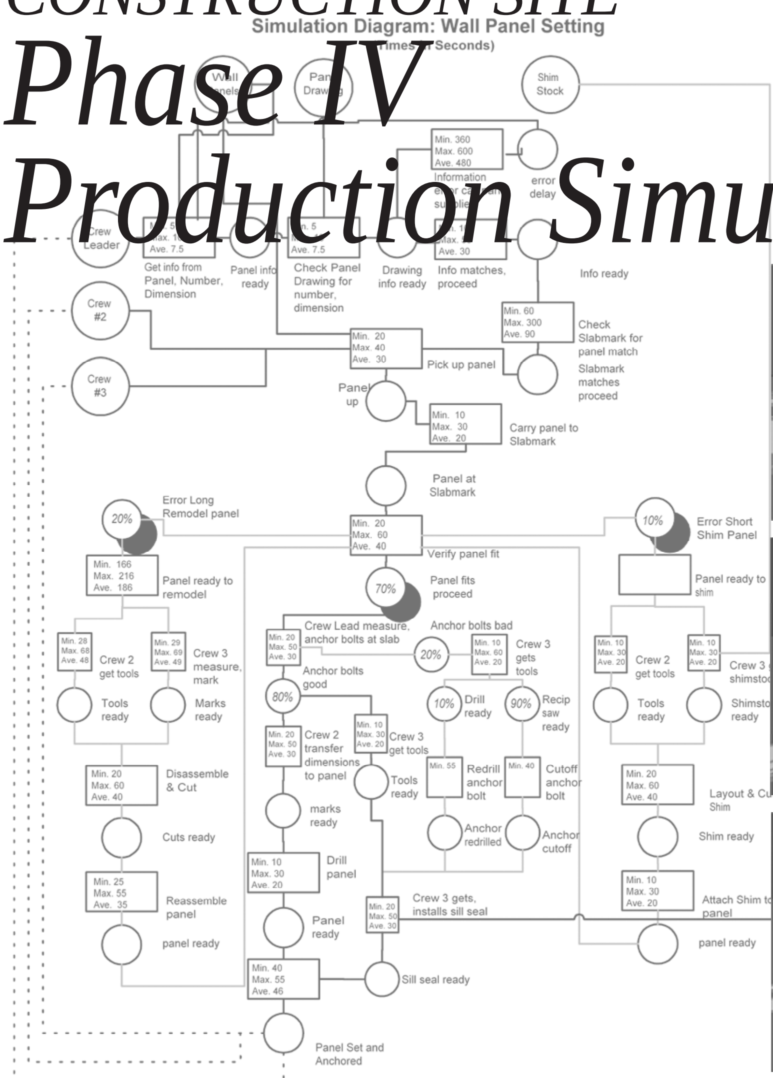
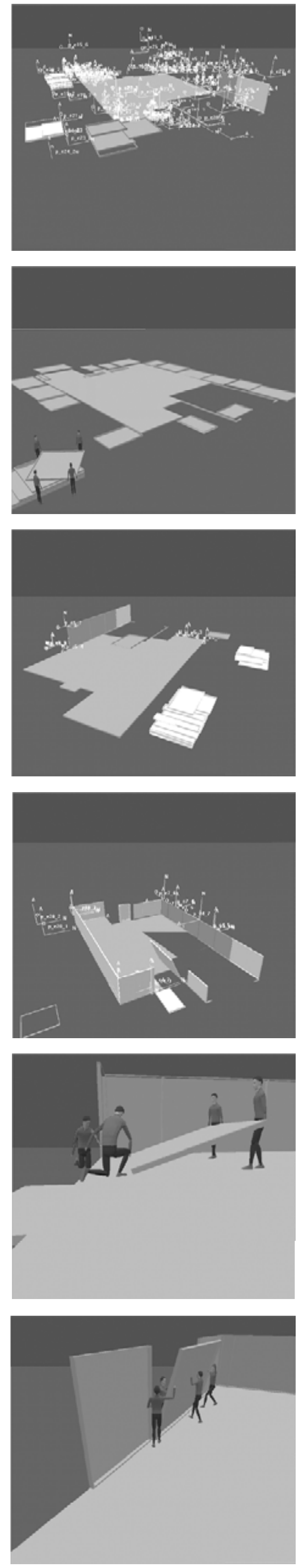
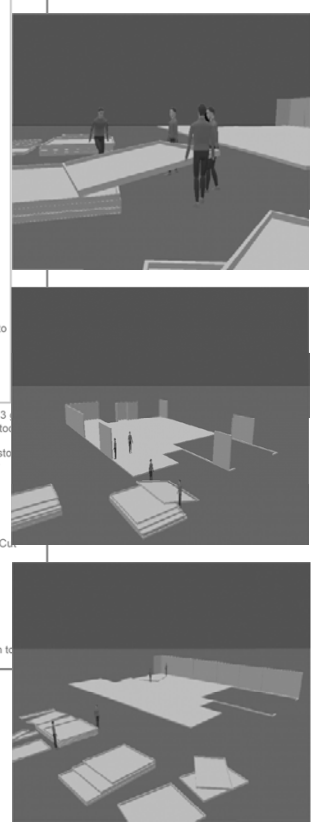
INDUSTRIALIZING
THE
RESIDENTIAL
CONSTRUCTION SITE

Phase IV
Production Simulation







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

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Preface

Millions of homes are constructed annually in the United States, resulting in a home ownership rate that has reached record highs in the last few years. This demand for new houses has greatly benefited the home building industry, which has implemented and used several design and construction improvements to keep up with the tremendous need for new homes in America's cities and towns. Yet most of these productions improvements focused on customization of individual houses rather than on the production process for a wide number of houses.

To gain insight into the main principles underlying production improvement, the U.S. Department of Housing and Urban Development (HUD) began to fund research in an area known as "industrializing the residential construction site." Four years ago, a new research focus examined ways to automate the home construction process, improve construction work flows, and practically coordinate construction sites.

Researchers identified five areas for transforming the construction site in the first year of the research program. Of these five, HUD chose "information integration" as the enabling form of knowledge key to transforming the residential construction site from a craft-based traditional model to an information-driven manufacturing model.

In year two, researchers focused on studying the flow, filtering, and timely availability of information. Research results indicated that the residential construction industry requires a coherent information integration strategy that will facilitate the meaningful flow of information as well as the effective provision of information management to all levels within the enterprise.

In year three, researchers studied the production framing process in detail and identified production bottlenecks at the interfaces between craft and mass production and between documents and subcontractors. It was found that the residential construction industry is laden with paperwork that facilitates the introduction of process and production errors. Contemporary information technology systems may eliminate several of the error types found and provide timely access to up-to-date information at the detail level in the appropriate formats and languages.

This fourth year of the research focused on predicting and modeling the kinds of information needed by the field installers of residential construction. Researchers concentrated on developing and calibrating simulations of the framing processes to accurately represent observations of current field practices, using the simulation as a benchmark to compare alternative processes and to evaluate the state of graphic and numerical simulators and their applicability and adaptability to residential construction production processes. This document reports on the findings of that research.

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1 Introduction: Information and Production Simulation

This report is the fourth phase of a multiyear project titled "Industrializing the Residential Construction Site." The overall goal of this project is to identify, map, and refine the overall process of information transfer among 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 "Industrializing 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 of "Industrializing the Residential Construction Site" 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.

Information and system conflicts between mass-produced components and site-crafted materials can require superintendents to coordinate up to a half-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 "Industrializing 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—Overview and Key Findings

The full report for Phase III of "Industrializing the Residential Construction Site" can be ordered or downloaded in PDF format from http://www.huduser.org/publications/manufhsg/ircs3.html. 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 premanufactured wall panels and 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 errors 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, misalignment), and
- 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 category, errors of precision, is attributed to incompatibility between field and premanufactured 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 home building 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.

Phase IV—Purpose

Phase III of "Industrializing the Residential Construction Site" found that a critical obstacle to a broader application of industrial strategies like panelized walls is found at the interface between site-built foundations and manufactured elements like wall panels. Errors of interpretation, precision, representation, and omission exact a significant penalty from the potential advantages of panelized construction.

Given the nature of the errors found through the Phase III study, Phase IV was primarily structured to focus on the kinds of information needed by field installers of residential construction structural components and the possible benefits of integrating this into the component producers' and residential designers' knowledge base.

The second purpose of this study was to calibrate a simulation to accurately represent observations of current field processes and to use this simulation as a benchmark for comparison to alternative processes.

The third purpose of this study was to evaluate the state of graphical and numerical simulators and their applicability and adaptability to residential construction production processes.

Phase IV—Why Simulation?

Simulation has long been established as a useful tool for analyzing construction operations. Work by Halpin (Halpin, 1973; Halpin and Riggs, 1992) on the CYCLONE system and its variants (Martinez and Ioannou, 1994) have been well documented in the literature. Other systems, such as SLAM II (Gonzalez-Quevedo et al., 1993; Pritsker 1986; Anonymous, 1994), system dynamics–based simulations systems (Senogles and Peck, 1994; Paulson, 1995), and Petri Nets (Wakefield and Sears, 1997; Sawhney, 1997), have also been used to model construction systems.

In general, all these systems use a symbolic graphical notation that is converted into a mathematical model. The model performs the simulation to produce results that provide information about the behavior of the system. While these systems are powerful, they are difficult for construction personnel to use, and adoption by the industry has been slow and generally restricted to specialized or academic applications. Recent developments in computer graphics are improving the usability of the software (Kamat and Martinez, 2000), but that widespread application of these abstract modeling systems still appears some way off. Nevertheless, numerical simulation does offer considerable opportunity in operations improvement, especially in the relatively repetitive environment of production home building. In this work, Petri Nets have been used for the numerical simulation of the residential construction operation.

In parallel with the development of numerical simulation, 3D modeling has made major developments and is beginning to make an appearance in the residential construction industry. Most 3D graphical representations are being used in marketing and customer "walk-throughs," but there is considerable potential for application to the construction process. Most of the applications of 3D graphics for process design and product development have been in manufacturing industries, where size of production runs and design development costs have meant that the considerable cost of developing a detailed and realistic 3D model can be justified through cost efficiencies paid back over thousands of production cycles.

Recent development work in construction simulation has focused on the development of so-called 4D simulations of construction operations (Fischer and Kam, 2002). In 4D simulation, a 3D graphic model is linked with the construction schedule, and the designer/constructor viewing the model can see the building parts appearing in the 3D environment as they would in the field based on the schedule. These 4D simulations are certainly impressive but have generally been used only on large, complicated commercial projects due to the cost of development of models. For this application where we wish to study actual construction operations, including worker involvement, connection of parts, path planning, and ergonomic effects, 4D simulations do not offer the level of physical detail necessary.

In this study, we have chosen to use virtual prototyping software from the manufacturing industry, which has the potential to include everything necessary to undertake virtual simulation of actual construction operations (Anonymous, 2003). Our purpose in using the software is to demonstrate what is possible, but also to highlight the difficulties of undertaking a simulation with a high degree of fidelity.

Phase IV—Methods and Findings

Most new homes in America include some basic form of prefabricated component or wall panels. Panelized wall systems make up only 5% of all walls built in residential construction (walls for approximately 65,000 houses). It is likely that the majority of these panelized walls go into houses built by high-volume production builders, i.e., builders having a regional or national presence and producing more than 1,000 houses per year.
Wall panels were chosen for study here because they fall at the interface between site-crafted foundations and industrially produced components that are only installed, not crafted on site.

The intersection of the information required by field personnel and the objects of the information, in this case prefabricated wall panels, raised the following productivity questions:

- Why doesn't the stack order of the panels to be delivered anticipate the panel placing process?

- What could be gained if the panels were stacked in the order of placement using a “last-on, first-off” strategy?
- Of the observed “scatter and place” or “layout and place” strategies, which panel placing strategy is more efficient?

Short of requesting that the panels be removed, the pallets be restacked, and each alternative to the panel stacking and placing method be empirically evaluated, simulations were constructed to assess the potential productivity gains. Simulations are the equivalent to a spreadsheet when used as a “what if” tool. They allow the complex process variations and interdependencies to interact under various “what if” scenarios and provide a broad array of data including resource utilization, error frequency, and overall process time.

The field processes of three builders who use on-site assembly/ erection of premanufactured wall panels were studied. Simulation models were developed based on field observations and data collection. For the fourth builder, who uses off-site modular construction techniques, production processes for roof element assemblies were studied and a simulation model developed. All simulation models developed were capable of capturing process information at some level of detail and aided the researchers in understanding the effects of production bottlenecks, errors in design, errors in execution, and construction system design.

A detailed numerical simulation of the panel erection process was developed using a simple discrete event simulator (see Chapter 3). This showed how an abstract modeling system could be used to represent a construction process and collect statistics on process behavior. This type of model is useful if detailed physical behavior is not an important factor in the modeling process.

The limited statistics from running this simulation 100 times showed that, when randomized stacking of the wall panels or an error was encountered, the process required 30%–40% (an hour and a half to two hours) additional time to install the wall panels.

A much more detailed 3D virtual model of the same construction process was also developed at two levels of detail: a macro model showing the panel paths and an overall erection strategy. This type of model is useful in understanding the process, including material/ assembly path planning, stacking priority of panels, and overall assembly details. Detailed description of the virtual model construction is reported, and the complex nature of model tasks is explained.

A 3D virtual micro model of a single panel was also developed to demonstrate how the virtual workers interact with the panels at a specific level of model detail. This type of virtual prototype is useful when the detailed work task, tool usage, and ergonomic analysis of the tasks are of interest. This level of specificity is particularly appropriate when developing a new industrialized construction system where worker interaction and capacity are important. The level of modeling effort required for this type of model is an order of magnitude greater than that required for the macro model described earlier.

Our purpose in using the software is to demonstrate what is possible, but also to highlight the difficulties of undertaking a simulation with a high degree of fidelity.

This study demonstrates the capacity of simulation models to accurately represent observations of current field processes. The simulation models can be used to refine existing processes or develop new processes. Virtual prototyping is particularly applicable to developing new processes and has the potential to provide a mechanism for integrating field knowledge into the design process. It can also be used to determine information needs of field personnel.

Use of virtual prototyping in design and planning should help to reduce or eliminate the design and production errors found during field studies of the production process. The next stage of this work, Phase V: Virtual Manufacturing, is a natural extension to the work described in this report. The project will develop a data-driven simulation model of a construction management sequence for a production house. The model will be used to make changes and improvements to the construction process using Design for Assembly principles. The model will then be used to develop strategies and mechanisms to prevent or recover from error.

Overview of Simulation Systems and Construction

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Previous research efforts in industrializing the residential construction site have identified a significant number of production and information bottlenecks. To address these bottlenecks, a literature search was conducted on computer modeling of construction projects and operations. It is believed that visualizing simulated construction activities may provide insight into the subtleties of construction operations and help understand the manner in which residential buildings are assembled. By improving communication among different stakeholders around a visual representation, it is further hoped that information and production can be integrated to solve some or most of the construction problems identified during previous phases of this research.

The literature search identified four paradigms for 21st century construction simulation modeling: computer simulation, virtual prototyping, information exchange protocols, and knowledge management. These four concepts and their applications to manufacturing in general and construction in particular are discussed in the following sections. In addition, we introduce two specific simulation methods (Petri Nets and physics-based virtual prototypes) and describe how their application demonstrates the four simulation paradigms.

Computer Simulation

Computer simulation is the process of designing a model of a physical system, executing the model on a computer, and analyzing the output. It is a mathematical-logical representation of the dynamic behavior of a system. According to Bardos (1998), the activities of the model comprise events, which are activated at certain points in time and, in this way, influence the overall state of the system. The points in time when the event is activated are randomized (e.g., equipment breakdowns and weather delays) so that input from outside is not necessary. Once a simulation model is developed, experiments can be performed to recreate the many predicted or unforeseen conditions of the proposed system without building it. In doing so, simulation models can be used for design, procedural analysis, and performance evaluation.

Once a simulation model is developed, experiments can be performed to recreate the many predicted or unforeseen conditions of the proposed system without building it.

The availability of powerful personal computers and the low cost of model development by "object-oriented animated" simulation packages make computer simulation applications possible, even for small projects. Since these animated packages are easy to use and provide exceptional realism, manufacturers can manage their operations by making use of simulation models customized for their particular application. For some purposes, it may be even better than the analysis of real data since the analyst never perfectly knows the real-world processes that caused the measured values to occur. In a simulation, on the other hand, the analyst controls all of the factors making up the data. By systematically manipulating these data, the analyst can see directly how specific problems and assumptions affect the analysis.

Over the years, computer simulations have advanced with computer technologies. As a result, many computer simulation models are in use today. The most common applications are found in the electronics, air transportation, and automotive industries (Anonymous, 1998). Most of these applications focus on designing complex operations to manufacture high-quality products in the shortest amount of time. Yet, it was found (Inanici, 2001) that, when simulation modeling is combined with visualization software, excellent communication tools are created that can provide users with a more realistic and comprehensible feedback from simulation analyses. Visualizing simulated manufacturing operations in 3D, for example, can significantly help establish the credibility of simulation models and provide valuable insight into the subtleties of manufacturing operations that are otherwise nonquantifiable and presentable.

In construction, the main application of computer simulation entails the creation of a model that represents how a construction operation is performed. The model considers the various resources required to conduct the operation, the rules governing the tasks to be performed, and the stochastic nature of events. Once the model is created, the operation can be simulated on a computer to study the statistical measures of performance for the operation. Usually, the results of the analyses point out parts of the operation with potential for improvement. Considering these observations, the operations analyst can modify the model to reflect changes in operating procedures, resource allocations, etc. The modified model can then be simulated and analyzed, with the results used to further improve the operation. The procedure continues until no further improvements are necessary.

Construction simulation was introduced by Halpin with the development of the CYCLONE modeling methodology (Halpin, 1973). Since that time, many construction simulation languages have been developed, including DISCO (Huang and Halpin, 1994), CIPROS (Odeh, 1992), and STROBOSCOPE (Martinez and Ioannou, 1994). State-of-the-art construction simulation systems enable the modeling of complex construction operations. These systems are capable of providing the project manager with detailed information about planned operations, including resource utilization, operation bottlenecks, and production rates.

Despite this obvious potential, the use of computer simulation for construction projects has been limited to a few large contractors (Hajjar and AbouRizk, 2002). This situation can be largely attributed to the lack of resources for investment in the tools by smaller builders, who dominate the home building industry. Secondly, there are no suitable supporting tools that can graphically illustrate the modeled processes and the resulting products in 3D. The result is the "black box" effect experienced by many simulation output analysts who have reservations about the credibility of the analysis based solely on the text and chart output provided by most simulation software. The process visualization/animation tools currently available are restricted to 2D. In the past, according to Ioannou and Martinez (1996), 2D systems have been effectively used to visualize modeled construction operations. Yet, although effective in establishing the credibility of many simulation models, 2D systems inherently lack in the real-world 3D capabilities that are indispensable for the realistic visualization of construction operations.

Computer-aided design (CAD) models have been used for many years in the construction industry. In the past, use of CAD has primarily been restricted to the preconstruction phase. Current advancements in CAD, however, give developers greater flexibility in CAD functionality, resulting in simplified simulation modeling through integration with 3D CAD. According to AbouRizk and Mather (2000), there are two ways through which integration of CAD and simulation can be achieved. The first is the "melting pot" approach, where the functionality of the two tools is combined into one. Although the advantages in doing so are numerous, the required investment in the development is prohibitively high. The second approach to integration involves sharing information between two distinct systems by extending each. This approach is cost-effective as most CAD and simulation tools are extendible. The result can be a 3D animation of discrete simulated (modeled) construction operations.

Construction projects usually involve a large number of direct and indirect stakeholders. Current methods of information exchange and communicating building design information among them can lead to various types of problems, including incomplete understanding of the planned construction, functional inefficiencies, and impediments called information filtering and information disconnects (Wakefield, O'Brien, and Beliveau, 2001). By visualizing construction processes in 3D, operational concepts can be validated and verified, design interferences checked, and construction operations reviewed. Also, by using visual representations of planned or completed construction activities, communication and information exchange among different stakeholders can be improved.

Virtual Prototyping

Like computer simulation, virtual prototyping (VP) has the potential to improve the design and performance of new products through visualization of product development operations. Unlike computer simulation, VP directly links visualization methods with simulation models. It is rapidly becoming an essential strategy for new product development as it provides manufacturers with a tool to carry out simulations and analyses on a fully developed computer model (Chua, The, and Gay, 1999). In performing the same tests as those on physical prototypes, VP has the potential to accelerate the product's design and development process, thereby reducing time-to-market and faultiness of the product. The combination of direct 3D interaction, 3D visualization, and lightweight interaction devices and applications makes VP ideal for 3D modeling tasks.

Unlike computer simulation, VP directly links visualization methods with simulation models. It is rapidly becoming an essential strategy for new product development as it provides manufacturers with a tool to carry out simulations and analyses on a fully developed computer model.

There seem to be two different understandings of what exactly constitutes VP: computer graphics or computer manufacturing. According to Gomes de Sa and Zachmann (1999), computer graphics is concerned with methods and techniques for converting data to and from visual presentation using computers. It has been used quite successfully for the modeling of many types of phenomena, including geographic mapping and architectural design. By applying virtual reality (VR) for prototyping physical mock-ups (PMUs), the VR system renders all characteristics relevant to the particular context as precisely and realistically as possible. In doing so, VP can replace PMUs with software prototypes that can easily be studied and manipulated.

Rather than using PMUs, computer manufacturing uses digital mock-ups (DMUs). These DMUs are realistic computer models of a product with the capability of all required functionalities from design/engineering, manufacturing, product service environments, maintenance, and product recycling. They are used as a platform for product and process development, for communication, and for making decisions from a first conceptual layout (Dai and Reindl, 1996), including all kinds of geometrical, ergonomic, and functional simulations with or without the involvement of human models. The goal of DMU is to replace the traditional business process based on PMUs by one which fully maximizes DMU technologies available today to create a process with only a single PMU for a final verification and release to volume manufacturing.

VP has been used by a number of industries, including the automotive, aerospace, electronics, and textile. According to Pratt (1995), the automotive and aerospace industries are among the leaders in applying VP to solving real-world, nontrivial problems. Boeing, for example, uses a virtual numeric control (NC) package of simulation and verification software to automate tool paths before cutting metal. By installing VP software, Boeing generated simulation models for 60% of product work cells. Paths machined with NC simulation and verification tools include air wings, skin, and spars (Waurzyniak, 2001). In the automotive industry, VP is used in the early stages of design to check assembly, tolerance, and fit before any parts are cut. The geometry comes directly from the CAD system of choice at each company (Fong, 2000).

In the electronics industry, VP is becoming commonplace in design and testing. Tools such as virtual test beds (VTBs) are being developed that use improved numerical-solver-technology and language translators to simulate complicated systems that incorporate new and legacy models at all levels (Hudgins et al., 1999) or to study product and process design issues (Cecil et al., 2002). In the textile industry, VP has been used to replace textile finishing machines (Farber, Dahmen, and Mohoupt, 1999). With VP, employing commercial software codes and high-performance workstations, the textile finishing's process performance can be predicted faster and with reduced costs. The rate of knowhow exchange between a manufacturer using VP and the customer can be increased dramatically, leading to a higher product satisfaction.

Despite these applications in the manufacturing industry, VP has not found much use in the construction industry. This fact is surprising, given the advantages of VP for buildings (Stribling, 2003). According to Kamat and Martinez (2000), construction prototyping can substantially help in designing complex operations and in making optimal decisions where traditional methods prove ineffective or are unfeasible. For example, Johnston and Wakefield (2003) describe the use of VP to evaluate panelized construction. In doing so, assembly scenarios are prototyped to examine known production efficiencies and to obtain valuable insight into the subtleties of the modeled construction operations that cannot be otherwise quantified and presented. The ability to realistically visualize modeled construction operations can provide a more pragmatic and comprehensible feedback to construction personnel as well as model developers.

Information Exchange Protocols

The next level of simulation involves dynamic information manipulation during the simulation rather than only before and after the simulation run.

The transfer of dynamic-state information from the construction site to project databases and augmented simulation systems is a new endeavor in the architecture, engineering, and construction industry. No protocol currently exists for this purpose although several information exchange protocols have surfaced recently. They include the Virtual Reality Modeling Language (VRML), the Extensible Markup Language (XML), and the Industry Foundation Classes (IFC).

VRML is a standard language for the animation and 3D modeling of geometric shapes. It allows 3D scenes to be viewed and manipulated over the Internet in an interactive environment. Using a special VRML browser, the user can connect to an online VRML site, choose a 3D environment to explore, and move around the 3D world. It is possible to zoom in and out, move around, and interact with the virtual environment.

Over the years, several versions of VRML have been released, including VRML 1.0 and VRML 2.0. In December 1997, VRML97 replaced VRML 2.0 and was recognized as the international standard for 3D modeling by the International Organization for Standardization (ISO, 1997). As such, VRML97 is considered the de facto standard for sharing and publishing data among CAD, animation, and 3D modeling programs.

VRML is an export option in many off-the-shelf CAD packages. AutoCAD, for example, uses the VRML-Export command to start the export of CAD files in VRML format. The objects in VRML format can be viewed easily by a number of Web browsers. This is an important feature, since all indications are that the Next Generation Internet (NGI) will permit large-model, real-time simulations to be transparently transmitted between remote sites and management locations without the need for any dedicated infrastructure (Stone et al., 1999).

Several companies the world over have used VRML models from

AutoCAD, including the Federal Aviation (USA), Telenor (Norway), Skoda-Auto (Czech Republic), Chung Pak Battery Works (Hong Kong), Jabatan Industries (Malaysia), Eagle Air (Australia), and CRAI (France). Currently, no construction industries are included in the list of users although several researchers have studied the applicability of VRML to construction industry applications (Lipman and Reed, 2000). This fact is surprising because AutoCAD is used extensively in the construction industry and the use of Web browsers available off-the-shelf may enhance the ability of management staff to simultaneously access and interpret construction site data.

While VRML is the standard for 3D modeling on the Web, XML has become the standard for information interchange on the Web. According to Teague, Palmer, and Jackson (2003), XML is a set of formatting rules that allows one to define structured information in a software-neutral text file. XML will work on virtually any computer hardware and operating system platform and with any software program, over any number of years. Interoperability occurs when electronic information can be intelligently exchanged and shared among collaboration partners who use different software systems without the need for human interpretation.

Originally, XML was designed to improve the functionality of the Web. Yet, XML is no longer just for Web pages. It can be used to store any kind of structured information. By enclosing or encapsulating data, one can pass between different computing systems information that would otherwise be incommunicable. In doing so, XML goes beyond simple document presentation. It strives to capture data in a meaningful and structured format so that it can be exchanged between applications that need the data.

A number of industries have used XML to perform information and data exchanges. They include the aerospace, automotive, telecommunications, and computer software industries. One area where XML has turned out to be particularly useful is in e-commerce on the Internet. It was found that the key to meaningfully applying XML in industry is to have a set of accepted data tags for describing objects and processes in that domain. Several efforts to standardize the use of XML for different domains are now in progress.

For example, cXML is being developed for e-commerce applications, to facilitate processes such as purchase and change orders, acknowledgments, status updates, shipping notifications, and payment transactions. Other applications include aecXML and bcXML, XML-based standards and applications specifically created for the architectural, engineering and construction (aec) and the building and construction (bc) industries, respectively.

AecXML is a framework based on the XML language to facilitate communication between and among the various entities involved in the architecture, engineering, and construction process. By providing a set of keywords and named attributes, a vocabulary for exchanging AEC facts is created that allows not only a standard way of structuring building data, but also enables automated processing of that data. The information exchanged may be resources such as projects, documents, materials, parts, organizations, and professionals or activities such as proposals, design, estimating, scheduling, and construction.

With bcXML, the focus is no longer on the aec process but rather on electronic business communication about construction products, resources, work methods, and regulations. Consequently, bcXML is a communication technology that provides the building and construction industry with a powerful infrastructure that (1) supports electronic business among clients, architects and engineers, suppliers of components, systems and services, contractors and subcontractors; (2) is integrated with e-commerce and design/engineering applications; and (3) supports virtual construction enterprises. By developing a communication technology specifically tailored to the needs of the industry, the building and construction industry can build faster, cheaper, and better.

Another new standard developed to attain interoperability across domains is the Industry Foundation Classes (IFC), developed by the International Alliance for Interoperability (IAI) for the construction industry. The IAI is an industry-based consortium and a division of the ISO with the mission to enable the sharing and exchange of accurate and consistent information between project stakeholders during a construction project's life cycle, including strategic planning, design and engineering, construction, and building operation.

The IFC system is a data representation standard used to assemble a project model in a neutral computer language that describes building project objects and represents information requirements common throughout all construction industry processes. The project model constitutes an object-oriented database of the information shared among project participants, including professionals, suppliers, contractors, subcontractors, clients, facility managers, and end users.

Several popular CAD tools now have implementations of IFC-compliant import/export capabilities that allow the geometry created in these tools to be written to and read from IFC data files. As a result, IFCs represent a realistic way to begin integrating information across the residential construction industry and clear the way for information and communication technology to realize its potential in residential construction.

To date, much of the IFCs' focus has been on representing the facilities that are being designed and constructed. Yet, recently, the scope has shifted to also include project management information such as costs, schedules, work tasks, resources, etc. According to Kam et al. (2002), such information can be used for studying design alternatives, analyzing life-cycle costs and environmental impacts, producing virtual reality models for group decision making, and improving the construction sequence through 4D visualization.

Industry Foundation Classes represent a realistic way to begin integrating information across the residential construction industry and clear the way for information and communication technology to realize its potential in residential construction.

Knowledge Management

Lastly, knowledge management (KM) represents the most far-reaching of all the simulation paradigms to date because of its dynamic response to information and its ability to facilitate decision-making processes, such as more comprehensively accounting for variations beyond simple technical variances.

Specifically, KM is a discipline that provides strategy, process, and technology to share and leverage information to more effectively solve problems and make decisions (Satyadas, Harigopal, and Cassaigne, 2001). Evolved from corporate organization in the 1960s to create the enterprise integration culture of the new millennium through knowledge sharing, KM incorporates components from such diverse domains as organizational effectiveness, business management, psychology, philosophy, and cognitive science (Harigopal and Satyadas, 2001).

Four different components make up the KM system: searching, indexing, content management, and collaboration (McCloskey, 2003). By scanning structured and unstructured information and looking for patterns of words, enterprise search platforms typically look for corporate and/or project knowledge and match them to common concepts. The knowledge thus gathered can be represented using schemes such as semantic networks, scripts, and expert systems.

For ease of retrieval, the information and knowledge captured must be organized and indexed. Several taxonomy-building and classification schemes exist to lay out the information collected in a navigational setting. Once the knowledge is organized and indexed, it is saved in a central repository in the content management system. This stores all the content of the site, along with other supporting details. It also supports the distribution of knowledge and information.

Knowledge captured, organized, and controlled is ready for distribution. Dissemination includes "pushing" the right knowledge within the right context and the right users "pulling" the right knowledge they need at the right time. The range of push mechanisms includes information and knowledge portals and intelligent agents. Search engines and knowledge map browsers aid users in knowledge pull activities (Satyadas, Harigopal, and Cassaigne, 2001).

Several business drivers for KM have been identified. The most typical are the need for a better way to share information and knowledge across organizational boundaries, the ability to rapidly respond to crises, and the need to retain the knowledge of experts who are retiring. Yet, despite this interest, the discipline is still in its infancy, and only a few large companies can be identified that have implemented KM systems, including Texas Instruments, Coca Cola, Monsanto, Accenture, IBM, General Motors, the U.S. Army, and Skandia (Davenport and Prusak, 1998).

In construction, the industry has been slow to implement KM systems. According to Rezgui (2001), the main reason for the slow start is the fact that data about a project, for example, is usually not managed when it is created but instead is captured and archived at the end of a construction project. By this time, people who have knowledge about the project are likely to have left for another project, their input never captured. Another reason is that the people responsible for collecting and archiving project data do not necessarily understand the specific needs of actors who will use the information and knowledge at a later time.

A number of advances in information and communication technology have been developed that may help overcome some of these limitations of current approaches to managing information and knowledge relating to construction projects. They include the semantic web and temporal databases. According to Christiansson (2003), they form an integral part of the next generation of KM systems for the construction industry.

The semantic web is an extension of current Internet search technology in which data on the Web is defined and linked so that it can be used by machines for automation, integration, and reuse across various applications. With temporal databases, extensions to traditional relational databases are made that enable time-dependent queries to be conducted like "What resources were used during the conceptual design of the building?" or "How many resources were used over different time periods at different building locations?" These types of queries are difficult to handle in conventional databases, yet they can help capture experiences and knowledge for better planning of resource allocation in building construction.

Types of Simulation: The Virtual Model and Petri Net (PN) Model of Construction Operations

Of the four paradigms discussed above, Computer Simulation using Petri Net software and Virtual Prototyping using Delmia's ENVISION software were chosen as the Knowledge Management model and Information Exchange Protocols are primarily enterprise tools not especially suited to research investigation.

Petri Net simulation will be discussed first, and the Virtual Model second in the context of the production builders framing process. The Petri net was focused on the overall process, evaluating the location, frequency and consequence of error and remediation in the wall panel process while the virtual model was developed to evaluate the ergonomic impact of panel sizing and weight upon the installing crews as well as the impact of alternative panel delivery and staging processes on production efficiency.

The Petri Net (PN) Model of Construction Operations

The following description of a simple Petri Net model of a construction operation, taken from Wakefield and Sears (1997), demonstrates the modeling process.

> Figure [2.1] is a graphical PN model of a crane hoisting materials from the ground to the workface. This network is made up of a number of connected symbols, each with the following attributes:
>
> 1. Circles (places) represent states of being. In construction,

these are often states of readiness. The crane moves through the following states of readiness: crane ready to attach, ready to lift, ready to detach, and ready to return.

2. Rectangles (transitions) are actions which change the state of the system. Attach the load, lift and swing, detach the load, and crane return are transitions.
3. Black dots (tokens) are the resources of the operation. In this case the tokens are the materials being hoisted and the crane doing the hoisting.
4. Arrows (directed arcs) indicate the direction the resources (tokens) move when an action (transition) takes place. In Petri Net jargon, transitions are said to "fire" as their action takes place.

The location of the materials and crane (tokens) in the network at any point in time is referred to as the "marking" of the net at that instant. In this example we start with two tokens, the crane and the materials to be lifted, both in their respective circles (places). At this point the transition "attach the load" is enabled and ready to fire. The firing of the transition moves the tokens from "crane ready" and "materials to be lifted" (the input places), and puts a single token in the place "ready to lift" (the output place). The result of this first transition firing is shown in Figure [2.2]. Transitions continue to fire as they are enabled until the supply of tokens is exhausted.

It is possible to build a logic model of most construction systems using a combination of these basic Petri Net constructs. However, for quantitative modeling and analysis of construction systems, the concepts of time and decision branching need to be added to basic Petri Nets.

Petri Nets are capable of modeling phenomena present in construction operations, including nondeterministic activity times, attaching priorities to particular activities, probabilistic branching, and queueing disciplines. The use of color-coded elements in Petri Nets gives further capability for the user to differentiate between different types of equipment, information, and resource flows. This feature is of particular use when modeling more complex construction operations. The other feature of the Petri Net modeling system, which is not possible to demonstrate in this report, is the ability to graphically step through the graphical model of the simulation. This feature is useful when debugging the simulation model and also in improving the construction process design. The modeling power of Petri Nets, when combined with their simplicity, makes them a powerful and accessible tool for construction engineers for the modeling and simulation of construction systems.

Petri Net terminology (state, place, token, transition) requires extensive translation to match the terms and work processes familiar to the residential construction industry. The Petri Net user interface poses a similar obstacle easy use by the residential construction industry as it is designed for process engineering professionals and contains few ready-made tools and functions that could be used intuitively by a residential designer or construction manager.

Figure 2.1: Tokens in a “ready-state” in the “materials-to-be-lifted” and “crane-ready-to-attach” place-circles

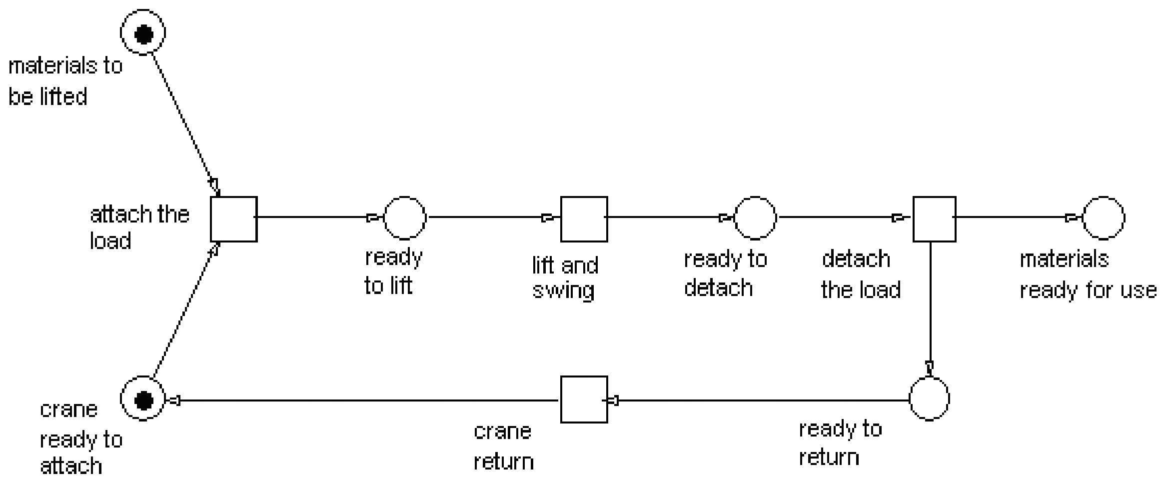
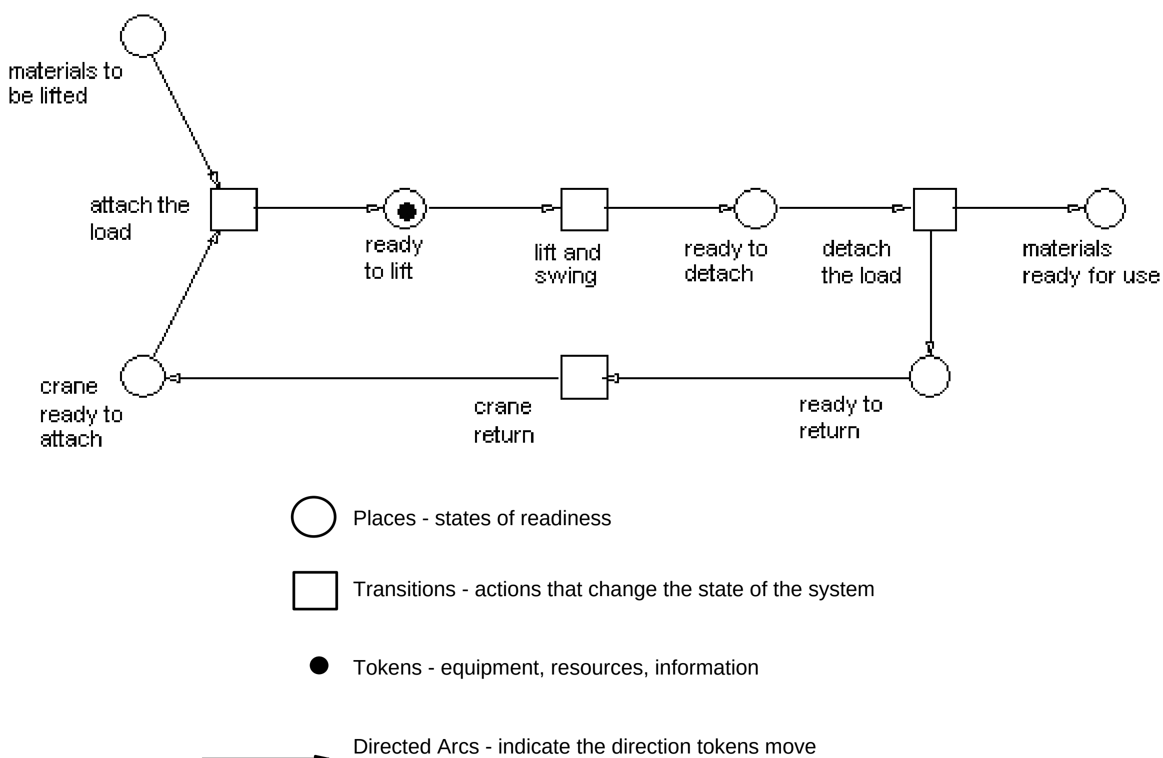


Figure 2.2: Tokens “fired” through the “attach-to-load” transition into the “ready-to-lift” place-circle



The Virtual Model of the Panelized Construction Processes

This is the second simulation method evaluated for applicability to the production builder's design and construction processes.

This section demonstrates the virtual prototyping of the panel erection process. It illustrates the steps in virtual prototype preparation including field data collection, generation of 3D CAD models, transfer of the 3D models into the VP environment, and the use of the VPs. The section concludes with a discussion of the practicality of virtual prototyping for developing and investigating construction processes.

Four different steps make up the virtual model development process. First, the panelized wall assembly process is reviewed, and the virtual model is prepared. Second, field data is collected to develop a sequential assembly task matrix. Third, data is collated into 3D for transfer into the ENVISION, DELMIA modular virtual prototyping and simulation-based design software, and, fourth, the virtual assembly prototype is synchronized to recorded site data. The following sections explain these steps in more detail.

Collation of Field Data into 3D

The virtual prototyping process requires an electronic representation of materials used for assembly. Three steps are involved for the input of this information. First, panel and foundation/slab dimensions are extracted from the panel manufacturer's supplied product data. Second, each panel is created as an unrendered 3D polyline model and saved as an individual AutoCAD file. Third, once translated, an AutoCAD file is imported and saved as an individual object file on the virtual prototyping platform.

Virtual prototyping of the panelized assembly sequence requires the following basic modeling procedures:

- Quantity and dimensional/structural identification of wall panels and slab/deck.
- Creation of a CAD-based 3D production model.
- Data export from CAD for import to the virtual prototyping simulator (related to file-sharing protocols and processes).

The production drawings supplied by the panel supplier provide basic geometric information for 3D panel construction. The drawings establish panel quantity and type (sheathed or unsheathed). Production drawings also provide basic slab/deck dimensions. These house characteristics are necessary to construct the virtual prototype and visualize panel assembly in the virtual environment.

Initial slab/deck models attempts were made with a simple extrusion of a fully assembled wall plan. Future simulation attempts may use a 3D wire-spline overlay derived from the final wall assembly or other architectural information and attach to the virtual slab/deck for a more realistic representation of the assembly. Initially, 3D CAD panel details were abstracted as an individual extruded geometric objects for ease of creation and file transfer/manipulation. The final 3D CAD panel model provided greater visual detail (exterior boundary studs and sheathing) (Figs. 2.3 through 2.8).

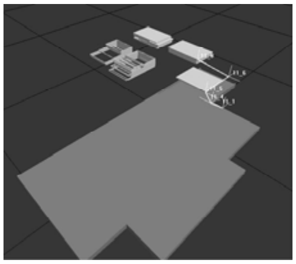


Fig. 2.3: Panel stacks, slab, and path for first panel

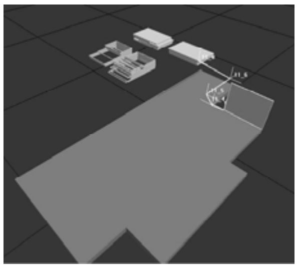


Fig. 2.4: First panel set

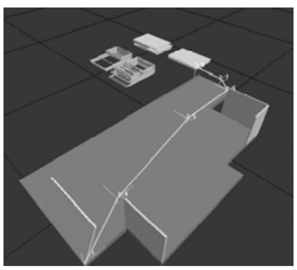


Fig. 2.5: Path for distant panel simulating installers' travel direction

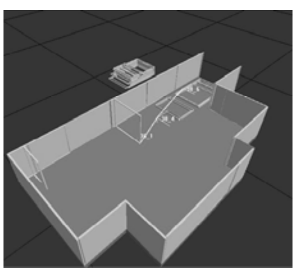


Fig. 2.6: Exterior panels set, paths for interior panel staging

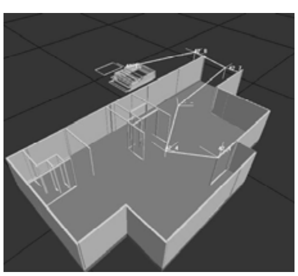


Fig. 2.7: Path complexity increases to avoid interference with standing panels

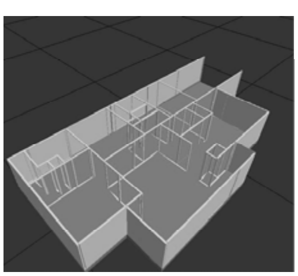


Fig. 2.8: All interior and exterior panels set

Individual panels with their constituent parts (studs/plates/sheathing) were grouped as CAD blocks and exported through AutoDesk 3D Studio Viz software for file transfer purposes to the end use simulation software. The end use software used in this report was the ENVISION modular virtual prototyping and simulation-based design software by Delmia. The ENVISION platform, "focuses on the integration of product, process, and system information with a powerful three-dimensional CAD physics-based graphical simulation environment."

Development of a Virtual Assembly Prototype

Once the parts have been generated, the virtual prototype can be assembled using the time sequence data collected and the elapsed times collected from the video clips (Figs. 2.3–2.13). Five different requirements need to be addressed to assemble the virtual prototype:

- material placement,
- palletized delivery stack order information,
- panel assembly process order/builder technique information,
- task times and field assembly notes of process categories, and
- the ENVISION software's assembly sequencing.

The assembly process parts are imported from 3D CAD into the Delmia ENVISION software. The modeled parts include panels, pallets, slab/deck, and bracing. Delivery pallet placement with the virtual workspace, panel selection order, and relevant micro assembly process such as panel delivery orientation are defined with field note referencing. Actual panel delivery paths can be approximated from the referenced video footage. This information can then be used to approximate X-Y-Z part-orientation tag points for the creation of virtual part trajectory paths.

Virtual panels are represented as palletized at the beginning of the delivery stage. Virtual pallet modeling requires that users manually compile a pallet in either the CAD block creation stage or within the ENVISION layout menu. Assembly prototyping from this stage then proceeds to mimic actual panel routing observed on site. A reverse sequencing feature of the simulation software allows users to disassemble a previously completed 3D model and initially was used for modeling expediency. Although this technique can cause part path and sequencing confusion when compared to the observed and recorded forward process panel assembly, its potential disadvantage can be offset by the ability to disassemble high-tolerance product models. Such models have been preassembled on the highly flexible and more geometrically accurate CAD platforms.

Although slightly different assembly techniques are employed by each builder, they can be accurately categorized and quantified utilizing macro and micro levels of prototyping. Macro assembly distinctions, such as those observed in different initial panel staging approaches, can be effectively modeled using the ENVISION prototyping software. Individual time and path assignments for virtual panels can discriminate from the prestage, random, and discard panel sequencing observed within the field. Similarly, micro assembly processes, which typically fortify the larger-scale macro activities, can also be analyzed using virtual prototyping (Figs. 2.9 through 2.13).

Fig. 2.9: Ergonomic simulation personnel set panel at slab

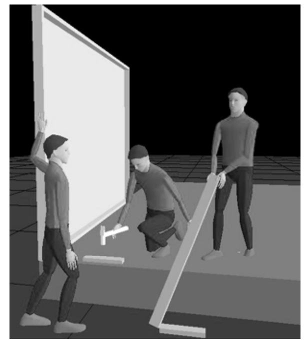


Fig. 2.10: Ergo team holds panel, prepares tools, picks up bracing material

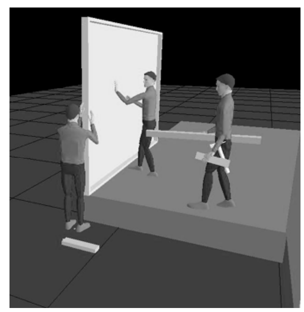


Fig. 2.11: Ergo team holds panel, plumbs panel, prepares to install brace

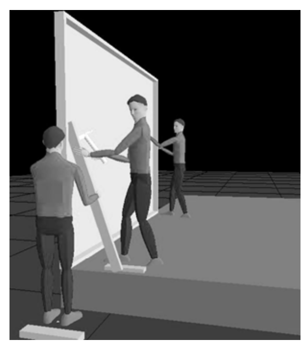


Fig. 2.12: Ergo team holds panel, holds brace, nails brace into position on wall panel

Fig. 2.13: Ergo team plumbs panel, adjusts panel plumb with a back, and nail brace into position at floor cleat

Thorough field notes and video data analysis inform virtual modeling attempts, which can reduce a “stand and affix” macro staging activity into specific micro processes (stand, align, get tool, nail) defined by material path and timing, information, and labor constraints. The attachment of panel bracing offers an example of how micro level sequence prototyping can be defined as a stand-alone micro assembly process or as integrated production factors that can be linked to and influence macro process prototypes.

After reviewing the characteristics of the four paradigms for 21st century construction simulation modeling: computer simulation, virtual prototyping, information exchange protocols, and knowledge management, two specific simulation methods (Petri Nets and physics-based virtual prototypes) were considered in greater detail for applicability to the production homebuilders process.

The next chapter applies computer simulation to production builder construction processes, and makes specific findings and recommendations for each.

3

Studies of Production Builders

Four production builders allowed the research team access to production documentation, field documentation, and construction sites for evaluation of computer simulation methods. Two discrete event simulators, ARENA and Petri Net, were used to assess production compatibility between workstations, identify production bottlenecks and evaluate the impact of error on processes.

Three of the builders use on-site assembly and construction techniques; one builder makes extensive use of off-site modular construction techniques. Construction processes documented in Phase III of "Industrializing the Residential Construction Site" became the beginning point for time and activity simulation in this Phase IV study. Field assembly/ erection of premanufactured wall panels were studied for the three builders who use on-site assembly/construction processes, and production processes for roof element subassemblies were studied with the modular home builder.

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 that the builder provide production documentation and access to a production site and associated personnel.

Builder project sites were observed by a team of research assistants to record details of the framing process, material paths, information flows, and times for each of the elements of the framing process. Over the course of the site visits, information disconnects and resulting production bottlenecks similar to those recorded in Phase III of "Industrializing the Residential Construction Site" were observed. Where possible, the impact of these situations on production time was recorded for use in the simulations.

Builder One

Builder One, a modular home builder with production facilities in two states, produces more than 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.

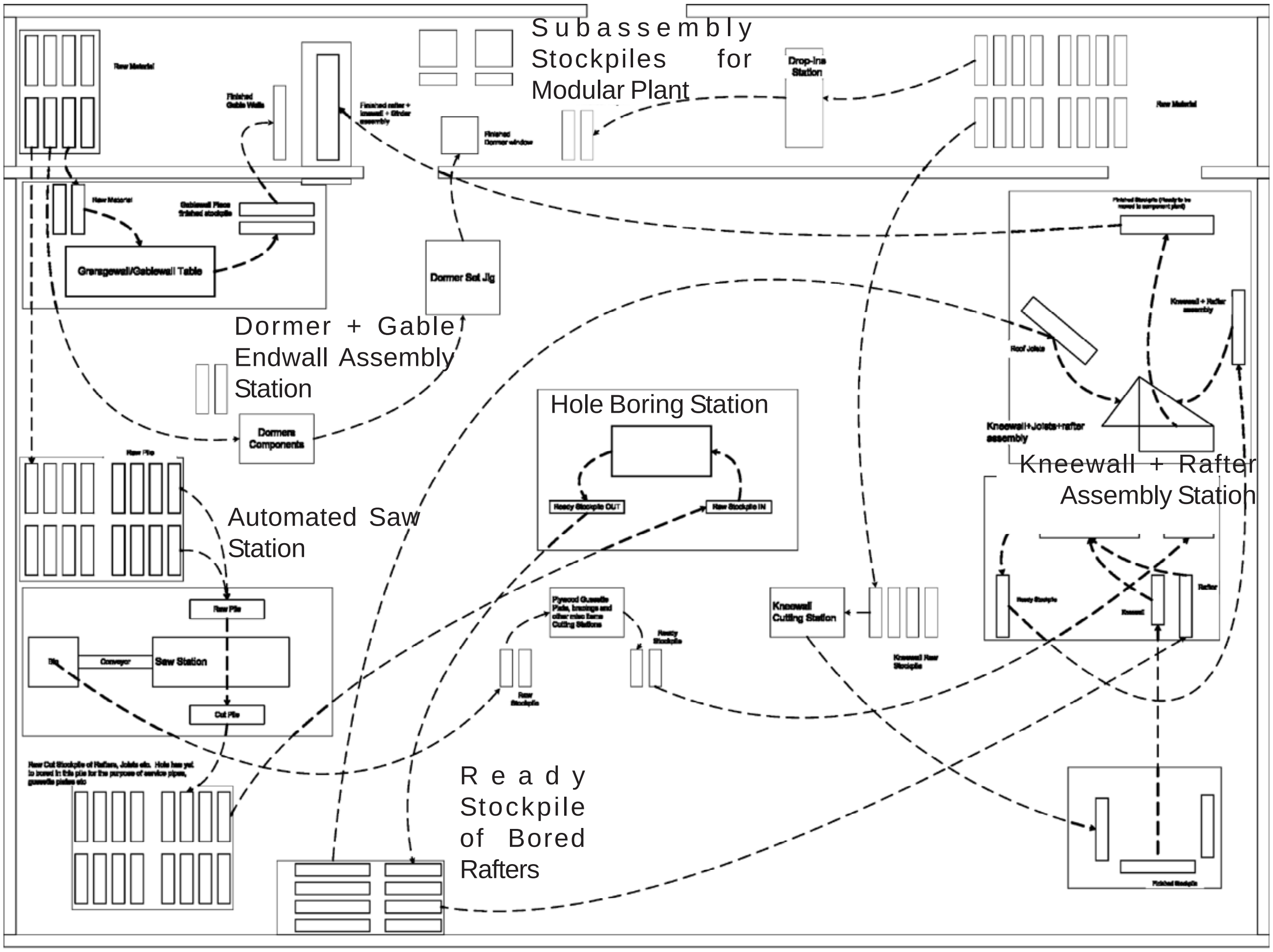


Fig. 3.1: Component plant layout diagram (source: HUD Phase III report)

Process Overview: Component Plant

The Phase III study documented the following characteristics of Builder One's production process. There are two primary stages of the modular production process. First, roof components and subassemblies are produced in the component plant (Fig. 3.1) for delivery to the modular plant assembly line, and second, the roof subassemblies and components are mated to the wall and floor assemblies in the modular plant where additional systems, finishes, and appliances are installed to complete the house modules.

Component plant schedules are established by the time frame faxed by the modular plant manager to the component plant manager. This time frame requires that all the subcomponents required for roof fabrication be ready for shipping to the modular plant at least one day prior to the day when the modular plant begins the assembly process. The component plant usually requires three days to fabricate all the necessary components for a typical folding modular roof.

The component plant manager studies the drawings, filters out information that doesn't apply to the production of roof components, and prepares cut sheets for each of the four primary component work stations. The cut sheet is a precise instruction to a work station regarding type, quantity, and dimensions of materials required for roof components and subassemblies. The component plant manager prepares and distributes cut sheets manually to the following work stations:

- automated saw station—a programmable saw that cuts rafters, joists, dormer frames, overhang, and gable end components (Fig. 3.3);
- rafter, kneewall, and joist assembly station—a layout table with jigs/ fixtures for assembly of various roof lengths, joist depths, and roof slopes (Fig. 3.7);
- dormer window station—an area of the component plant floor where dormers are framed, sheathed, roofed, sided, and glazed (Fig. 3.10); and
- gable wall assembly station—where flip-up gable end closure panels are framed, sheathed, and stockpiled (Fig. 3.12).

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 work stations 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 assembly station attendant sets up the jig to match rafter and joist depths and roof slopes as 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 delivered batch of rafters and kneewalls and produces a ready stockpile of hinged kneewall and roof joists.

Fig. 3.2: Raw material stockpile for automated saw station

Fig. 3.3: Automated Saw Station

Fig. 3.4: Saw station ready material stockpile

Fig. 3.5: Forklift operator updating component plant personnel on modular plant stock status

Fig. 3.6: Kneewall cutting station (Source: Phase III report)

Fig. 3.7: Rafter/ kneewall/joist assembly station (Source: Phase III report)

Fig. 3.8: Rafter/ kneewall assembly

Fig. 3.9: Hinged connection between rafter and joist

Fig. 3.10: Dormer assembly station (source: HUD Phase III report)

Fig. 3.11: Exterior ready stockpile of dormers

Fig. 3.12: Dormer cutting and gable end wall assembly station (Source: Phase III report)

Fig. 3.13: Folded joist/rafter/kneewall assembly installed in roof subassembly in modular plant

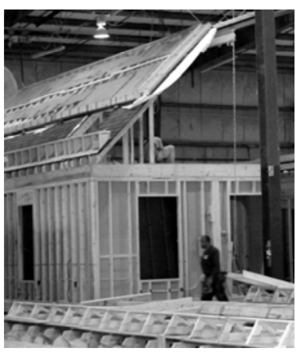


Fig. 3.14: Unfolded joist/ rafter/kneewall assembly installed in roof subassembly in modular plant (Source: Phase III report)

This stockpile is taken to a second table in the same work station. This work station also draws 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 types of dormer windows (Fig. 3.10). Like the saw station, this station maintains a designated quantity of dormers (Fig. 3.11). 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, it produces the required gable end walls and stockpiles them (Fig. 3.12).

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. After fabricating their designated material, individual work stations pack and transport assemblies to the storage area. Forklift operators transport the material to the modular plant for further processing. (Fig. 3.13, 3.14)

Relationships with Associated Systems

In the context of Builder One's overall process, the component plant supplies four products to the modular plant:

- precut floor joists,
- preassembled folding roof joists,
- preassembled folding gable ends, and
- preassembled dormers.

The timely production and delivery of each of these to the modular plant as called for by the house under production is critical to the efficient use of the builder's plant, tooling, and personnel.

Known Bottlenecks and Disconnects

The results of the functional analysis mapping conducted in Phase III of "Industrializing the Residential Construction Site" revealed places in the work flow where errors and production bottlenecks had occurred or were likely to occur. This functional analysis mapping was the basis for the construction of an ARENA discrete event simulation. For the purpose of that 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 formal information supplied to the production floor;
- errors in the interpretation (filtering) of formal 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 errors in coordination of the design documents; and
- bottlenecks caused by mismatched production capacity between adjacent stations in the work flow.

This study examined the last of these bottlenecks, those caused by mismatched production capacity between adjacent stations in the work flow. In the component plant, this bottleneck was specifically identified as the hinge bolt boring station. The overall production of a modular folding roof requires 54 folding rafter/kneewall/ceiling joist subassemblies, two dormer end subassemblies, and one dormer assembly. Fabrication of these subassemblies involves seven steps and five work stations.

Process Elements and Times to Produce 54 Subassemblies

- Cut ceiling, kneewall, and roof, components: 25–30 min.
- Cut kneewall studs: 30 min.
- Bore roof joist, ceiling joist: 28–40 min.
- Join kneewall studs with roof rafter: 45 min.
- Join kneewall stud/rafter to ceiling joist: 45 min.
- Construct two gable end walls: 180 min.
- Construct one dormer: 210 min.

Simulation Alternatives

The ARENA simulation identified a mismatch between the production capacity of the automated saw, the assembly station, and the boring station that falls between them. This mismatch had been reported during the Phase III study and was quantified by the numeric simulation to cause a bottleneck taking 6–10 minutes. The alternative simulated here introduced an additional boring station as a process refinement. Rerunning the simulation with two boring stations resulted in a reduction of the bottleneck. The simulation also showed that unless the additional boring station personnel could be flexibly tasked to assist in reducing the production time for gable ends, drop-in panels, and dormers, the additional personnel might result in underutilized production capacity at the boring station.

Builders Two, Three, and Five

One predesigned house plan was selected from each builder's product line to become the model subject for the simulations. Each house was 2,000–2,500 square feet and one or two stories with no basement. All house designs in this project are currently being produced using premanufactured components and construction processes similar to those in the simulations.

Field drawings for placing the wall panels were available for each of the three site-built houses simulated. The physical characteristics for the house designs related to the wall panels, and the characteristics of the wall panels themselves were extrapolated from these drawings and guided the development of the simulation.

Characteristics of panelized house designs:

- The 2,500-square-foot house required approximately 70 wall panels total, 30 exterior and 40 interior.
- Panels broke on the near or far side of the double stud supporting lintels or headers over openings, never in mid-opening.
- The average length of a sheathed (exterior) panel was approximately 8 feet.
- The average length of an unsheathed (interior) panel was approximately 5 feet.
- Ideal panel length for two people to lift and carry was approximately 12 feet.
- Panel lengths appeared to be set by the number of 16-inch stud-center spaces unless the design required a shorter panel to "close" the length of a wall.
- The longest panel (the garage door panel) was 20 feet long. The research team assumed this was the largest panel that could be lifted by the full setting crew (five people) as no cranes were observed on the construction sites.
- The shortest panel was a 1-foot-long panel at an interior linen closet partition.
- The house design did not appear to anticipate the panelized method of construction, as only 15 of 70 panels (21%) met the 16-inch stud-center spacing increment. Of these, 12 were dimensioned to meet the size of a full or half sheet of sheathing.
- Assuming a weight of 21.8 pounds per linear foot for an 8-foot-high sheathed wall panel and 9.1 pounds per linear foot for an 8-foot-high unsheathed wall panel, the weight of a standard 12- by 8-foot sheathed wall panel is 261 pounds, and a standard 12- by 8-foot unsheathed panel is 109 pounds.
- A pallet of wall panels was assumed to be 5 feet tall, containing 15 panels, each approximately 4 inches thick.
- The 2,500-square-foot model house would require four to six pallets of wall panels.
- If floor plans were designed with wall lengths that could be sequentially broken down into wall panel lengths totaling 12 feet, panels could be stacked sequentially at the manufacturing plant. These would remain stable during shipping as it would not require balancing a 12-foot length upon a 4-foot length. The 4-foot panel would be immediately followed or preceded by an 8-foot panel to make a stable strata for stacking larger or smaller panels above.

Panelized Process Review and Model Preparation

The panelized wall systems are typically factory-framed using 2x4 dimensional lumber. Panel sizes vary 2–20 feet in length and 8–9 feet in height. Panel framing components include top and bottom plates, cripple studs under and above openings, windowsill plates and headers, and exterior sheathing, along with any supplemental bracing and connection hardware.

Panel manufacturers provide a wall panel assembly plan to guide on-site production. The assembly plan identifies each wall panel in its appropriate on-site position and also shows the foundation outline and an inventoried listing of each panel with its corresponding dimensional characteristics. Each wall panel's assembly position is identified by a corresponding reference number, which is labeled on the panel at the factory.

Bundled wall panels are banded together and delivered to the centralized workspace as a pallet. Before the panels are placed, the construction foreman lays out the wall locations on the floor using the production drawings supplied by the panel manufacturer to identify panel placement locations. At the pallet, workers identify and sort out desired panels. The number of crew members required to move a panel is typically influenced by worker availability, panel weight, and panel dimensions. Direct material delivery paths are cleared of obstructions, and panels are hand-carried to a staging position near the installation location marked on the floor.

Crews prepare staged panels for anchor plate bolt drilling and sill seal application and recheck panel placement measurements where applicable. Anchor bolt positions are measured, marked, and drilled along a wall panel's base plate, with panels typically receiving two drilled bolt holes per panel. Sill seal is measured, cut, and tacked along the bottom of each exterior panel base plate. Crews tilt or lift panels into place from the staged position to the final location on the floor.

Panel placement is initially checked for panel-to-panel adjacency, floor-to-panel contact, and overall layout alignment. Once a panel has been properly aligned, workers nail panel base plates to the deck/slab. Panels tend to stand freely with little extra support at this point in the process. Crews align panel top plates of adjacent panels and then nail all panel edges in a top-down direction. Large panels are then temporarily braced to the floor using scrap 2x4 material. The crew leader consults production drawings to start the installation of subsequent panels, and the process continues until all of the wall panels are installed.

The simulation identified a mismatch between the production capacity of the automated saw, the assembly station, and the boring station that falls between them.

For this study, field observation was the primary method used to collect data and to develop a sequential assembly task matrix. The data collection process consisted of four different steps. First, field observations were made of specific panelized wall system installation activities. These observations were later used to compile task categories relevant to the level of detail required for the process being prototyped. Second, using a stopwatch, task times were collected of specific panel assembly activities, including carrying and delivering the panel, lifting and setting the panel on the slab, drilling anchor bolt holes and attaching the seal sill, and nailing and bracing the panel to adjacent panels. Observations were recorded for problems encountered during the panelization process for each assembly category. Third, to ensure that all relevant activities and events were captured, the work process was documented with continuous video footage and still photographs of the panel assembly process. Fourth, field production drawings were obtained to identify panel dimensions and to reference final slab/deck placement.

Builders Two, Three and Five use prefabricated wall panels that are fundamentally similar, the difference being the extent to which sheathing panels are applied by the panel manufacturer or applied on site.

Relationships with Associated Systems

Premanufactured wall panels function as the primary structural elements of the house, the backing for the exterior finish, and the primary support for the following subsystems:

- moisture management,
- thermal insulation,
- vapor management,
- plumbing,
- electrical,
- telecommunications and alarms,
- interior finishes,
- interior cabinets, and
- doors and windows.

In this primary role, the precision and accuracy achieved during panel setting affects virtually every construction sequence that follows. Imperfections or errors in the panels themselves or in their installation can cause delay due to the additional shimming or trimming required to compensate for the error. Wall panel installation is equally sensitive to errors in precision and accuracy of the foundation system and in-slab utilities. Panels and panel layout frequently require modification ranging from adjusting panel length to equal foundation length by the simple installation of site-cut shims to the substantial modification and on-site reconstruction of panels.

Builder Two

Builder Two is a high-volume production builder and a regional division of an international home builder. 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 constructed by independent subcontractors under the direction of an on-site superintendent. Both the superintendent and subcontractors use a Web-based responsive schedule to coordinate the project. The 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 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 in Phase III of “Industrializing the Residential Construction Site.” This study identified three types of problems in the framing process:

- Precision problems: Information disconnects between the foundation subcontractor, in-slab systems subcontractors, and the framing subcontractor were observed to require extensive on-site modifications of framing components. Adjusting the premanufactured components to match a lower level of precision significantly reduced productivity increases possible with premanufactured framing components.

- Damaged materials and components: Suboptimization of the framing process from materials and components supplied to crew contributes to pressure on the crew to install any and all components delivered to the project site, including damaged components. Resolution of damaged components requires consultation with the component manufacturer, framing installer, engineer, and superintendent. This costly process frequently leads to delays while the new component is manufactured and delivered. Resolution costs include the rework associated with partial framing system disassembly, new component installation, and reassembly of the framing system.
- Interpretation problems: These were primarily attributed to the framing crew’s difficulty in interpreting the installation drawings sent to the job site by the manufacturer of the framing components. This has been observed to contribute to incorrect assembly of multi-ply girder trusses requiring costly consultation, disassembly, and rework.

Precision-related errors and staging-related productivity losses were chosen for simulation study in this Phase IV project.

Context: Townhome Panel Installation

A townhome construction site similar to that studied in past phases of the “Industrializing the Residential Construction Site” was the subject of the Builder Two study. The builder used a combination of sheathed and unsheathed wall panels for exterior load-bearing walls and unsheathed panels for interior partitions. A crew of three installed the wall panels. Smaller unsheathed panels 1–4 feet in length were carried by a single crew member, sheathed and unsheathed panels 4–8 feet were carried by two crew members, and 12-foot-long wall panels whether sheathed or unsheathed were placed by all three crew members.

Process Overview

The construction process had not changed in the twelve months that had lapsed since the previous study. In general this process is described as follows:

- Gypsum part-wall panels and supporting metal framing are delivered to the concrete slab.
- Full-height, two-story gypsum firewall panels and framing are erected.
- Premanufactured wood bearing wall panels are delivered in pallet form to a staging site approximately 100 yards from the slab (Fig. 3.15).
- Panels are inventoried; panel layout plans are taken to the concrete slab for layout (Figs. 3.16 and 3.17).
- Inside and outside panel layout lines are marked on the slab (Fig. 3.18).
- Utility conflicts with slab layout are noted for panel adjustment.
- Wall panels are sorted and loaded onto an all-terrain forklift for transport to the slab.
- Wall panels are transported to the slab and slid off the forks onto the slab.

Fig. 3.15: Palletized wall panels as delivered to townhouse slab

Fig. 3.16: Project and panel labeling

Fig. 3.17: Review of wall panel placement drawing

Fig. 3.18: Panel layout lines, numbers on slab

Fig. 3.19: Locating anchor bolt at slab edge

Fig. 3.20: Transferring anchor bolt locations to bottom plate of wall panel

Fig. 3.21: Drilling anchor bolt holes in panel

Fig. 3.22: Sill seal gasket laid over anchor bolts

Fig. 3.23: Carrying sheathed panel to slab location

Fig. 3.24: Preparing to lift panel vertical

Fig. 3.25: Three-person lift to vertical

Fig. 3.26: Handhold to restrain from overturning

Fig. 3.27: Seating over anchor bolts

Fig. 3.28: Adjusting panel to slab marks

- Panel numbers are transferred to their location on the concrete slab.
- Wall panels are laid on the slab at the location indicated on the concrete slab.
- Anchor bolt and utility stub locations are transferred to the panels (Fig. 3.20).
- Panel bottom plates are drilled to fit over the anchor bolts or utility stubs (Fig. 3.21).
- Sill sealer is installed on the slab over the anchor bolts and utility stubs (Fig. 3.22).
- Panels are set over the anchor bolts/utility stubs (Figs. 3.23–3.27).
- Panels are plumbed, braced, and anchored to the slab with nails and bolts (Figs. 3.28–3.30).
- Corners are shimmed or corner panels rebuilt to meet foundation line (Fig. 3.31).
- Panels are nailed off to adjacent framing (Fig. 3.32).
- A top or splice plate is nailed to panel tops to tie panels together.

Known Bottlenecks and Disconnects

Phase III of "Industrializing the Residential Construction Site" concluded that mismatches between the level of precision achieved in premanufactured components and that commonly obtained in foundation and in-slab utilities results in significant losses in production efficiency.

The installation of damaged components had been observed in the Phase III study and attributed to economic pressures on the framing installer to accept the components provided by the builder and install these components in the least time possible to ensure profitability. The existing information flows and process management don't support rapid (same-day) replacement of materials or components damaged in manufacture or shipping. Given the short time period the framing subcontractor has to fully erect the frame (one to two days), the choice is made by the installer to assemble the frame with whatever has been delivered, leaving detection and remediation to subsequent parties. Once installed, if the damaged component is detected, it is difficult to clearly assign the origin of the damage to manufacture, delivery, on-site handling, or installation. Remediation costs spread across the involved parties are not sufficient incentive for implementing a zero-defect practice at the site of manufacture or for on-site installers. We speculate that a fully responsive production and supply chain would facilitate rapid detection and replacement of damaged components prior to installation.

Phase III also concluded that errors could be reduced and production efficiency could be further enhanced through minor modifications to design, drawing, packaging, and staging of wall panels and building components.

Process Elements

1. Delivery of components to site (full buffer).
2. Layout on slab from drawings (factor to account for percentage of correct and incorrect interpretations).
   a. Compensate for errors in precision of the foundation (square, dimension, level).
   b. Compensate for errors in precision of the in-slab utilities.

c. Compensate for errors in anchor bolt layout (move studs, add quick-bolts).
3. Install sill seal over anchor bolts and utility stubs.
4. Begin panel assembly.
    a. Find the panel in the pallet (factor to account for variability of stack order).
        - Read panel designation.
        - Pick up panel.
        - Move panel to side.
    b. Pick up needed panel.
    c. Walk panel to foundation.
    d. Place panel next to layout marks.
    e. Transfer location of anchor bolts/utility stubs.
    f. Drill/cut plate for bolts/stubs.
    g. Lift panel into place.
    h. Brace panel plumb.
    i. Nail panel to adjacent panel.
5. Go get next panel.
6. Repeat until all panels are installed (empty buffer).


Fig. 3.29: Placing panel over anchor bolts


Fig. 3.30: Anchor nailing into position


Fig. 3.31: Placing small exterior closure panel

Process Times

Fig 3.35 shows a sample of process times for panel installation for Builder Two. (The remainder are listed in Appendix B.)

Panel Number	Crew Members	Activity	Cumulative Time (Min.)
7	3	Carry and deliver	1:06
	2	Hold panel in place	3:32
	3	Lift & set panel	4:34
	3	Anchor bolt stud interference	5:40
	3	Redrill anchor bolt holes	6:58
	3	Lift & set panel	7:18
	3	Anchor panel into position	8:13
	2	Affix to side of other panel	8:30

Fig 3.35: Example of panelization data for Builder Two


Fig. 3.32: Nailing to adjacent panel


Fig. 3.33: Carrying interior unsheathed wall panel


Fig. 3.34: Anchor nailing interior panel to slab

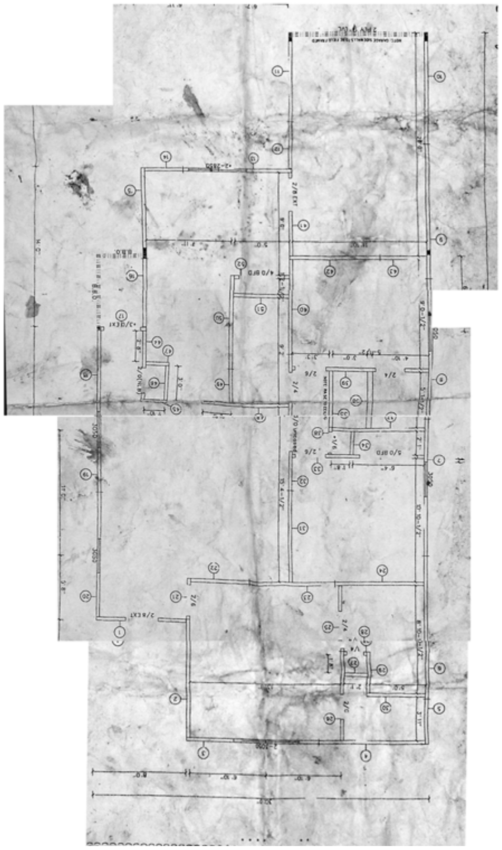


Fig. 3.36: Field copy, wall panel placement plan

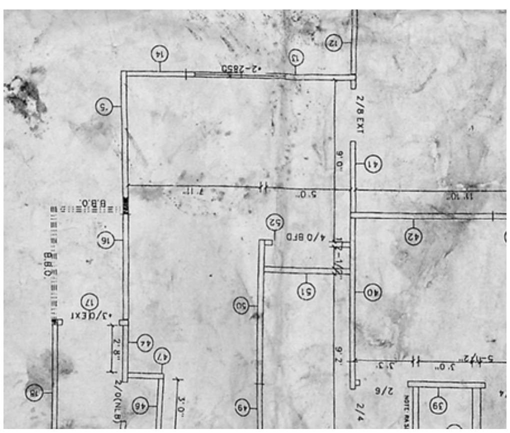


Fig. 3.37: Detail of the panel placement plan

Fig. 3.38: Panel numbering as delivered

Builder Three

Builder Three is a high-volume production builder and a regional division of an international home builder. 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, primarily by independent subcontractors under the direction of an on-site superintendent. The superintendent and subcontractors use 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.

Framing Process

The framing process includes the erection of prefabricated wall panels for the first and second floors, prefabricated floor trusses, and prefabricated roof trusses. The framing crew is made up of two to four people, including the framing foreman.

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.

The framing crew unloads the panels from the delivery truck using a forklift. The panels are stacked close to the concrete slab. The crew then takes each panel from the stack and places it according to its location on the panel drawing plan (Figs. 3.36–3.38). The panels are then connected to the slab with anchor straps. This process is repeated for the entire stack of wall panels. The exterior panels are anchored to the slab and adjacent panels; then internal panels are positioned and squared to the exterior panels. After all the panels are set, the framing foreman climbs on the top plate of the panels and squares them to the concrete slab below and each other using a hammer and a spirit level. A splice plate is nailed across the top of the panels, which ties them together.

After the framing process is complete, mistakes in the plumbing rough-in become evident. If panels cannot be modified to accommodate the error, the plumbing subcontractor must return to 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. The pipes are then reinstalled to correspond to the correct wall locations. During this process, the wall panels are also in place, further frustrating the repositioning of rough-ins.

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, saving time and ensuring higher overall quality, but the resulting delay is a strong disincentive for the panel assembly crew.

After the framing process is complete, the truss manufacturer delivers floor and roof trusses to the construction site. The truss manufacturer is required to provide a truss layout drawing when the trusses are delivered. This drawing indicates the installed location of each truss in the overall component layout. Occasionally, this document is not delivered with the trusses. In this case, the truss installation procedure cannot proceed, and the superintendent has to request this document from the truss manufacturer, causing delays for the truss installer.

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. 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.

Known Bottlenecks and Disconnects

The following potential problems were observed in the framing process for Builder Three during the Phase III study:

- Mismatches in precision between plumbing rough-in locations laid out from surveyors' control point and the framing layout from the slab edge, which assumes that the slab edge is accurate. There is no precise layout coordination between slab edge, wall center, and in-slab plumbing and electrical stubs.
- Mismatches in precision between anchor bolt location in slab and panel sizes.
- Filtering errors between the builder and panel manufacturing company related to right- and left-handed and reversed orientations of the predesigned plan.
- On-site rework of wall panels related to sheathing on wrong face as a result of information filtering error.
- Suboptimization of each subcontract resulting in more difficult and costly rework of errors discovered by one subcontractor in the work of another. Schedule pressure is a disincentive for the discovering subcontractors to delay their own work until the problem is corrected.
- Delays resulting from rework of plumbing and electrical in-slab utility conflicts with foundation edge/wall panels.

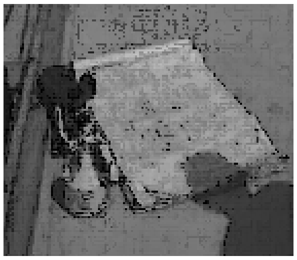


Fig. 3.39: Wall placement drawing


Fig. 3.40: Snapping lines for wall placement


Fig. 3.41: Sill seal gasket installed on slab


Fig. 3.42: Drilling anchor bolt holes


Fig. 3.43: Carrying sheathed panel to slab location


Fig. 3.44: Nailing to adjacent panel


Fig. 3.45: Anchor nailing into position

Process Elements

The construction process can be described as follows:

1. Premanufactured panels are delivered to a staging area approximately 100 yards from the slab site.
2. Panel layout lines are taken from the drawings and marked on the slab (Figs. 3.39, 3.40).
3. Wall panels are transported by forklift and stacked on the slab.
4. The crew sorts the stack and picks up the needed panel.
5. The crew carries the panel to the foundation and places the panel according to its number on the slab.
6. Sill sealer is installed on the slab over the anchor bolts and utility stubs (Fig. 3.41).
7. Anchor bolt and utility stub locations are transferred to the panels.
8. Panel bottom plates are drilled to fit over the anchor bolts or utility stubs (Fig. 3.42).
9. Panels are lifted and set over the anchor bolts/utility stubs (Fig. 3.43).
10. Panels are braced and/or anchored to adjacent framing (Fig. 3.44, 3.45).
11. The process is repeated until all panels are installed.

Process Times

Fig. 3.46 shows an example of the process times for panel installation for Builder Three. (The remainder are listed in Appendix B.)

Panel Number	Crew Members	Activity	Cumulative Time (min.)
NA	2	Drill anchor bolt holes	0:32
	2	Carry and delivery	1:30
	2	Hold in place	2:10
	2	Lift & set panel	3:30
	2	Verify panel fit	4:30
	2	Nail side to side	5:01
	2	Anchor panel	7:27

Fig. 3.46: Example of panelization data for Builder Three

Builder Five

Builder Five is a medium- to high-volume production builder and a regional division of a national home builder. 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. This study focuses on a regional division operating in the southern mid-Atlantic portion of the United States.

Panelization Process

The panel component manufacturers 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 wall 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 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.

Builder Five specifies that wall panels be delivered to the site unsheathed; this practice is consistent with observations conducted during Phase III of "Industrializing the Residential Construction Site." Wall sheathing is field-applied by the framing subcontractor.

Known Bottlenecks and Disconnects

The following potential problems were observed in the framing process for Builder Five during the Phase III study:

- Subcontractors are operating on instructions from multiple information paths. Builder requirements are not reaching field crews in a uniform manner.
- Precision is lacking in layout, excavation, and construction of footings.
- Layout control points are not fixed. Each subcontract foreman chooses control points for layout.
- If the subcontractor is not aware of the builder's specification for alignment of sheathing and slab, the interior dimensioning is affected, causing further field adjustment modification of interior partition panels that could affect cabinet, millwork, and appliance installation.
- The on-site installation of additional framing members to the prefabricated wall panels to support the horizontal application of sheathing panels slows production and could be included as part of panel manufacturing.
- Anchor bolts, plumbing, and electrical risers are often in conflict with panels, requiring field adjustment and often resulting in reduced panel integrity.

Anchor bolt placement and foundation precision errors are the most significant obstacle to rapid installation of wall panels. Where no conflicts are present, a wall panel can be carried, marked, drilled, placed, and braced in five to seven minutes. When anchor bolts need to be removed, the time per panel doubles. These error conditions were noted during on-site observations conducted to collect data for simulation of the installation of wall panels.

A crew of three completes the assembly of the wall panels for a one-story single-family detached home in approximately one working day. The most frequent delay during the panel installation process results from conflicts between anchor bolt locations in the slab foundation and the vertical studs in the wall panels. Remediation typically requires sawing off the anchor bolt, placing the panel, and drilling a new anchor bolt into the slab. Delays caused by conflicting dimensions between the wall panels and foundations were also observed. Remediation requires shimming or partial disassembly/reassembly of the wall panel to meet the foundation dimension.

Panel Line Layout

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

Fig. 3.47: Wall panel layout

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 the longest unbroken slab perimeter line). The foreman usually uses the panel layout or the site’s architectural drawings to make his decision. The Phase III study found neither set of drawings shows the relationship of the walls to the foundation or indicates control points. When snapped, the lines are inset four inches from the edge of the slab’s face (Fig. 3.47) to enable the exterior stud walls (2x4s) and sheathing to sit fully flush to the slab surface with no overhang to company specification.

Fig. 3.48: Panels being shuffled at delivery pallet to find needed panel

Fig. 3.49: Two workers move a wall panel to the slab

Fig. 3.50: Transferring anchor bolt location to panel

Panel Assembly

The Phase III study observed two different approaches to setting wall panels. The first assumes the foundation to be precise and places each panel on the slab in the order it is removed from the stack. This approach requires frequent shimming and panel adjustment. The second observed approach places panels around the foundation slab in their appropriate locations before drilling, anchoring, and bracing them in place. This second approach seemed to require fewer but somewhat larger adjustments to the wall panels. 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. 3.48).

The two approaches also vary when measuring the anchor bolt holes for placement on the panels. In the first approach a worker pulls the measurement off the panel while another worker measures the placement space on the slab (Figs. 3.49 and 3.50). 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.

The second approach pre-positions 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. Holes are then drilled in the wall panel base plates (Fig. 3.51). 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. 3.52).

Interference errors significantly impact the production efficiency of wall panel systems, requiring extensive panel handling and field modification (Fig. 3.53). 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 (Fig. 3.54), 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 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 (Fig. 3.56).
- 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.

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. In option one, plywood or OSB wall sheathing is applied 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 uses nine-foot plywood or OSB sheathing panels oriented vertically to extend from slab to bottom


Fig. 3.51: Drilling baseplate for anchor bolt clearance, sill seal gasket in place


Fig. 3.52: Seating wall panel over anchor bolt

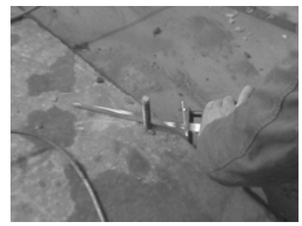


Fig. 3.53: Cutting off misplaced anchor bolt


Fig. 3.54: Repositioning stud to avoid interference with anchor bolt


Fig. 3.55: Cut nail temporary anchors


Fig. 3.56: Tying top plates together


Fig. 3.57: Anchor bolts set too close to slab edge for flush fit between foundation and OSB sheathing

plate of second-floor framing panels. No additional nailers are required in option two.

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. This step becomes an additional bottleneck as it typically occurs after the panel sheathing process and the sheathing obstructs clearance for the wrench in the stud cavity.

Process Elements

The elements of the wall panel installation process are as follows:

- Delivery of the wall panel from the staging area to its final location on the floor plate.
- Measuring location of anchor bolts or utility stubs on the floor plate and scribing these locations on the bottom plate of the wall panel.
- Drilling holes for the anchor bolts in the bottom plate or cutting away the bottom plate for utility stubs as needed.
- Installation of the foam sealant gasket over the anchor bolts on the slab.
- Lifting the panel over the anchor bolts or utility stubs and setting it on the sealant gasket.
- Anchoring the panel to the slab by placing washers and threading and tightening nuts over the anchor bolts and nailing the wall panel to adjacent panels.
- Bracing the wall panel in a vertical position.

If conflicts with anchor bolts are encountered, the additional steps of moving the stud or cutting off the bolt and drilling/installing a new anchor bolt are required (Fig. 3.53).

Process Times

Figure 3.58 shows a sample of process times for panel installation for Builder Five. (The remainder are listed in Appendix B.)

Panel Number	Crew Members	Activity	Cumulative Time (min.)
2	2	Carry and delivery	1:12
	2	Orient panel	1:26
	3	Measure & scribe	2:30
	2	Drill anchor bolt holes	Not recorded
	2	Resolve anchor bolt & stud conflict	Not recorded
	2	Cut anchor bolt	5:15
	2	Redrill anchor bolt holes	6:10
	2	Install sill seal gasket	6:40
	2	Lift & set panel	7:40
	2	Anchor panel into position	8:40
	2	Affix to panel # 21	10:19

Fig. 3.58: Example of panelization data for Builder Five

Simulation of Builder Processes

Earlier in this report several questions were posed in relation to the overall efficiency and efficacy of the residential construction process as examined. The issues included the following:

- The effect of panel design on constructability in the field.
- The compatibility of panelization scheme with the design of the house.
- Stacking protocols of panels on pallets employed by panel manufacturers for delivery to the site and effect this has on site erection. (Generally panels appear to be stacked to optimize shipping rather than field erection.)
- The impact of panel size on placing efficiency.
- The impact of crew size on placing efficiency.
- The impact of subsystem and subassembly design on construction efficiency (e.g., design and construction control over slab/panel penetrations for plumbing, wiring, windows, etc.).
- The effect of using fixtures and templates to improve precision of subassembly and panel locations.
- The effects of errors on construction efficiency (e.g., drawing error, panel error, foundation error, placement errors).

In this section the numerical and graphical simulators introduced in Chapter 2 are applied to these and other issues based on the builder statistics earlier in this chapter. We begin by looking at the types of simulators available for both graphical (3D virtual prototyping) and numerical simulation. Exemplars of both graphical and numerical simulators are chosen, and the advantages and disadvantages of each are discussed before we embark on the simulations of the residential construction processes.

The example simulations are used to explain how to capture variability and error in both graphical and numerical simulations. A discussion of data collection, sample sizes, and simulation value follows.

The Petri Net Model of the Panelized Construction Process

Figure 3.59 shows a Petri Net (PN) model of the panel erection process described in Chapter 2. Circles with text inside them represent the resources available to the construction tasks, for example Wall Panels, Crew #2, Sill Seal, Shim Stock, etc. Quantities of resources are not shown for clarity.

The rectangles represent work tasks undertaken by the crews or crew members. The numbers inside the rectangles are the values used to construct the triangular distribution of work task times in seconds. The triangular distributions are used to represent variability in the time taken to execute work tasks in the field. The values and distributions were taken from historical records of field observations. The circles with shadows represent branches in the construction process for errors or adjustments to field conditions. The probabilities of each branch being taken were also inferred from field observation and are shown inside the circles (places). The field data recorded in this study was limited and is not statistically representative. The times and probabilities, while reasonable for field operations, are illustrative only for the purpose of this study. Note

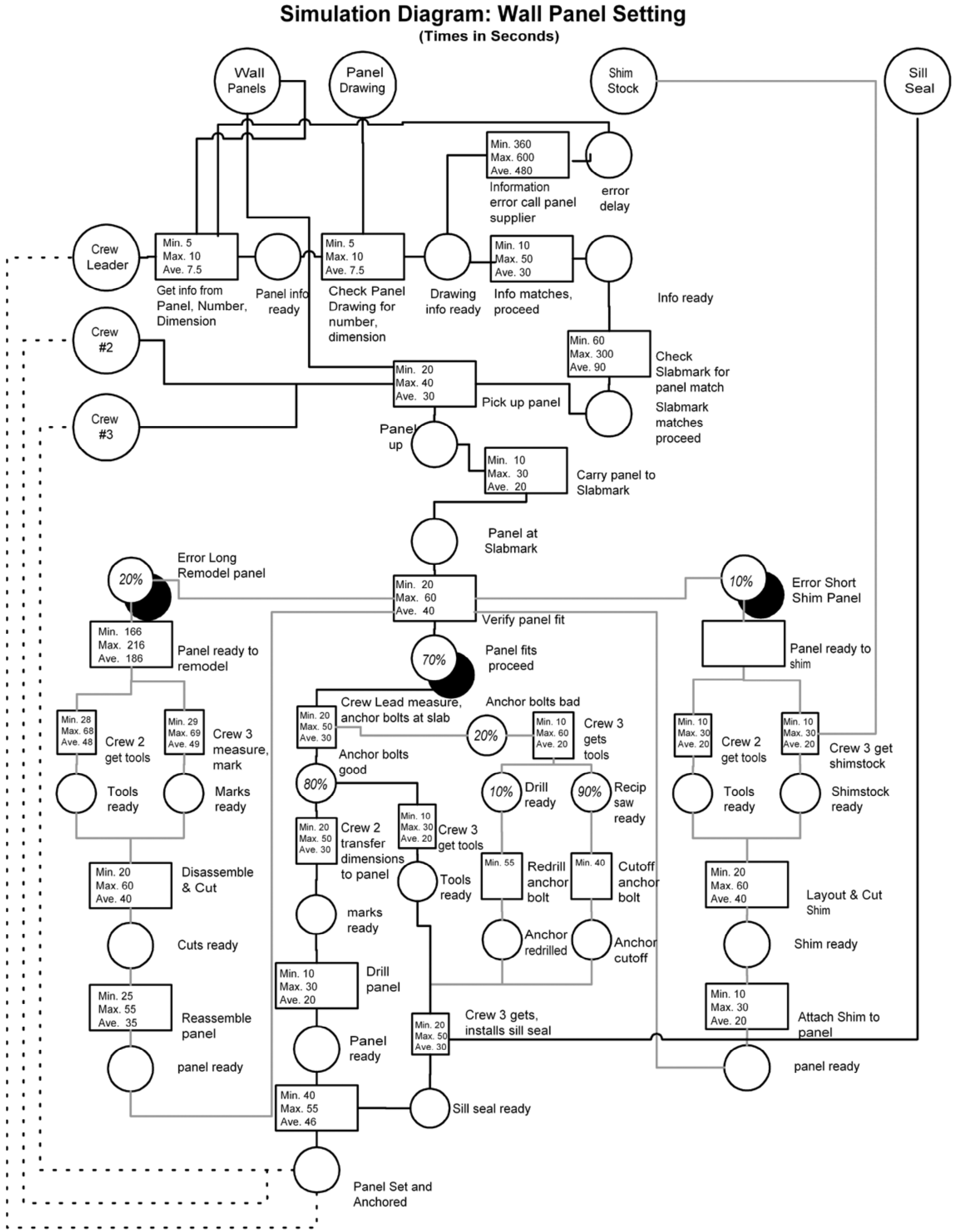


Fig. 3.59: Petri Net simulation diagram for wall panel setting

also that for clarity, the simulations do not include break times for workers between erection of separate panels.

The process of panel erection can be simulated a number of times, and conclusions can be drawn about the process operation. In this example, the simulation was run 100 times without including potential errors. The average error-free time for erection of the 27 panels that make up the house was 3.08 hours. The longest error-free time to complete the erection was 3.38 hours and the shortest time was 2.94 hours. A frequency error-free distribution of results is shown in Figure 3.60.

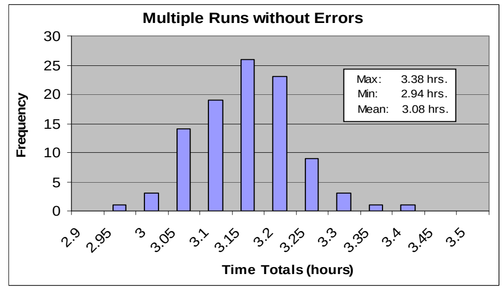


Figure 3.60: Histogram of multiple panel simulation run without errors

The error probabilities were then activated and the simulation run 100 times. The average time for erection of the 27 panels that make up the house was 4.37 hours. The longest time to complete the erection was 4.95 hours, and the shortest time was 3.81 hours. A frequency distribution of results is shown in Figure 3.61. Other data can be captured from the simulation relating to idle times for equipment and labor, waiting times for delays in the operations or errors, and resource utilization figures.

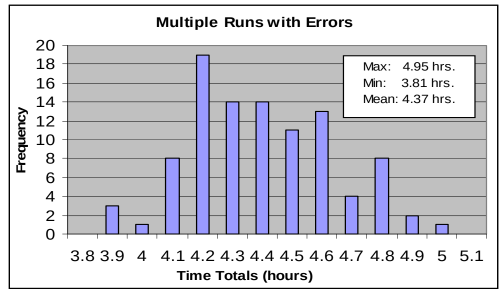


Figure 3.61: Histogram of multiple panel simulation run with errors

Plotting the results as a cumulative graph gives information on the 95th, 50th, and 5th percentile completion times. Figure 3.62 shows that in an error-free process, 95% of the time the panels could be placed in 3.26 hours. Fifty percent of the time the panels were placed in 3.14 hours, and 5% of the time in 3.0 hours due to the triangular distribution of times programmed to account for process variability at each transition between places in the simulation.

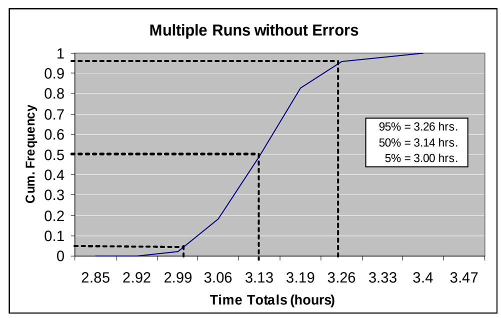


Figure 3.62: Cumulative frequency distribution of multiple panel simulation run without errors

Figure 3.63 is a similar cumulative graph of the same process simulation, this time run with probabilities of error included. In these runs, 95% of the time the panels took 4.79 hours to place. The same triangular distributions revealed that 50% of the time the panels were placed in 4.35 hours, and 5% of the time panels were placed in 4.04 hours.

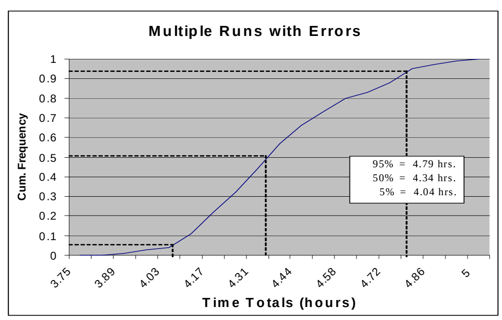


Figure 3.63: Cumulative frequency distribution of multiple panel simulation run with errors

Further experiments could be carried out to investigate the effects of reducing error probabilities, increasing crew sizes, and altering the process logic. Inferences could then be drawn on the new processes in relation to efficiency and cost-effectiveness. It is relatively straightforward to model, test, and investigate new industrialized processes and construction systems using this simulation. The difficulties come in understanding human and spatial interactions between components and actors in the simulation model. Planning paths, material ergonomic analysis, connection details, and physical problems cannot be investigated in the Petri Net because of the abstract nature of the simulation model. The virtual prototyping system described in the next section has the capacity to tackle these difficult problems.

Observations on Simulation Process

The macro and micro simulation methodology described at the end of Chapter 2 is a simple but intensive approach to virtually dissect the complex processes which influence and result from the activity of construction. With an accurate virtual assembly prototype, one might begin to suggest descriptive and predictive analyses that could benefit design and production performance. Specific ergonomic analysis features are available which might suggest performance optimization at both the macro and micro activity levels. Path optimization related to both activity levels is made possible with ENVISION's 3D real-time interference checking and part volume sweeps. The use of these tools suggests that virtual construction modeling has many potential benefits for the residential construction industry, particularly if a construction-specific interface and tool set is developed for graphical simulators.

Increased use of simulation/virtual prototypes will require greater investigation of the cultural, managerial and, technical complexities of the residential construction process. Future work might suggest specific data areas requiring greater definition. One of these areas includes more accurate on-site sequence timing. This change requires not just increased mechanical accuracy but more specific methodological definitions of an activity's start and stop points. Accuracy related to on-site position information must also be refined to better inform work path optimization in the virtual environment. Actual material characteristics, such as product weights or their ergonomic handling procedures, might also greatly enrich any prototype hoping to reflect (at a minimum) the realities of an actual assembly environment.

Gaps in activity continue to pose problems with field data. Clearly some crew inactivity is attributed to physical recovery after placing large components, some inactivity is attributed to the crew leaders' need to consult the production documents, and some remain unexplained. Proper attribution of inactivity may require more intrusive data collection methods such as mid-activity interview, or post-activity survey to characterize these unexplained periods of inactivity. These more intrusive methods were not employed in this study in order to capture work processes in the least self-conscious state.

In light of the preengineered wall panels examined within this report, the influence of material packing, labeling, delivery, and on-site staging need to be studied in detail to further increase the fidelity and ability to evaluate alternative approaches using the virtual prototype.

4

Findings and Conclusion

Summary

In Phase IV of "Industrializing the Residential Construction Site," production simulation focused on the simulation of the framing processes used by builders in the study to

- understand field operations and the information needed by field installers,
- model the variances in productivity between installer crews to better understand the causes and effects of errors and uncertainties in field operations and consider the role of process design in reducing these errors, and
- represent current field processes and be used to compare alternatives processes.

The final objective of the study was to evaluate the applicability and adaptability of graphical and numerical simulators for designing and evaluating new industrialized production processes for residential construction.

Overall, the simulation of the panel placing process showed that errors added just under two hours to the framing time for each unit. Considered by itself, two hours is financially insignificant and cannot cost-justify the investment a builder would need to make in data collection and simulation. It is conceivable that the consequences of errors occurring during the construction of the structural frame and thermal/moisture-controlling building enclosure are not isolated but affect the performance of subsequent building trades and indeed the long-term performance of the house itself.

If the two-hour differential were typical for each subcontract, then it is possible that the incidence of error adds just under one week to the construction of a house (17 subcontractors x 2 hours = 34 hours), not including the time to compensate for and resolve the apparent error. If the average billable rate for a tradesperson were $29/hour, this cost is still under $1000 per home, or just under $1.5 billion per year nationally.

But if the cost or error is not limited to the tradesperson's time and also includes the loss of performance and associated payouts by FEMA or court settlements such as the industry is currently experiencing in mold/mildew cases associated with building enclosure errors, the cost of error grows exponentially.

Simulation promises to be a tool the home building industry could employ to understand where the most costly errors occur and test alternative products and processes designed to reduce/eliminate the error.

Simulation may also become the most promising tool to evaluate "what-if" scenarios for staging materials, positioning equipment, and balancing production capacity across the subcontracts.

The challenges to broad implementation of simulation to residential construction include the following:

- lack of knowledge of the magnitude of losses from error and inefficiency in residential construction,
- the absence of an industry advocate for simulation,
- lack of statistically valid work process data sets,
- the high initial cost of simulation models, and
- the inconsistency of training and dependence on tradition by the work force.

The field processes of three builders who used on-site assembly/erection of premanufactured wall panels were studied. Simulation models were developed based on field observations and data collection. Production processes for roof element assemblies were studied, and a simulation model of the component manufacturing plant was developed for the fourth builder, who employs off-site modular construction techniques. All simulation models developed were capable of capturing process information at some level of detail and aided the researchers in understanding the effects of production bottlenecks, errors in design, errors in execution, and construction system design.

In Chapter 3 a detailed numerical simulation of the panel erection process was developed using a simple discrete event simulator. This effort showed how an abstract modeling system could be used to represent a construction process and collect statistics on process behavior. This type of model is useful if detailed physical behavior is not an important factor in the modeling process.

A much more detailed 3D virtual model of the same construction process was also developed at two levels of detail. A macro model showing the panel paths and an overall erection strategy was developed. This type of model is useful in understanding the process, including material/assembly path planning, stacking priority of panels, and overall assembly details. Detailed description of the virtual model construction was reported, and the complex nature of model tasks was explained.

A 3D virtual micro model of a single panel-setting process was also developed to demonstrate how the virtual workers interact with the panels at a specific level of model detail. This type of virtual prototype is useful when the detailed work task, tool usage, and ergonomic analysis of the tasks are of interest. This level of specificity is particularly appropriate when developing a new industrialized construction system where worker interaction and capacity are important. The level of modeling effort required for this type of model is an order of magnitude greater than that required for the macro model described earlier. The macro and micro simulation methodology mentioned above is a simple but intensive approach to virtually dissect the complex processes which influence and result from the activity of construction.

This study demonstrates the capacity of simulation models to accurately represent observations of current field processes. The simulation models can be used to refine existing processes or develop new processes. Virtual prototyping is particularly applicable to developing new processes and has the potential to provide a mechanism for integrating field knowledge into the design process. It can also be used to determine information needs of field personnel.

Recommendations on Data Collection, Level of Model Detail

Chapter 3 demonstrated several methods of simulation analysis from the relatively abstract discrete event simulation modeling to the detailed virtual prototyping of micro sequences that enable ergonomic analysis of assembly processes. It is important to realize that, while these simulations are extremely useful in designing, analyzing, and improving industrialized operations, there are limitations inherent in the data collected and its use in the simulation. If the user intends to use the simulation to analyze field operations, the field data collection needs to proceed at a level of detail similar to that of the analysis being performed. Video data collection is appropriate in this case. In other cases of macro simulation, video recording is probably not justified. It is also important that a significant data sample be assembled if reasonable conclusions are to be drawn.

Evaluation of Simulators for Use in Modelling and Evaluating Industrialized Residential Construction Processes

These simulator systems have wider applicability in the design and development of new industrialized building systems. The next stage of this work will look at virtual prototyping of construction systems. The aim is to develop virtual prototyping capacity that allows designers to design for assembly and proof those designs in a virtual environment before beginning fabrication and field assembly. These tools should result in substantial improvements in the following:

- quality and integration of the design and production processes,
- quality of construction,
- speed of construction,
- integration of systems in the design, and
- overall performance and value of the housing product.

Virtual prototyping will enable designers and construction managers to have a better understanding of the information requirements and system interactions that subcontractors encounter during the construction of the house. The systems should enable designers to provide information to subsystem designers and installers in a more usable and concise form that simplifies the overall construction process. Many of the questions that were raised during the field studies in this report in relation to panelization will be resolved during the design phase instead of being solved in an ad hoc manner during construction. This approach is applicable to all subsystems in the construction of the house.

To be effective, a simulation needs clear goals. In this project a physics-based simulator was used to evaluate physical interference during panel installation, and a Petri Net simulator was used to consider alternatives to the micro decision processes of a crew unbundling and installing wall panels. While a complete simulation of all micro and macro processes involved in residential construction is possible, the following would be required to assemble a Petri Net simulation and extract meaningful results:

- information maps of the complete process, macro and all micro processes;
- decision maps of the complete process, macro and all micro processes;
- error maps of the complete process;
- error-resolution processes;
- resource inventory;
- transaction inventory;
- work duration at each transaction stage;
- error-resolution duration at each transaction stage; and
- data on frequency, magnitude, and propagation of error at each transaction stage.

A complete 3D physics-based simulation of construction processes would further require:

- 3D geometry for materials, tools, components, and work spaces;
- physics and chemistry data for materials, tools, components and construction processes.

Future Research

Use of virtual prototyping in design and planning should help to reduce or eliminate the errors in both design and production found during field studies of the production process. The next stage of this work should include the following:

- Develop a data-driven simulation model of a construction management sequence for a production house. The model could be used to make changes and improvements to the construction process using Design for Assembly (DFA) principles. The model should then be used to develop strategies and mechanisms to prevent or recover from error.
- Develop an accurate virtual assembly prototype to begin to suggest descriptive and predictive analyses that could benefit design and production performance.
- Conduct specific ergonomic analysis using existing capabilities of ENVISION to suggest crew performance optimization at both the macro and micro activity levels.
- Conduct component path optimization related to macro and micro activity levels using ENVISION's 3D real-time interference checking and part volume sweeps.
- Develop a construction-specific interface and tool set for graphical simulators to simply and speed simulation development and use by the residential construction industry.
- Investigate the cultural, managerial, and technical complexities of the residential construction process to map work process planning, decision paths, and error remediation paths.
- Develop robust field methodologies for capturing accurate on-site work sequence time lines. This effort would include more specific methodological definitions of an activity's start and stop points as well as refining capture methods for accurate on-site position information of components as they move along placement paths.

- Develop material characteristics libraries, such as product weights or their ergonomic handling procedures, to support simulation of ergonomic stresses on component installation crews and material handling–related damage.
- Test the virtual prototype and simulation to evaluate “what-if” scenarios for material packing, labeling, delivery, and on-site staging.
- Conduct field trials of “what-if” scenarios and detailed studies of results to further increase the fidelity and ability to evaluate alternative approaches using the virtual prototype.

Simulation and virtual prototyping are proven methods for improving quality, productivity, and reducing new product development costs. Product manufacturers have made extensive use of simulation and virtual prototyping to insure correct functioning of production plants and to support zero-defect quality goals in the products made. As the residential construction industry continues its trend towards consolidation, fewer contractors are producing more of the homes built each year. With adequate support, production simulation will become an enabling technology for continued industrialization of the residential construction site, helping builders to reduce errors, improve profitability, and safety and extracting more value and performance for the American homeowner.

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Appendix B. Panel Process Times

Builder Two Panelization Data: Three Crew Members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
104	3	Carry and Deliver	1:25
	3	Adjust & Affix	2:20
	3	Nail top to top and side to side	3:50
	3	Brace	4:20
104T	3	Carry and Deliver	1:20
	3	Adjust & Affix	3:10
	3	Nail top to top and side to side	5:00
	3	Brace	NA
104 Firewall Panel	3	Affix Fire Strip	1:46
	3	Carry and Deliver	2:01
	3	Adjust & Affix	2:30
	3	Nail top to top and side to side	3:30
	3	Brace	4:50
105	3	Carry and Deliver	1:00
	3	Adjust & Affix	NA
	3	Nail top to top and side to side	NA
	3	Brace	NA
106	3	Carry and Deliver	2:35
	3	Adjust & Affix	3:57
	3	Nail top to top and side to side	5:22
	3	Brace	6:00
107	3	Carry and Deliver	0:50
	3	Adjust & Affix	1:35
	3	Nail top to top and side to side	NA
	3	Brace	2:15
110	3	Carry and Deliver	0:50
	3	Adjust & Affix	6:00 (problems)
	3	Nail top to top and side to side	8:45 - > 20:00 (problems)
	3	Brace	6:50 – 8:45 (problems)

Appendix B. Panel Process Times (Continued)

Builder Two Panelization Data: Three Crew Members (continued)

Panel Number	Crew Members	Activity	Cumulative Time (min.)
111	3	Carry and delivery	1:50
	3	Adjust & Affix	3:50
	3	Nail top to top and side to side	4:50
	3	Brace	6:17

Builder Two Panelization Data: Two crew members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
104T	2	Carry and delivery	1:20
	2	Adjust	5:00
	2	Nail top to top and side to side	NA
	2	Brace	5:30
106	2	Carry and deliver	1:21
	2	Adjust & Affix	4:40
	2	Nail top to top and side to side	4:40
	2	Brace	NA
114T	2	Carry and deliver	1:13
	2	Adjust & Affix	3:00
	2	Nail top to top and side to side	6:38
	2	Brace	9:00
115T	2	Carry and deliver	0:50
	2	Adjust & Affix	NA
	2	Nail top to top and side to side	3:51
	2	Brace	7:05
116T	2	Carry and deliver	2:15
	2	Adjust & Affix	4:09
	2	Nail top to top and side to side	4:09
	2	Brace	NA
119	2	Carry and deliver	1:40
	2	Adjust & Affix	NA
	2	Nail top to top and side to side	5:02
	2	Brace	No Brace

Appendix B. Panel Process Times (Continued)

Builder Two Panelization Data: Three Crew Members

Panel Member	Crew Members	Activity	Cumulative Time (min.)
7	3	Carry and deliver	1:06
	2	Hold panel in place	3:32
	3	Lift & set panel	4:34
	3	Anchor bolt stud interference	5:40
	3	Redril anchor bolt holes	6:58
	3	Lift & set panel	7:18
	3	Anchor panel into position	8:13
	2	Affix to side of other panel	8:30
19	2	Measurement of anchor bolts	2:00
	2	Carry and deliver	3:00
	2	Anchor & nail	6:00
20T	3	Carry and deliver	0:15
	3	Adjust & affix	1:34
	3	Anchor & nail	2:30
21	1	Drill anchor bolt holes	0:36
	3	Carry and deliver	1:00
	3	Sit on pile	5:00 (anchor bolt problems)
	3	Anchor & nail	7:00
22	2	Measure, scribe & drill on pallet	1:00
	2	Carry and deliver	NA
	2	Stand & set	1:30
	2	Anchor & nail	3:15
24	2	Carry and deliver	0:40
	2	Stand & set	NA
	2	Anchor & nail	3:30
26	3	Carry and deliver	0:15
	3	Stand & set	1:20
	3	Adjust & affix	3:00
	3	Anchor & nail	3:20

Appendix B. Panel Process Times (Continued)

Builder Two Panelization Data: Three Crew Members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
27	3	Carry and deliver	1:00
	3	Stand & set	NA
	3	Anchor & nail	1:55
28	2	Stage	0:20
29	2	Anchor measurement & drill on pallet	10:00
	2	Carry and deliver	NA
	2	Stand / set	11:00
	2	Anchor / nail	16:00
30	2	Carry and deliver	0:30
	2	Stand & set	NA
	2	Anchor & nail	1:50
31	2	Stage	0:12
33	3	Cut off anchor bolts	6:00
	3	Carry and deliver	NA
	3	Stand & set	7:00
	3	Anchor & nail	10:30
34	2	Carry and deliver	0:20
	2	Cut and refit panel	10:50 (problems)
	2	Stand & set	11:30
	2	Anchor & nail	12:50
36	3	Carry and deliver	0:30
	3	Stand & set	2:45
	3	Anchor & nail	4:25

Appendix B. Panel Process Times (Continued)

Builder Three Panelization Data: Two Crew Members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
NA	2	Drill anchor bolt holes	0:32
	2	Carry and deliver panel to slab location	1:30
	2	Hold in place	2:10
	2	Lift & set panel on slab foundation	3:30
	2	Verify panel fit	4:30
	2	Nail top to top and side to side	5:01
	2	Anchor panel into position	7:27
NA	2	Read panel drawing and locate panel	NA
	2	Carry and deliver panel to slab location	NA
	2	Measure, drill holes and attach sill seal	2:14
	2	Lift & set panel	3:46
	2	Nail top to top and side to side & brace	6:07
NA	2	Read panel drawing and locate panel	NA
	2	Carry and deliver panel to slab location	NA
	2	Measure, drill holes and attach sill seal	2:41
	2	Lift & set panel	5:19
	2	Nail top to top and side to side / brace	7:40
NA	2	Read panel drawing and locate panel	NA
	2	Carry and deliver panel to slab location	NA
	2	Measure, drill holes and attach sill seal	2:36
	2	Lift & set panel	3:41
	2	Nail top to top and side to side & brace	6:02

Appendix B. Panel Process Times (Continued)

Builder Three Panelization Data: Two Crew Members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
NA	2	Read panel drawing and locate panel	NA
	2	Carry and deliver panel to slab location	NA
	2	Measure, drill holes and attach sill seal	2:38
	2	Lift & set panel	5:51
	2	Nail top to top and side to side	8:12
NA	2	Read panel drawing and locate panel	NA
	2	Carry and deliver panel to slab location	NA
	2	Measure, drill holes and attach sill seal	1:00
	2	Lift & set panel	3:12
	2	Nail top to top and side to side	4:53
NA	2	Read panel drawing and locate panel	NA
	2	Carry and deliver panel to slab location	NA
	2	Measure, drill holes and attach sill seal	4:37
	2	Lift & set panel	6:33
	2	Nail top to top and side to side	8:54

Appendix B. Panel Process Times (Continued)

Builder Five Panelization Data: Three Crew Members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
2	2	Carry and deliver	1:12
	2	Orient	1:26
	3	Measure & scribe	2:30
	2	Drill anchor bolt holes	Not recorded
	2	Anchor bolt stud interference	Not recorded
	2	Cut anchor bolts	5:15
	2	Redrill anchor bolt holes	6:10
	2	Install sill seal gasket	6:40
	2	Lift & set panel	7:40
	2	Anchor panel into position	8:40
	2	Affix to panel # 21	10:19
4	2	Carry and deliver	1:25
	2	Measure & scribe	2:14
	2	Drill anchor holes	2:54
	2	Install sill seal gasket	4:00
	2	Lift & set panel	4:27
	2	Anchor panel into position	5:10
10	3	Carry and deliver	0:40
	3	Measure & scribe	2:00
	2	Drill anchor bolt holes	3:00
	2	Install sill seal gasket	3:25
	2	Lift & set panel	3:40
	2	Anchor panel into position	5:10
	2	Brace panel	7:00
13	2	Sort	0:14
13	3	Carry and deliver	1:15
	3	Measure & scribe	3:00
	3	Drill anchor bolt holes	4:05
	3	Install sill seal gasket	4:30
	3	Cut anchor bolts (2)	5:10
	3	Lift & set panel	6:25
	3	Anchor panel into position	7:15
	3	Affix panel to # 41	8:00

Appendix B. Panel Process Times (Continued)

Builder Five Panelization Data: Three Crew Members

Panel Number	Crew Members	Activity	Cumulative Time (min.)
14	1	Carry and delivery	0:35
	1	Measure & scribe	1:10
	2	Drill anchor bolt holes	1:45
	2	Install sill seal gasket	2:15
	2	Lift & set panel	3:00
	2	Anchor panel into position	3:30
	2	Brace panel	5:00
15	3	Carry and delivery	0:50
	3	Measure & scribe	2:50
	3	Drill anchor bolt holes	Not recorded
	3	Install sill seal gasket	3:35
	3	Lift & set panel	4:15
	3	Anchor panel into position	4:45
	3	Affix panel to # 16	5:35
	3	Brace panel	7:00
20	3	Carry and delivery	1:50
	3	Measure & scribe	3:30
	3	Cut anchor bolts (2)	4:50
	2	Drill anchor bolt holes	7:20
	2	Install sill seal gasket	8:14
	2	Lift & set panel	8:50
	2	Anchor panel into position	9:55
	2	Affix panel	11:00

Appendix C. Builder Questionnaires

Questions for Builder Two

- Can we see the entire panelization process from panel layout through panel installation, window installation, and flooring?
  Reply: Yes, but the process is usually spread out over several days.
- Can we photograph or videotape the panel layout process for simulation purposes?
  Reply: Yes.
- Are the panels laid out the same day as panel installation or the night before?
  Reply: There is no layout. Panels are carried and delivered as needed.
- Are the panels laid out at the foundation?
  Reply: The panels are stored at the stack site and delivered to the construction site by sky-jack. Crew members then carry the panels to the slab site.
- Do panelization workers work within a specialized time frame?
  Reply: The work is contracted out, and contractors usually work from Monday through Saturday.
- Does a panelization plan exist?
  Reply: Yes, a panelization plan is handed to the crew leader.
- Is the number of workers always the same that move and/or set the panels?
  Reply: The number of people per crew changes. It is determined by the panel crew foreman.
- How many crew members carry the larger, sheathed panels?
  Reply: Usually three, sometimes four.
- How many panels are usually braced together?
  Reply: Panels are not braced together. They are tied at the top and exterior panels may be braced.
- Does the builder have information on installation time, performance, materials, equipment and man-hours?
  Reply: Not normally. The work is all contracted out.
- If panels are arranged in serial order, how much time (on average) does it take between the installation of one panel and the next?
  Reply: Panels are arranged in semiorderly fashion. Only the small panels are usually stacked out of order, but this is for transportation safety. The time element depends on the number of crew members participating in the carry and delivery of the panel and the distance from panel stack to panel slab mark.
- If all panels were to come in serial order, how much time will it take to complete the panelization process?
  Reply: For a five-unit townhouse complex, the panelization process takes about 10 days.
- How much time does it take to sort out panels in serial order?
  Reply: A couple of minutes, at the most. Most panels are stacked in semiorder, so it does not take long to find the next panel.
- How far away from the actual construction site are the panels stacked.
  Reply: The panels are stacked about 100 yards from the actual construction site and are delivered to the construction site by sky-jack.
- Has the builder had any problems with panel alignment and rough-in?
  Reply: Yes, both can be problematic.
- Does the interface between panels and rough-in work?
  Reply: Not asked.
- Does the builder have specifications for panel heights and widths, frame-types, windows, and doors?
  Reply: The standard height of an exterior panel is 8 feet.
- What are the minimum and maximum panel sizes?
  Reply: The minimum size of an 8-foot-high panel is 1 foot in width and the maximum size is 20 feet.
- Does the builder, or its contractors, use any “rules of thumb” for panelization?
  Reply: Not really. All contractors and projects are different. There is a lot of variation between them.
- Are the panel plans and drawings that the contractor or subcontractor use always the same and similar to the ones given to us?
  Reply: Yes, we receive copies of the plans and drawings handed out to the contractor/subcontractor.
- What is the level of detail of the plans given to the crew?
  Reply: The plans are fairly detailed and give the panel number and panel dimension.
- Do all townhouse complexes consist of three units?
  Reply: There are five units in a townhouse complex.
- How much time does it take to break out a panel?
  Reply: Less than a minute.
- Are interior and exterior panels installed in the same fashion?
  Reply: Yes.
- Are garage panels different from other townhouse panels?
  Reply: No, the garage is part of the same townhouse complex.
- Are the panels staked or sorted in a certain order?
  Reply: The panels are in stacked in semiorderly fashion. Yet, they are primarily stacked for transportation and distribution, not for delivery.
- How is the firewall supported by the panels and how does the firewall affect the panel production procedure process?
  Reply: There is a 4- to 6-inch gap between the firewall and the wall panels. Braces attach to the wall panels and make sure that the wall panels stay in place and separate from the firewall.

Appendix C. Builder Questionnaires

Questions for Builder Three

- Can we see the entire panelization process from panel layout through panel installation, window installation, and flooring?
  Reply: Yes, but it is usually spread out over several days. Thus, you won't be able to see all of the activities during the same day.
- Can we photograph or videotape the panel layout process for modeling purposes?
  Reply: Yes, that will be OK.
- Are the panels laid out the same day as panel installation or the night before? Are they laid out on the foundation?
  Reply: Panels are not laid out. The panels are delivered from the manufacturer to a stacking site. Prior to installation, the panels are moved by sky-jack to the construction site. Crew members then move the panels to the installation location.
- Do panelization workers work within a prespecified time frame?
  Reply: No, the work is all contracted out. Generally speaking, the panelization crews work from Monday through Saturday.
- Does a panelization plan exist and are the number of workers always the same that move and/or set the panels? How many workers typically carry the larger panels?
  Reply: Yes, a panelization drawing exists and is consulted during the fieldwork by the crew leader. Typically, larger panels are hand carried by three crew members, sometimes four.
- How many panels are usually braced together and how does the flooring or the roofing system fit on the panels? Can we see details and can we see the details of truss assembly?
  Reply: Panels are not braced together. They are individually braced. There are, however, top plates that tie in several panels.
- Does the builder have information on installation time, performance, materials, equipment, and man-hours?
  Reply: Yes, the information is available, but all of the work is contracted out.
- If panels are arranged in serial order, how much time does it take between the installation of one panel and the next? How much time if the panels are arranged at random?
  Reply: Don't know; observe in the field.
- If all panels were to come in serial order, how much time will it take to complete the panelization process?
  Reply: Don't know; observe in the field.
- How far away from the actual construction site are the panels stacked?
  Reply: Depends on the site, but usually within 100 yards.
- Has the builder had any problems with panel alignment and rough-in.
  Reply: Yes, but they are usually solved in the field.
- Does the builder have specifications for panel heights and widths. What are minimum and maximum panel sizes?
  Reply: Yes, panels are typically 8 feet high and less than 20 feet in length. The longest panels belong to the garage.
- Does the contractor, or subcontractor, use any rules of thumb for panelization?
  Reply: Not asked.
- Does the builder order a certain panel package from the manufacturer, and are the panels stacked or sorted in a certain order?
  Reply: The panel manufacturer has a copy of the panel drawing plan. The panels are typically shipped for transport efficiency, not distribution.
- How much time does it take to break out a panel and lay out the floor of a unit?
  Reply: Don't know; observe in the field. Panels are typically not laid out.
- How is the firewall supported by the panels, and how does the firewall affect the panel production procedure process?
  Reply: Not asked.
- What documents are used for panel layout and production?
  Reply: Panel drawings.
- Are the plans and drawings used in the field the same as what was given to the research team?
  Reply: You have a copy of the contractor's plans or drawings.
- Are interior and exterior panels installed in the same fashion?
  Reply: Yes.
- Are garage panels different from house panels?
  Reply: Apart from being longer, they are the same.
- Do stairs come preassembled or are they assembled on site?
  Reply: They come preassembled and only need to be attached.

Appendix C. Builder Questionnaires

Questions for Builder Five

- Can we see the entire panelization process from panel layout through panel installation, window installation, and flooring?
  Reply: Yes, but usually accomplished over a time span of several days.
- Can we videotape and/or photograph the process of panel layout?
  Reply: Yes.
- Are the panels laid out the same day as installation or the night before and how are they laid out on the foundation?
  Reply: Panels are not laid out on the foundation. They are hand carried from the stacking site to the construction site when needed.
- Do panelization workers work within a prespecified time frame, and can we videotape the panelization process to obtain time estimates for modeling purposes?
  Reply: No prespecified time frame. The work is contracted out, and the contractor determines the number of resources and schedule to finish the job.
- Does a panelization plan exist, and are the number of workers that move and/or set the panels always the same?
  Reply: The workers work off a panelization drawing plan which provides the number and size of the panels as well as the location for installation. The number of workers is usually three but varies depending on the size of the panel.
- How many panels are usually braced together and how does the flooring or roofing system fit on the panels. Can we see connection details?
  Reply: Panels are not braced together. They are braced on the bottom and tied in on the top. Panel connections can be observed in the field.
- Does the builder have information on installation time, performance, materials, equipment, and man-hours. Are they willing to share this information with the research team?
  Reply: The builder has little if any specific information. All of the construction work is contracted out. Can ask the contractor.
- Has the builder had any problems with panel alignment or rough-in? Does interface between panels and plumbing work occur often?
  Reply: Problems with panel interference are known to occur. They are usually solved in the field.
- Does the builder have specifications for panel heights and widths, frame types, windows, and doors?
  Reply: The builder uses standard window and doors. The panel sizes range from 2 to 20 feet in length and 8 feet in height.
- Does the builder, or its contractors, use any “rules of thumb” for panelization?
  Reply: No rules of thumb for panelization are used. The contractor uses rules of thumb for the mechanical system.
- Are the plans and drawings that the contractors or subcontractors use always the same and are they the same as what is handed out to the research team?
  Reply: The research team can get a copy of the panelization plan drawing handed out to the contractor.
- Does the builder order a certain panel package for a certain model from the panel manufacturer and are the panels stacked or sorted in a certain order?
  Reply: Not asked.
- Who does the calculations for the HVAC system. Do contractors perform any calculations or make recommendations on equipment?
  Reply: Not asked.
- Can we see a model where they are installing an HVAC system?
  Reply: Yes, they are installing an HVAC system in one of the models.
- What is the installation cost for the HVAC system used in Design #1 (minus man hours)?
  Reply: Proprietary information.
- What is the most popular style of house sold by the company (Design #1, Design #2, Design #3)?
  Reply: Not asked.
- What is the cost of Design #1 design without any options added?
  Reply: Proprietary information.

Glossary of Terms

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

CAD: computer-aided design

Computer Graphics: a standard file format for storage and communication of graphical information widely used on personal computers and accepted by desktop publishing and technical illustration systems

Computer Simulation: the process of designing an imitation of a physical system, executing the model on a computer, and analyzing the output

Concurrent Engineering: team approach to the design and development of products and related processes that shorten lead times, reduce costs, and increase product quality

Cut Sheet: piece of paper displaying the items measured and containing every saw cut requirement for each piece of lumber and what piece of lumber to cut it from

Digital Mock-Up (DMU): computer-generated model of a real product that can be altered at will and contains all product information in a 3D virtual prototype for study or testing

Enterprise Resource Planning (ERP): information management tool commonly used in manufacturing systems to handle integrated sales, marketing, finance, manufacturing, and human resources

Extensible Markup Language (XML): flexible way to create common information formats and share both the format and the data on the World Wide Web, intranet, and elsewhere

First In First Out (FIFO): approach to handling work requests from queues or stacks where items are taken out in the same order they were put in

Graphic Simulator: interactive graphic representation system that enables testing and analysis of a target physical structure in a virtual environment

High-Volume Builder: contracting firm building more than 1,000 homes per year and using on-site construction methods with a regional or national presence

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

Hypertext Modeling Language (HTML): set of markup symbols or codes inserted in a file intended for display on a World Wide Web browser page

International Alliance for Interoperability (IAI): industry-based consortium with a mission to enable the sharing and exchange of information between project stakeholders during a project's life cycle

Industry Foundation Classes (IFC): data representation standard used to assemble a project model in a neutral computer language

Glossary of Terms (continued)

International Standards Organization (ISO): 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

Knowledge Management (KM): discipline that provides strategy, process, and technology to share and leverage information to more effectively solve problems and make decisions

Last In First Out (LIFO): approach in which the most recent request is handled next and the oldest request does not get handled until it is the only remaining request on the queue or in the stack

Last In Last Out (LILO): a method of storage, similar to FIFO, where items stored last will also be retrieved last

Medium-Volume Builder: contracting firm building up to several hundred homes per year in regional markets

Manufacturing Resource Planning (MRPII): information system used to plan and control all manufacturing resources, including inventory, capacity, cash, personnel, facilities and capital equipment

Numeric Simulator: virtual replica of a physical system that uses arithmetic and differential equations to analyze and test the target system architecture

Oriented Strand Board (OSB): performance-based structural use panel made of strands, flakes or wafers sliced from small-diameter, round wood logs and bonded with exterior-type binder under heat and pressure

Panelization: the process of making wall sections or walls in a factory in stead of out at the construction site

Partnership for Advancing Technology in Housing (PATH): public-private initiative dedicated to accelerating the development and use of technologies that radically improve the quality, durability, energy efficiency, environmental performance, and affordability of America's housing

Portable Document Format (PDF): file format that has captured all the elements of a printed document as an electronic image that you can view, navigate, print, or forward to someone else

Physical Mock-Up: full-scale model of a product or system with instruments for testing the behavior of a real or targeted product

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

Random In Random Out (RIRO): approach in which items are both entered and retrieved from stacks in a nonorderly fashion

Simulation: mathematical model of a physical process that can be used to analyze the behavior of a system or object

Small-Volume Builder: contracting firm building fewer than 20 homes per year

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

Glossary of Terms (continued)

Virtual NC: interactive 3D simulation tool specifically designed for visualizing and analyzing the functionality of a machine tool, its CNC controller, and material removal process

Virtual Prototyping: 3D software model with behavior properties that looks the same as and mimics the behavior of the physical target or real system

Virtual Reality (VR): the use of computer technology to create the effect of an interactive 3D world in which the objects have a sense of spatial presence

Virtual Reality Modeling Language (VRML): a computer language for describing 3D image sequences and possible user interactions to go with them

Virtual Test Bed (VTB): a problem solving environment for full 3D simulation of a system's behavior or a product's performance