knowledge of the corporate headquarters across multiple production sites.
- Careful examination of physical facility and production sites to evaluate potential gains against costs for facility upgrades. This study would also include observations of contemporary production facilities to understand the possible costs and benefits

of precision positioning equipment, materials-handling methods, and temporary jigs and fixtures.

- Examination of information requirements for each workstation in terms of type, form, and level of detail. This may be the most cost-effective step towards a manufacturing focus (versus a construction focus) for the enterprise. Facilitated conversations with plant managers, crew leaders, and engineering documents personnel may reveal simple steps such as preparation of tables of quantities and dimension that would free up some plant manager or crew leader time to focus on productivity or quality rather than system conflicts or material counts. It is very likely that this could be accomplished with existing systems, software, and drawing distribution methods.

Builders Two, Three, and Five

In the panelization cases observed two strategies for extracting additional efficiency, quality, and savings emerge:

- Focus on the precision of the foundation/slab and anchor bolts placement as a field process. This step will require a careful survey of available formwork systems or development of a formwork system capable of inherently producing foundations that are in square, with precise placement of anchor bolts, utility risers, and anything that breaks the plane of the surface of the foundation.
- Focus on the precision of the panel break locations, placement of anchor bolts, plumbing, HVAC, and electrical risers as a part of the design process. This approach promises to be the simplest, most cost-effective strategy for builders employing panelization. A close dialogue between the builders architect/engineer and panel producers and careful attention to coordination of anchor bolt spacing and utility risers on the documents should produce an immediate payback in field installation of wall panels. This benefit should be particularly apparent with production builders employing a given number of model designs.

Next Steps

Development of Integration Strategies for Design and Construction

The architect/engineer/draftsperson has changed from the graphite pencil to the digital pencil, but the widespread use of CAD packages has not begun to impact the types of drawings produced and has not fully employed the existing capability of the CAD program to support the field installers' need for just the right information, in the right form, at the right time. There exists great potential to extract additional field efficiency from the engineered and panelized systems observed in these case examples. To capitalize on this potential, the existing process of design, then engineer, then draw, then give all parties the full set of drawings, then expect the site superintendent to "pull it all together" needs to be reconsidered to more fully integrate design, engineering, and documentation into "subcontractor-friendly" information that has been prefiltered so it is just what is necessary to carry out the work. The drawings and specifications must be custom tailored to be just what is critical to the subcontract.

Each subcontract should have a set of drawings that is filtered either to present only that information critical to the subcontract or, at a minimum, to highlight the work of the subcontract. This filtering should include the following:

- requirements for license, bonding, insurance, prior performance
- description of work by others affecting this subcontract
- procedures for changes
- estimates of costs
- permits, approvals required to commence the work
- location of the work
- schedule for the work
- contact information for site superintendent
- quantities and dimensions
- quality of materials and execution
- materials delivery and protection directions
- staging of materials and tools
- layout control points, directions
- details of execution
- mitigation/rework procedures
- cleanup
- inspections
- warranty

This step will require a cultural change for many architects/engineers/draftspersons who traditionally represented construction with lines and symbols in two dimensions.

Closing

The field studies make clear that building houses continues to undergo significant transformation. The recent cycle of large builder consolidation has produced a smaller number of national builders active in most of the primary and secondary home building and buying markets of the United States. These national builders effectively employ subcontractors as the central performers in the current model of production. The production builder has become a branding entity, assuring the consumer of quality in design, production, and operation. An emerging side effect of the national builder model is that the builder's buying power in any given local market provides a powerful incentive to the subcontractors performing the work to be as efficient as possible with their own work processes to maximize profit by completing a large volume of projects. The production schedules, Web access, and stretching on-site superintendents to coordinate and quality check more houses simultaneously have indirectly given subcontractors a higher degree of autonomy to complete their work. The subcontractors, in effect, act as Special Expertise Centers (SEC) while the builders project manager and onsite superintendent function as the In House Controllers (IHC) in a Virtual Manufacturing (VM) concept. If the VM model was more rigorously applied to the builder - subcontractor relationship, the subcontractor, as SEC would begin to act earlier in the product design and development process to assure efficiency within their production domain while the IHC would be acting on behalf of each SEC to assure quality, efficiency and productivity at the scale of the whole house.

The economic and scheduling pressures on subcontractors to arrive on time, perform their work, and move on to the next project on time have intensified conflicts between errors in the work of a preceding and subsequent subcontractor. Performing to the letter of the drawings as well as can be interpreted and installing whatever materials have been delivered regardless of accuracy or damage have become the profitable operating model for subcontractors. The impact of this increased autonomy is that the full array of subcontractors building a house is seldom on a house site at the same time to work out problems. The superintendent's historical role as master builder and coordinator of one house at a time has evolved into the superintendent being responsible for coordinating dozens of subcontractors on 8–12 houses simultaneously.

It is likely that the new production model will feature a manufacturing approach to all the subsystems and subcontracts making up a house. The centerpiece of the manufacturing model is precision in communication and execution. Historically ambiguous forms of representation (2-D plan, section, elevation) will give way to representations specifically tailored to the user, e.g., a list, table, photograph, or 3-D pictogram. These user-specific representations will have a higher level of detail than traditional drawings and will likely include step-by-step process images of especially critical assemblies.

This increased emphasis on complete, accurate, prefiltered, production documents will require more time and more knowledge to produce. The limited observations conducted in this study did not uncover any subcontractor, superintendent, or production personnel who were knowingly making errors in interpretation, coordination, or precision. Given the right information in the right form at the right time, the performance of all parties involved will meet or exceed the level of quality required to build a production house.

Manufacturers have been employing strategies to encode knowledge of suppliers, production personnel, and customer service personnel in their design documents since the early 1980s. They quickly learned it was easier to design the product correctly the first time than it was to hold up production personnel and pay additional rework costs to correct or improve the production documents. Historically, mass-produced products were physically prototyped, and through successive prototype iterations, assembly and performance characteristics were fine-tuned to minimize errors and problems during production. Today manufacturers employ virtual prototypes capable of simulating the physical characteristics of materials, tools, and personnel to minimize prototyping costs and production problems. Alternative production processes for production builders will have to employ similar methods to minimize the propagation on-site errors and reduce product liability exposure.

What lies in the balance of this adjustment is the societal benefit of home-ownership by the broad spectrum of socioeconomic groups making up the lower-middle, middle, and upper-middle class.

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Glossary of Terms

agile manufacturing approach that uses flexible, programmable machinery to respond to customer demands and produce highly customized products.

AutoCAD computer-aided design software, with application in architecture and engineering.

bottleneck disconnect in the construction process where information exchange or material flow interferes with and/or slows down production.

business intelligence collection of tools, applications, and technologies designed to handle information choking in organizations.

CAM computer-aided manufacturing software.

change order written order to a contractor, signed by owner and designer after the execution of the contract authorizing a change in the work.

computer-integrated manufacturing integrated manufacturing approach that uses computers to design products, plan production, control operations, and perform business-related functions.

concurrent engineering team approach to the design and development of products and related processes that shorten lead times, reduce costs, and increase product quality.

data element individual piece of information that makes up information flow.

design for assembly technique for designing parts from the viewpoint of how they will be assembled and manufactured.

design for disassembly design process for systematically removing parts from an assembly while ensuring that there is no impairment of the parts due to the process.

design for manufacture technique for optimizing product development, production, and delivery.

design for manufacture and assembly technique enabling designers to consider product material selection, design, manufacturability, and assembly prior to production.

design for X collective term for product design processes to reduce total life-cycle costs through design innovation while complying with legislative mandates.

design function deployment system used to integrate manufacturing and use into the design of products.

direct materials path information flow formally controlled by the production/assembly process.

direct information path information flow directly involved in the production process.

dry runs lost time on a construction project derived from delays that impede subcontractors to carry out specific tasks on a previously specified date.

E-plot plans and drawings created in a digital medium.

enterprise resource planning information management tool commonly used in manufacturing systems to handle integrated sales, marketing, finance, manufacturing, and human resources.

flexible manufacturing approach using a group of machining, assembly, or general fabrication stations, each supplied with components by a variable conveyor system and all controlled by computer.

Glossary of Terms (continued)

hard-copy plot plans and drawings created on traditional written or paper-based media.

high-volume builder contracting firm building more than 1,000 homes per year and utilizing on-site construction methods with a regional or national presence.

holonic manufacturing approach that uses autonomous and cooperative building blocks of a manufacturing system (e.g., machines, work centers, plants, parts) to produce a high mix, low volume of highly customized products.

house information system fixed time schedule for house construction published on the Web and updated periodically to represent the field construction process.

HUD U.S. Department of Housing and Urban Development.

information model a procedure for constructing an entity relationship diagram that formally represents the policy and procedures used by a business.

information flow systematic transmittal of written documents within a preestablished system.

information filtering step in the information flow process when information is interpreted, modified, and retransmitted.

information technology computer-aided technology.

information node the point at which different information paths converge in a system.

indirect information path information flows not directly involved in the production process.

indirect materials path information flows not formally controlled by the production/assembly process.

integrated manufacturing approach that integrates business processes, human resources, hardware, and software to manufacture products.

International Standards Organization network of national standards institutes from 140 countries working in partnership to ensure that materials, products, processes, and services are fit for their intended purpose.

job initiation order written order, signed by the designer and the owner, authorizing the builder to construct a house and its agreed-upon options.

just-in-time manufacturing approach to eliminate all sources of waste in production activities by providing the right part at the right place and at the right time.

lean manufacturing system view of an organization centered on customer-defined value and eliminating steps in the production of goods and service that do not add value to the customer.

manufacturing execution system software function used to create a real-time link between corporate level resource planning systems and automated systems that control machinery and equipment on the plant floor.

manufacturing resource planning information system used to plan and control all manufacturing resources, including inventory, capacity, cash, personnel, facilities, and capital equipment.

material requirements planning inventory control system used to support the master schedule by releasing manufacturing and purchase orders for the right quantities at the right times.

Glossary of Terms (continued)

MEP mechanical, electrical, and plumbing.

medium-volume builder contracting firm building up to several hundred homes per year in regional markets.

milestone event activity which signifies the beginning or ending of essential events in a construction schedule.

oriented strand board performance-based structural use panel made of strands, flakes, or wafers sliced from small-diameter, round, wood logs and bonded with an exterior-type binder under heat and pressure.

Open System Interconnection reference model for how messages must be transmitted between two points in a telecommunication network.

parametric design linkage of three-dimensional models with two-dimensional plans; in an ideal system, parametric design indicates information paths and material paths.

production builder construction company that uses off-site fabrication, including modular and factory-based panelizers, and undertakes the majority of the work in a factory environment.

process map graphical representation of data, document, management, and field relationships.

regulation rule promulgated by an administrative agency authorized by legislation.

reconfigurable manufacturing approach that uses reconfigurable machines, controllers, and methodologies to facilitate the rapid adjustment of manufacturing production capacity and functionality to new market conditions.

site factory construction site using assembly line production types.

small-volume builder contracting firm building fewer than 20 homes per year.

telemanufacturing approach that uses manufacturing services acquired via communication networks and the Internet to perform, in real time, operations and processes necessary to design and produce items.

trigger action event set of circumstances that establish a chain of events.

virtual manufacturing graphical computation systems used to design and evaluate machines, machine parts, machine cells, parts, and facilities on-screen before actual facilities and products are made.

Web-based system software or administration tools that use a World Wide Web or Internet platform.

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