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PRODUCTION AND MATERIAL FLOW PROCESS
MODEL FOR MANUFACTURED HOUSING

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OMAR SENGHORE

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M G [signature]
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# PRODUCTION AND MATERIAL FLOW PROCESS MODEL FOR MANUFACTURED HOUSING

BY

OMAR SENGHORE

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# ABSTRACT

## PRODUCTION AND MATERIAL FLOW PROCESS MODEL FOR MANUFACTURED HOUSING

By

Omar Senghore

The manufactured housing industry has been lagging behind in its technological innovations compared to site-built housing according to PATH (Partnership for Advancement of Technology in Housing. This report is a contribution to the improvement of the production process of manufactured housing. A detailed description of the production process and industry terminology was made in Chapter three to help readers not familiar with the industry. The research showed how the production process of manufactured housing plants can be improved and resource utilization streamlined. First, a process flow diagram of all the major activities in each station is developed with the help of ANSI flowcharting concepts. An extensive data collection phase followed the process mapping stage. A detailed production process and material flow model was then developed. This model was then transformed into a computer simulation model using basic modeling techniques developed by Halpin (1992). Combis, Queues, and Normals, were used to input the model into a simulation software called EZSTROBE. The simulation software showed bottlenecks in the production process based on the time data inputted. The bottlenecks were used together with other generic what if scenarios to show how the process can be improved.

## ACKNOWLEDGMENTS

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# CHAPTER ONE

# INTRODUCTION

## 1.1 OVERVIEW

The United States Census Bureau has estimated that Housing and Urban Development code manufactured homes represented 22.7 percent of all new single-family housing starts in 1998 (MHI Quick facts 1999-2000). The HUD code manufactured housing has been evolving since 1976 and goes even further back in the early part of the $20^{th}$ century when they were called trailers. These "trailers" were only 8ft wide and designed to be very mobile. They were mostly used in campgrounds but slowly changed into mobile homes, which were less easily transported. Mobile homes served veterans returning from World War II and their families very well, in the midst of the housing shortages of that period, because of their mass production. The homes continued to evolve, growing from 8ft to 12ft to 14ft. In the mid 1970's, doublewide manufactured homes were introduced, followed by multi-section homes in 1985. Today, it is a thriving industry with growing increases in sales, production and size. "Over 19 million people across the country have decided to make a manufactured home their way of life" (MMHA 2000). The trends, as summarized in Table 1.1 clearly show that manufactured housing has become a viable option to homebuyers in America.

Table1.1 - Manufactured Home Shipments

(Source: MHI Quick Facts 1999 – 2000)

| Year | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 |
|---|---|---|---|---|---|---|---|
| Total | 210,787 | 254,276 | 303,932 | 339,601 | 363,411 | 353,377 | 372,843 |
| Single-Section | 112,117 | 134,440 | 156,171 | 173,785 | 173,674 | 148,809 | 144,328 |
| Multi-section | 98,670 | 119,836 | 147,761 | 165,816 | 189,737 | 204,568 | 228,515 |
| % Of Single-Family Starts | 17 | 18 | 20 | 24 | 24 | 24 | 23 |
| Estimated Retail Sales (Billions) | $5.99 | $7.76 | $10.18 | $12.33 | $13.96 | $14.52 | $16.33 |

## 1.2 NEED STATEMENT

According to the Partnership for Advancement of Technology in Housing (PATH), manufactured housing industry has been lagging behind compared to technological innovation of the site-built housing industry (PATH-HUD, 1999). A typical manufactured housing plant is unable to meet the desired production rate and capacity due to the lack of a streamlined assembly process and the efficient flow and utilization of material in the production process. Despite the growing market in this industry, manufactured housing industry has not been able to emerge as a technologically advanced industry. A typical manufactured housing plant fails to produce at desired capacity and production rate because of several shortcomings in the production process. Such shortcomings include (1) the lack of extensive repetition in the manufactured housing production process. Each housing unit going through the assembly process is unique in itself. (2) The difference between site-built and factory-built housing hinders application of production process innovations in site-built housing research to manufactured housing. In order to develop an effective and efficient system for production and material utilization, it is important to identify the deficiencies in the current production processes used by the manufactured housing industry (Syal and Hastak 2000).

According to 1995 census bureau data on housing affordability, 42% of all married couples could not afford a median priced home in their community and well over half of them (54%) could not afford a new single-family home.

Table 1.2 – Affordability Status of Families by Type of Housing
(Source: Census 2000)

| Using Conventional, Fixed Rate, 30-Year Financing | Cannot Afford Criterion home in U.S. | | | |
|---|---|---|---|---|
| | Total | | Married-couple | |
| Type of Home | Number | Percent | Number | Percent |
| Median Price Home | 38,075 | 52.2 | 23,110 | 42.2 |
| Modestly Priced Home | 32,396 | 44.4 | 18,739 | 34.2 |
| Low-Priced Home | 29,002 | 39.8 | 16,479 | 30.1 |
| New Single-Family Home | 45,916 | 63 | 29,729 | 54.3 |
| Condominium | 37,713 | 51.7 | 22,829 | 41.7 |
| Price Adjusted Home | 37,534 | 51.5 | 22,686 | 41.4 |

Manufactured housing can offer a potential solution to the affordability problem. The link between production, cost, and affordability is that if manufactured housing production can be improved, and done at a lower cost, this makes it affordable to most people who otherwise cannot afford a home of their own. Furthermore, the affordability of manufactured housing will contribute to the overall housing affordability problem in the U.S. This is a major undertaking because manufactured housing as stated earlier, constitute around a quarter of all housing starts in the U.S.

## 1.3 RESEARCH SCOPE

The scope of the proposed research is on how to develop a production process and material flow model for manufactured housing with focus on multi-section homes. The production process of two manufactured housing plants will be studied extensively. The process will be documented in the form of a production process model. Part of this model will be transformed into a simulation model. Using time data that will be collected during the study, the simulation will be run and resource utilization investigated. "The process modeling of the assembly process along with the material inventory, storage, in-plant delivery, and utilization process; promises the possibility of improving the production efficiency, cost effectiveness, and quality" (Syal and Hastak 2000). Before explaining the goals and objectives of this research, it is important to note that the research for this thesis is part of a research project sponsored by the National Science Foundation. The research is a joint effort between Michigan State University (MSU) and The University of Cincinnati (UC). The team from MSU is headed by Dr. Matt Syal and two of his research assistants; Namita Mehrotra and Omar Senghore. The team from UC is headed by Dr. Mark Hastak and three of his research assistants; Ayman Abu Hammad, Vamshi, and Qingbin Cui.

## 1.4 GOALS AND OBJECTIVES

The overall goal of this research is to show how the production process of manufactured housing can be improved and material utilization streamlined. The objectives of the research are:

1. To develop a production process flow diagram for multi-section manufactured housing production.
2. To develop a production and material flow process model for manufactured housing.

3. To select a section of the production line consisting of 3-4 stations and transform the process model into a computer simulation model. The computer simulation model will help in answering a number of what if questions to determine how the process can be improved.

## 1.5 METHODOLOGY

The proposed research steps consists of:

### 1.5.1 Developing a Production Flow for Manufactured Housing

Figure 1.1 below is a typical process flow for a manufactured housing assembly layout developed by the research team. To finalize a generic production flow model as such, with a little more detail, a process mapping activity will be engaged in. This process will entail visiting the factory for a whole day and spend the time studying the factory. While at the factory, certain things as activity relationship, location of materials, amount of materials stored in the factory, equipment used, number of labor per activity, and feeder station relationship to main station, among other things will be observed. This will be the beginning of the development of the production flow diagrams.

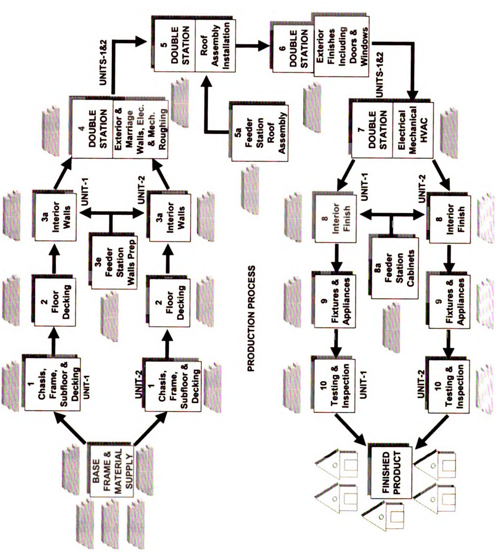



Figure 1.1 - Manufactured Housing Production Process
(Source: Research Team)

### 1.5.2 Perform Time Studies for Each Production/Assembly Step

The time studies will be performed to measure the duration of production work at various workstations. This will help in identifying bottlenecks and resource utilization at each station. The format to gather time data as detailed in Table 4.2 was developed by the research team. Crew size, composition, and material and equipment usage will also be gathered during this step. Each activity in the workstation will be measured together with the required labor force and material. The time data will be used during the simulation stage to depict the functioning of the production process. While doing the time studies, both the absolute cycle time and total cycle time for each station will be recorded. Absolute cycle time is the time when work is actually being done on the unit while at a station. Total cycle time is the time the unit spends on a station. This could also be translated into effective time and idle time. These two cycle times will help to determine the type of delays that occur at each station.

### 1.5.3 Development of Detailed Individual and Integrated Process Model for Production and Material Flow.

Two sets of data will be collected from two different factories in the Northern Indiana area. This area is considered the manufactured housing capital of the world. Two companies with plant layouts similar to the one shown in Figure 1.1 will be selected for study. This is to ensure the uniformity of the data collected from the time studies. To develop the material flow model, a materials list for the housing modules is needed. This list will be used to determine how material is used on each workstation and the frequency of material usage on each workstation. With that data in hand, the material flow will be developed together with the detailed production process flow model and with the help of observations made during the time studies and data collection. The process model will eventually be used to show constraints in the assembly line when it is transformed into a simulation model.

The development of the process model will be based on process mapping concepts explained in Chapter four. These concepts are also compatible with the process modeling concepts, which will be used to transformation the process model of 3 to 4 stations into a computer simulation model.

#### 1.5.3.1 Process Modeling Concepts

"Construction operations contain the basic work processes in construction. Their definition requires knowledge of the construction technology involved, a breakdown of the processes into elemental work tasks, the identification of the required resources, and definition of the work assignment to the labor force involved" (Halpin and Riggs 1992).

BASIC MODELING ELEMENTS

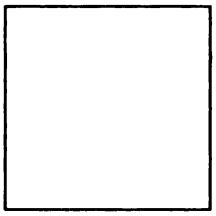
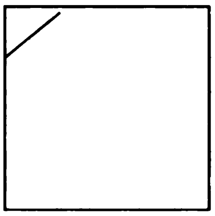
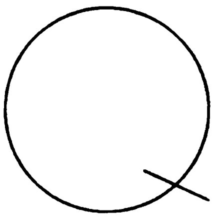
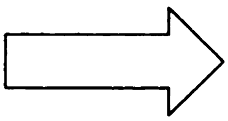
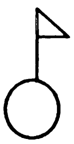
| Modeling Element | Name of Element | Description of element |
|---|---|---|
|  | NORMAL | The Normal work task modeling element, which is unconstrained in its starting logic and indicates active processing of or by resource entities. |
|  | COMBI | The constrained work task modeling element, which is logically constrained in its starting logic, otherwise similar to the normal work task modeling element. |
|  | Q NODE | The idle state of a resource symbolically Representing a queuing up or waiting for use of passive state or resources. |
|  | ARROW | The resource entity directional flow modeling element. |
|  | COUNTER | A node which keeps track of the number of times a unit passes it. |

Figure 1.2 Basic Modeling Elements
(Source: Halpin and Riggs, 1992)

#### 1.5.3.2 The Modeling Procedure

"The first step in model formulation is the identification of the flow units that are relevant to or descriptive of the operation or process to be modeled. Normally the units selected are physical items such as production units or resources such as materials, money, and space. The more obvious types of flow units that are of interest in construction are (1) machines, (2) labor, (3) materials, (4) space or location, and (5) informational or logical permits (inspection releases)" (Halpin et al. 1992).

The flow units that Halpin and Riggs (1992), are discussing could include constituent activities within each station. Constituent activities are actual work tasks performed on the house within the station. To illustrate, the roofing station may consists of certain constituents activities as roof setting, roof decking, and roof shingles. These constituent activities and flow units are the building blocks of the process model. Figure 1.3 below shows a schematic relationship of constituent activities on a roofing station.

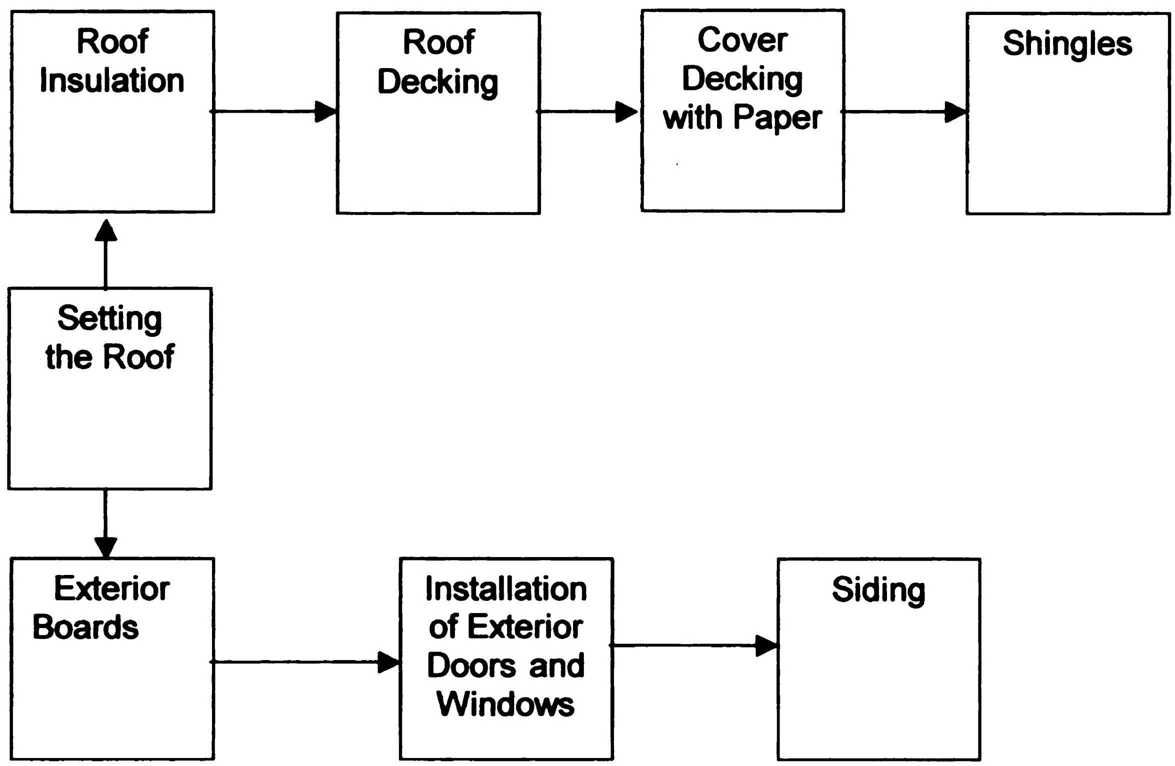



Figure 1.3 – Schematic Relationship of Constituent Activities on a Roofing Station.

After all the flow units / constituent activities are identified, their relationship with each other is mapped out. The mapping of the constituent activities on each station represents the production process flow diagram. Material flow units will be used to model the material flow.

### 1.5.4 Transformation of Process and Material Flow Model into a Computer Simulation Model

In this research, simulation is used to imitate production processes happening in the factory and to help in making decisions among alternatives. It is expected that this will help identify bottlenecks in the system and understand how to better utilize resources and materials. If such constraints are identified, then the process can be manipulated to answer a number of "what if" questions. The object of developing the model of a production system is to examine the interaction between flow units, determine the idleness of productive resources, locate bottlenecks, and estimate production of the system as constituted (Halpin and Riggs, 1992). To illustrate how the integrated process model is going to be transformed into a simulation model, let us follow an example of a hauling operation (Sawhney and AbouRizk, 1993). This example follows the process modeling concepts presented in the previous section. Figure 1.4 gives a schematic representation of the hauling operation.

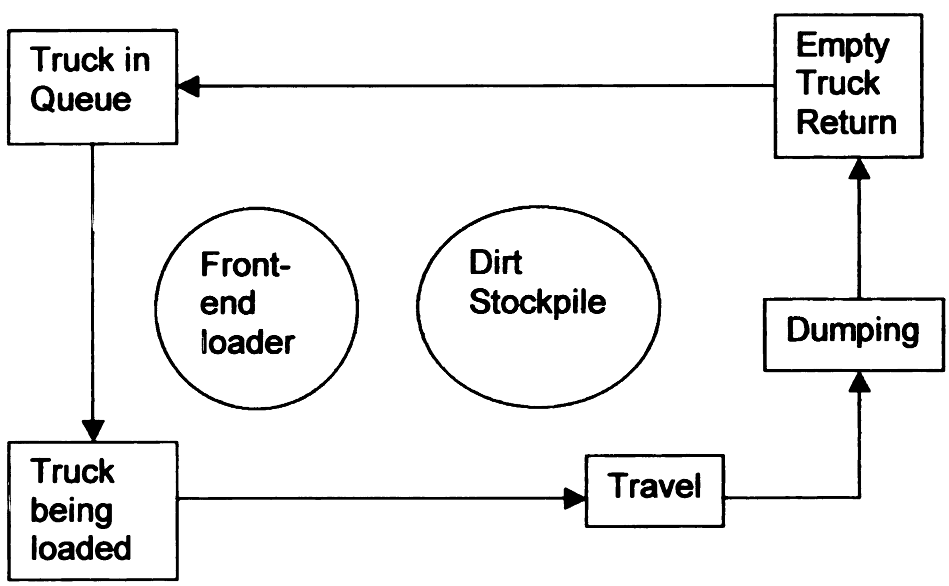
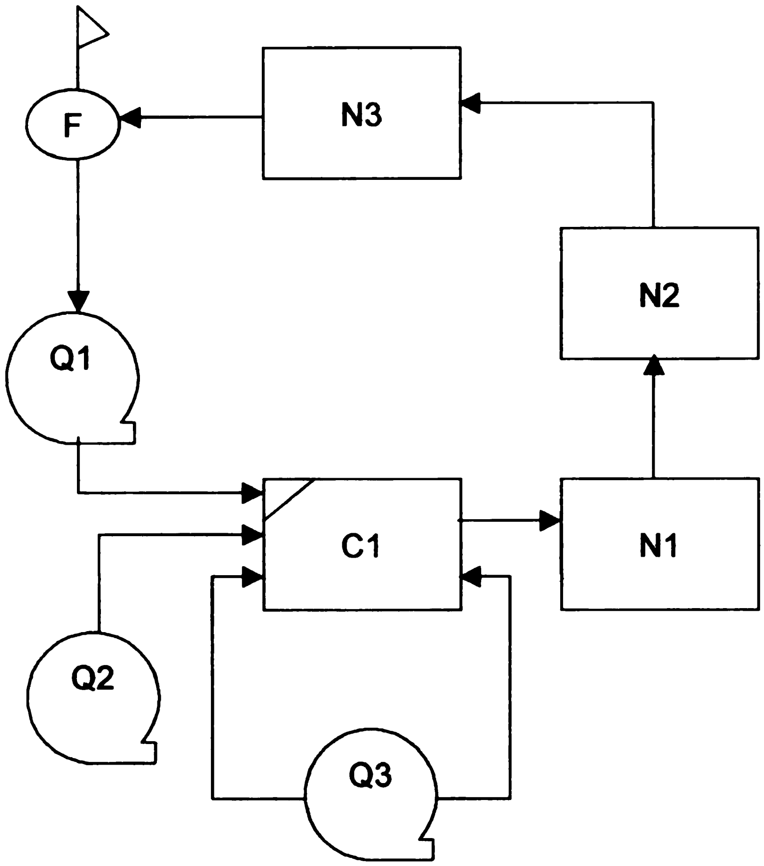



Figure 1.4 – Schematic Representation of Hauling Operation
(Source: Sawhney and AbouRizk, 1993)

Using the basic modeling concepts and elements as shown in Figure 1.2, the above operation can be converted into a simulation model. The simulation model for this operation is shown in Figure 1.5. "In Figure 1.5, a COMBI node is used to model the loading operation of the truck. The truck can be loaded only when all the required resources are available. The resources that are required for this operation are an empty truck modeled as queue 1, a front-end loader as queue 3 and a dirt stockpile as queue 2. The loading operation can only proceed when one unit is available at Q1, Q2, and Q3. Once the loading operation is complete, the trucks can start the travel activity, which is modeled as a normal code. Similarly, the other two work tasks namely dumping and travel of empty trucks are also modeled as a normal node. In addition to these nodes, there is a function node that is provided to determine the number of truck cycles completed and to stop the experiment based on the number of cycles" (Sawhney and AbouRizk, 1993). The above simulation will be carried out using STROBOSCOPE simulation software.




Q1 – Empty Trucks in Queue  Q2 – Dirt StockPile  Q3 – Front-end loader idle

N1 – Truck Travel  N2 – Dumping  N3 – Empty trucks return

C1 – Truck Loading  F1 – Function Counter

Figure 1.5 – Simulation Model
(Source: Sawhney and AbouRizk, 1993)

## 1.6 EXPECTED OUTCOME

### 1.6.1 Streamline Production Process

The main outcome of this research could be that it can provide guidelines for the efficient use of the production plant. This can result in savings on material and labor if the material flow process can be optimized. Timesaving and hence, higher production would result in improvement in the production process. It is expected that bottlenecks in the system will be found, especially labor and material bottlenecks. These bottlenecks are expected to be the major barriers to the system not being streamlined. Correcting these bottlenecks will lead into a streamline production process.

### 1.6.2 Technological Improvement

A streamline manufactured housing process delivering at low cost and highly efficient can offer a potential solution to the affordability problem in housing. For many consumers, manufactured housing has had a negative stigma for producing low quality housing. This research can produce a technologically sophisticated plant to produce better quality housing at reduced cost. This will lead to more acceptance of the industry in general by the public. It could be a way of showing the public that manufactured housing is a viable option to affordable housing.

### 1.6.3 Computer Simulation Software for Plant Layout

The simulation part of this research can help in the future development of an ideal manufacturing plant layout. The simulation concepts could be tailored specifically to the plant layout process. This could require inputs such as materials used, equipment used, desired shape of plant, and type of housing produced. The software can be interactive and allow the user to try many different options to suits her needs before producing their ideal plant.

## 1.7 REPORT ORGANIZATION

This thesis report contains six chapters. Chapter one, the introductory Chapter, presents an overview of the history of manufactured housing, need for this research, scope of research, goals and objectives of the research, methodology, and expected outcome. Chapter two contains literature review of related work in areas of manufactured housing, construction simulation, and production planning. In addition, some industry terminology is defined to help the reader understand the rest of the thesis. Chapter three gives a detailed description of the manufactured housing production process and presents a comparison of manufactured housing and site built housing in the areas of code, production environment, foundations, and cost. Chapter four contains background work on data collection and presents the concepts and procedures of developing the production process and material flow model. Chapter five is where the transformation of the process model to simulation model takes place and analysis of input data and results. Chapters six presents the summary of the report.

## 1.8 SUMMARY

This chapter presented the proposed research with overview of the history of the manufactured housing industry and future trends, the need for the research, scope of the research, goals and objectives, and research methodology. A description of expected outcomes followed as to what could be gain from this work by the industry in general. Finally, the organization of the rest of the chapters was presented.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter is organized into two categories. First, the industry terminology is presented. The manufactured housing industry is not as well known as the site-built housing and most people are not familiar with some of the terms used in the industry. The second category on this chapter is the summary of available research information in areas related to proposed research. This information is presented in three categories; manufactured housing, construction simulation, and production planning.

## 2.2 DEFINITIONS

For the reader who is not familiar with manufactured housing and manufactured housing terminology, it may be helpful to introduce basic definitions before writing any further. The Michigan Manufactured Housing Association introduced some of the following definitions to help potential customers to the industry, have a better understanding of the terms used in the industry (MMHA Fact Sheets, 2000).

### 2.2.1 Manufactured Home

A home built in a controlled, factory environment on a permanent chassis that is designed to be used with or without a permanent foundation when connected to the required utilities. Manufactured homes are built to the federal Manufactured Home Construction Safety Standards enforced by the Department of Housing and Urban Development (HUD) in Washington, D.C. Manufactured homes are single story and are delivered to the home site in one, two, or occasionally, three sections; they may be placed on private property or in a manufactured home community.

### 2.2.2 Modular Home

These are Factory-built homes that begin as components and are designed, engineered, and assembled in a controlled factory environment. These components come together at the building site and the home is completed by a licensed builder under standards enforced by state and local agencies. In Michigan, modular homes are regulated by the BOCA Code. Modular homes may be one-or-two-story dwellings and are placed only on private property.

### 2.2.3 Mobile Home

The federal government mandated the term "manufactured housing" in 1976, making the term "mobile home" obsolete. All of the homes built after 1976 must comply with federal standards. These standards regulate the things such as durability, materials, systems, wind safety, fire safety and energy efficiency.

### 2.2.4 Panelized Home

Panelized homes are defined as homes where panels (flat units that represent a whole wall with windows, doors, wiring and outside siding) are constructed in the factory and then transported to the site and assembled. Panelized homes must meet the state or local building codes of where they are sited.

### 2.2.5 Pre-Cut Home

Pre-Cut homes are another type of factory-built housing. Materials for this type of home are factory-cut (pre-cut) to design specifications, transported to the site and then assembled. Pre-cut homes include kit, log and dome homes. These homes are built to meet either local or state building requirement codes.

### 2.2.6 Manufactured Home Communities

Private land developed as homes sites for manufactured homes. In Michigan, most sites are leased to the homeowner for a monthly fee. They are sometimes referred to as a land-lease community.

### 2.2.7 Single-Section Home

A manufactured home delivered to the home site in one intact section; the average square footage is 1,130 square feet.

### 2.2.8 Multi-Section Home

A manufactured home delivered to the home site in two or three sections. The average square footage is 1,640 square feet, but may be as large as 2,400 square feet. It may have a (site-built) garage attached after the home is installed.

### 2.2.9 Site-Built Housing

Housing constructed mostly at the home site.

### 2.2.10 Retailer

A retailer is a licensed, professional seller of manufactured homes. A retailer assists in arrangement for financing, and has home installed on home site and prepared for move-in.

### 2.2.11 Dealer

Any person engaged in the sale, leasing, or distribution of new manufactured homes primarily to persons who in good faith purchase or lease a manufactured home for purposes other that resale.

### 2.2.12 Distributor

Any person engaged in the sale and distribution of manufactured homes for resale.

### 2.2.13 Manufacturer

Any person engaged in manufacturing or assembling manufactured homes, including any person engaged in importing manufactured homes for resale.

### 2.2.14 Installer / Servicer

Any person including a mobile home dealer, who for compensation installs or repairs homes.

### 2.2.15 Consumer

Any person who purchases a manufactured home, mobile home, or commercial coach for her own use and who does not intend to resell it.

### 2.2.16 HUD Code

This is a code developed by the Department of Housing and Urban Development. A HUD code regulates the home's design and construction, strength and durability, transportation, fire resistance, energy efficiency, and quality control. It also sets stringent performance standards for the heating, plumbing, air-conditioning, and electrical systems. The HUD Code specifically preempts local building codes as they relate to construction codes for manufactured homes.

### 2.2.17 BOCA Code

Building Officials and Code Administrators International, Inc. It is the oldest of three "model" codes used in the United States. Site-built and modular homes fall under this code. It is used by states in the Midwestern and Eastern parts of the United States.

### 2.2.18 International Residential Code

Code provisions for one- and two-family dwellings which apply to the construction, alteration, movement, enlargement, replacement, repair, equipment, use and occupancy, location, removal and demolition of detached one- and two-family dwellings and multiple single family dwellings (townhouses) not more than three stories in height with a separate means of egress and their accessory structures (International Residential Code).

## 2.3 EXISTING RESEARCH

The literature review will be divided into three different subtopics. The first subtopic will deal with research that has been done in the manufactured housing industry. The second subtopic will cover research on simulation of construction processes. The third topic is about production planning. A single research was not found that dealt with production aspects of manufactured housing.

### 2.3.1 Manufactured Housing Industry Research

The manufactured housing industry has several research projects and literature, many of which argue that it is a viable option to provide affordable housing.

In 1993, the College of Architecture and Urban Planning at the University of Michigan, published a study in six reports addressing manufactured housing quality, manufactured housing costs and finance, manufactured housing values, manufactured housing impacts on adjacent property values, manufactured housing and the senior population, and manufactured housing as an alternative ownership and innovative uses (Warner and Johnson, 1993).

The first area the researchers tackled was the area of quality and how manufactured housing compares to site-built housing. "... The researchers concluded that manufactured housing has demonstrated reasonable performance in areas related to structural durability, maintenance, wind safety, fire safety and thermal efficiency" (Warner and Johnson, 1993). They also cautioned that there is room for improvement.

The second issue the team looked at is cost and finance. The research concluded that the cost is not only comparable to that of site-built houses, but that manufactured housing is the most affordable option available to most consumers.

The third focus was on housing values. The question they wanted to answer was, whether manufactured houses appreciate. "The researchers concluded that a sizable proportion of the manufactured homes sold between 1987 and 1990 in Michigan, most of which were located in rental communities, can be shown to have appreciated" (Warner and Johnson, 1993). Most site-built residential communities do not want to allow manufactured housing communities in their neighborhood for fear of loss of property values.

The University of Michigan's forth study was about the impact manufactured housing communities have on adjacent property values. "The researchers concluded that rental manufactured home communities, have not been shown to have a significant effect, positive or negative, on adjacent residential property values" (Warner and Johnson, 1993).

The fifth issue examined is how manufactured housing can meet the needs of senior citizens. The study found potential for the manufactured housing community within the senior population and this potential are being slowly realized but cautioned on the rising cost of rent.

Finally, the study closed with an overview of how to broaden consumers' residential choices. The study suggested that manufactured housing has promising use in areas of affordability and redevelopment.

A multidisciplinary faculty group from the construction management program and the department of human environment and design at Michigan State University, undertook a research project in 1995 to help "Harvest Foundation" expand the manufactured housing industry's position in Michigan's housing market. The Harvest Foundation is the educational outreach branch of the Michigan Manufactured Housing Association (MMHA). The project was divided into two phases. Phase one's goal was to do an assessment of the industry's current position with the help of key groups and their perception of the industry. Phase two was to develop a ten-year educational plan for the industry based on the findings from phase one. In the first phase, nine groups related to the industry were identified: manufacturers, retailers, community managers, installers, inspectors, site/modular builders, consumers, and local government officials. Geographically diverse focus groups were utilized to gather information for the project. Findings and recommendations from each focus group were then presented. Installers for example would like to see the state institute standard requirements for the installation and site preparation of manufactured homes. Overall key issues where then identified by the researchers and recommendations made. For example in the case of sales persons, the researchers found that since salespeople interact with the general public, their behavior affects customer perceptions positively or negatively about the industry. Therefore, sales people must be more knowledgeable about the product and the industry in order to present if correctly (Burkhardt et al, 1996).

Bayazit (1997) did an extensive and detailed comparison of the BOCA and HUD codes and analysis from planning considerations to transportation of the house from factory to the site. The HUD code was up to standard to the BOCA code in most aspects and even more stringent in other aspects although there were cases in which it was below standard to the BOCA code.

A doctoral dissertation by Nader Taghavi (1984), investigated the changing market of manufactured housing by seeking the opinions of salespersons and consumers in the industry. The study was also looking for ways to improve the market segment for manufactured housing in the future. Nader (1984) concluded that salespersons believe the quality of manufactured homes has improved since 1976, when the department of Housing and Urban Development were initially involved in the industry. He also concluded that advances have been made in easing zoning restrictions for manufactured housing. Nader's (1984) results also showed that younger people are less attracted to manufactured housing communities because they believe it does not provide privacy. He suggested that subdivisions and private lands would provide a better market for the industry and the possibility of new kinds of buyers.

Diane R. Suchman formerly of the Urban Land Institute (ULI) wrote a paper for the ULI in March 1995 on manufactured housing as an affordable alternative to housing problems. She identified cost savings among other things, as aspects that make manufactured housing attractive in different market segments. "The cost savings, design flexibility, and expanding financing opportunities possible with manufactured housing today makes this housing type attractive in many markets and for many specific uses" (Suchman, 1995). She also encouraged public officials to be more proactive in creating more affordable housing options using this industry by stating that "... by encouraging wise use of manufactured homes, public officials can help create more opportunities for affordable homeownership within their communities" (Suchman, 1995).

Finally, "Factory Constructed Housing Developments", is a book by William F. Albern (1997), which looks at the planning, design, and construction of housing developments and housing units in the factory.

### 2.3.2 Construction Simulation Research

Abourizk and Mather (2000) discussed an approach to simplify the process of building and manipulation of computer simulation models of heavy earthmoving construction operations. Their approach is based on integrating 3D CAD with simulation. "The simulation models are automatically generated from high-level descriptions in CAD by using add-on tools to capture key information" (Abourizk and Mather, 2000). Information to be captured includes product information, resources used, construction methods, and general product data. Using a case study, they developed a prototype earthmoving simulation system by extracting the information they need form 3D CAD. Their conclusions were that the simulation system used was too general and the integration was not very efficient. They suggest improvements by developing a simulation system based on hierarchy.

Tommelein, Carr, and Odeh (1994), presented a way of modeling construction processes, using designs, plans and construction methods. "An object-oriented and interactive computer system is presented that realistically models construction processes by matching resource properties with design component properties and operation durations" (Tommelein et al, 1994). The modeling procedure was done by creating a discrete-event simulation model using CIPROS, which includes a seven consecutive step knowledge-based representation and simulation primitives. The seven steps are:

1. Define project design and specifications
2. Create activity-level plan and relate activities to the design components
3. Choose construction method for each activity in the plan
4. Initialize product components
5. Identify construction resources
6. Custom-tailor simulation network
7. Simulate and interpret results

Their conclusions were that "CIPROS can realistically model construction processes by integrating data from design drawings and specifications, and construction plans, in combination with a library of construction methods" (Tommelein et al, 1994).

Sawhney and AbouRizk (1993) gave a very easy to understand overview of construction simulation and its applications. In their paper, they gave a brief history of construction simulation, described the tools that have been developed over the years and their application, and outline the procedure for doing construction simulation. The paper had a target audience of students in the early stages of learning construction simulation. It discussed the CYCLONE software; its early and recent developments, other software like INSIGHT, RESQUE, COOPS, MicroCYCLONE, SLAMSYSTEM, SIMSCRIPT, GPSS, and SLAM II. The authors closed by arguing for construction simulation as a great tool in the areas of construction planning and control and analysis of construction operations.

### 2.3.3 Production Planning Research

Effective production planning can give a company a strategic advantage over its competitors in a very competitive market. A production process that can be simulated to help in the allocation of company resources is a vital tool in the production planning, project controls or procurement stages of the process. Production planning is a very important part of any production process.

Warszawski's (1996) paper, presents a methodological procedure for strategic planning in a construction company. The procedure consists of five stages. Stage number one examines the company's mission. "The mission of a company, as defined here, involves the scope of its business activities, objectives, and special codes of behavior" (Warszawski, 1996). The second stage is for the company to analyze its main resources. Warszawski divided main resources into construction, marketing and procurement resources. Construction resources for example must have the capability to support the physical construction of a project from start to finish. 'Construction, as viewed here, refers to the capability of a company to perform a variety of direct activities for the physical realization of construction projects, i.e., construction planning, coordination, monitoring, directing, and control" (Warszawski, 1996). The third stage is the development of a competitive strategy. "The development of a strategy is based on "mapping" of the relative attractiveness of the various possible activity areas" (Warszawski, 1996). The fourth and fifth stages consist of developing alternative strategies and selecting the preferred one.

Shaked and Warszawski (1995) discussed a knowledge-based system called HISCHED for construction planning of high-rise buildings. "The system uses an object-oriented representation of the building and production rules, routines, and functions to manipulate objects and to generate the construction plan" (Shaked and Warszawski, 1995). The paper first described the organization of the knowledge base.

> "*The knowledge about the system involves an object-oriented representation of the building and production rules, routines, and functions for the manipulation of object attributes and generation of the construction plan. The representation of the building includes three types of objects: (1) Zones, which define the topology and nature of the building; (2) functional systems, which define the components of the building and their construction technology; and (3) works, which define the construction activity*" (Shaked and Warszawski, 1995).

The paper then went on to explain how project construction activities are generated and the determination of the dependencies between them. Generation of the tasks can be either interactive with the user or done automatically and it consists of four stages:

> *(1)Zoning – user defines all the floors of the building, their sequence, area and designation, and assigns the repetitive floors into multimodules. (2) Identification of functional systems – Functional system for each zone can be selected by the user, or can be automatically defined by HISCHED on the basis of the designation of the zone (for such typical designations as office floor, lobby, mechanical floor, and others). (3) Definition of Works – Each functional system is defined in HISCHED by works necessary for its completion (their nature and quantity). (4) Generation of Tasks – Tasks are generated by the assignment of works to zones.* (Shaked and Warszawski, 1995).

The next part of the paper is to show how different managerial objectives affect planning considerations. Finally the paper closed with an example of the HISCHED application. The authors concluded by stating that " the system can be farther extended to consider additional managerial strategies to integrate graphical representation of the building and to reason about selection of works in view of different economic and non economic considerations" (Shaked and Warszawski, 1995).

In 1999, Andrew Seidel submitted a masters thesis to the construction management program at Michigan State University in which he developed a production planning methodology for large homebuilding firms. "The methodology includes planning systems; estimating, scheduling, cost and progress control, financial and accounting, subcontracting, and material acquisition" (Seidel, 1999). After developing the methodology, Seidel (1999) did an industry analysis to evaluate the applicability and essentiality of the methodology. He concludes that the production planning methodology provides a detailed sequential process for production planning system development for large homebuilding firms.

Robertson and Ulrich (1998) argued that a good product planning platform was necessary to gain and keep market share. In their paper, they define what a platform is as it relates to production planning, benefits and challenges of platform planning, presented a method for planning a new platform of products, and provide recommendations for managing the platform planning process. They define platform as the collection of assets a set of products share such as the manufacturing processes, design knowledge, parts and components, and the manufacturers (Robertson and Ulrich, 1998). Benefits to platform planning include reduced development cost, time, and lower investment required for new products. The authors advocated the development of a product plan, differentiation plan, and commonality plan as a structured platform planning process. Product plan included the specification of distinct market offerings over time. Differentiation plan encompasses specifying each product's differentiating attribute. Finally, commonality plan describes the extent to which the products share physical elements. Recommendation for managing platform planning process include getting top management involved since the products developed from the process may determine what the company introduces to the market for five to ten years. One person should be in charge of each of the plans (product, differentiation, and commonality) and a different person overseeing the whole process.

## 2.4 SUMMARY

This chapter presented the reader with important terminology needed to have a basic understanding of the manufactured housing industry and research that has been done in three different areas pertaining to the thesis topic were also discussed.

More acceptance of manufactured homes into the mainstream housing industry is required since it can provide affordability for low income families as argued by Suchman (1995). The study performed at the University of Michigan in 1993 demonstrated that manufactured housing is of good quality when compared to site-built housing at comparable prices. The study showed manufactured housing appreciates in value in contrast to the conventional wisdom, which says manufactured housing depreciates. The study performed at Michigan State University in partnership with the Harvest Foundation of MMHA, gave insightful recommendations to help the industry advance in the state of Michigan coupled with an analysis of the state of the manufactured housing industry in the state of Michigan.

Three papers on construction simulation research were discussed. The paper by AbouRizk and Mather (2000) attempted to simplify the process of building simulation models. Their approach was to automatically generate simulation models from 3D CAD drawings by integrating them. Although there demonstration was not successful, the approach showed some promising signs. The second paper was very similar in a way since it also wanted to develop a new way of developing simulation models except in this case, the authors were proposing using designs plans and construction methods. For anyone being introduced into the field of construction simulation, Sawhney and AbouRizk (1993) gave a through introduction to the subject

Numerous research has been performed both in the field of construction and manufacturing. Warszawski (1996) presented a five-stage procedure for strategic planning in construction companies. A major part of his analysis of company resources stage deals with construction resources. Warszawski and Shaked (1995) looked at a knowledge-based approach to construction planning utilizing a system called HISCHED. A production planning methodology for large homebuilding firms developed by Seidel (1999) as part of a masters thesis was discussed. Finally, in the area of production planning in general, Robertson and Ulrich's (1998) paper on platform planning, discusses how consolidating product, design, development, and manufacturing can help lower risk and reduce time and cost.

# CHAPTER THREE

# MANUFACTURED HOUSING PRODUCTION PROCESS

## 3.1 INTRODUCTION

The construction process of manufactured housing is both similar and different to that of site-built housing in various ways. Some of the similarities they share are in materials used and differences occur in areas such as the environment in which the house is built. This chapter explains the process of building a HUD code manufactured home using the practices of two companies in illustrations. An attempt is also made to compare and contrast the process with that of a site-built home in areas of codes, production environment, and foundations. Finally, a cost comparison is presented.

## 3.2 PRODUCTION PROCESS

The names of the two companies utilized in the research process will not be mentioned for competitive reasons. Their practices will be illustrated in this Chapter and the entire report, but it does not mean that the way they do things is a complete representation of the industry's practices. The description will be made as generic as possible. The activities and stations in Figure 1.1, represents the typical manufactured plant as the title implies. It will be used to walk through the description of the process.

A manufactured housing plant can generally be divided into five areas. These are floors, walls, roof, exterior, and finishes. On Figure 1.1, floors consist of stations 1 and 2, walls consist of stations 3 and 4, roofing is station 5, Exteriors is station 6 and 7, and finishes consist of stations 8, 9, and 10. A plant can have up to 16 stations depending on the complexity of the homes they build, the number of activities in various stations or the size of the plant.

### 3.2.1 Floors

Manufactured houses are built on a steel base frame called a chassis. The process starts with the floor frame constructed on top of the chassis. The floor joists are put in place with the right spacing and according to plan. After the floor frame is finished, all the mechanical work that needs to go underneath the house is installed at this point. Mainly HVAC and water lines are installed during this stage. The floor is then properly insulated. All the above activities take place in station 1. Figure 3.1 shows a floor being built with insulation and floor joists already installed.

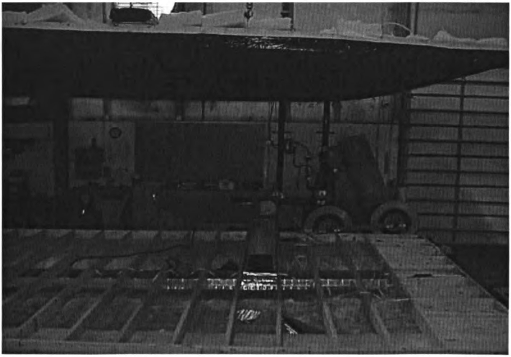


Figure 3.1 – Floor System Being Built

Then it is moved to station two for floor decking. The movement of the units itself can take place in many different forms depending on the plant. One method observed in one of the plants is the use of inflatable base plates that make it possible to move the house with only four or five workers. On station 2, the floor joists, attached to the chassis with mechanical lines running through it and insulated, is covered by adding decking. Up to this point, the house is separated in two units as shown in Figure 1.1. All the activities described above are performed on both units in parallel. Next, the process moves on to the wall stations.

### 3.2.2 Walls

The walls are generally built at a feeder station and then hoisted in place using an overhead crane that run on tracks attached to the ceiling of the plant building. Figure 3.2 shows a picture of a wall being built at a feeder station.

Figure 3.2 – Wall Feeder Station

Although it is not shown on the diagram in Figure 1.1, certain activities from feeder stations have to be performed before the walls are in place. These activities are installation of kitchen cabinets, some bathroom fixtures such as tubs, and installation of water heater and furnace. The items are installed because of the ease without the walls in place, and then the partition/interior walls are placed. After the partition walls are placed, the house moves to station four for the marriage and exterior walls. All the walls are completely built with insulation at the feeder stations. At station four rough electrical and mechanical works are performed.

### 3.2.3 Roofing

Roof assembly usually takes more than one station. First, the feeder stations for roof stations will be described. Fabrication of the individual roof trusses is generally contracted out to independent contractors. They are then stored in the plant and used as needed just like any other material to assemble the whole roof and ceiling structure.

First, the sheets of gypsum ceiling boards are laid on a flat surface, and then the individual trusses are placed at the correct spacing. From there, the trusses are nailed together with 2 X 4's between them. A special type of glue is sprayed to the trusses at its point of contact with the ceiling board to hold them to each other. Insulation is placed on the down side of the roof slope and then it is ready to be moved to the adjacent feeder station for paint to be sprayed on the ceiling. Before the paint is sprayed, the joint between the boards are covered with tape and mud for a smooth connection. After the paint is applied, the roof is ready to be hoisted up for connection to the house. This process just described happens in a feeder station. When the whole roof and ceiling structure is ready, it is sent to the main line for assembly. Figure 4.3 shows very good pictures of a roof structure at various stages of its assemble process. The picture on the left shows the trusses being placed on the gypsum board at the correct spacing. The picture on the right shows a completed roof still at the feeder station with insulation being sprayed on top. The bottom picture illustrates the installation of shingles after the roof has been secured on top the house.

Figure 3.3 – Shingles Installation

The first activity that takes place when the roof is moved to the line is it has to be set on top of the house in which it belongs to. The structure is properly secured to the two units, which have been joined together at this point. The two units will be separated again when it gets to station 9 as shown in Figure 1.1. In fact, the main reason why the two units are attached at this point is to make sure the roof structure properly fits on the house. The activity that follows is roof insulation. This activity is accomplished by having one worker standing on top of the house and using a powered hose to spray the insulation between the trusses and on top of the ceiling. This activity can also happen when the roof structure is still at the feeder station. After insulation is sufficiently packed on top of the structure, the roof has to be covered with decking. This activity usually takes a crew of three workers about ten to fifteen minutes to finish one unit. It consists of laying down sheets of plywood on the roof and nailing them to the trusses. The lower edge of the roof is then covered with paper for proper drainage measures before the shingles are placed. Placement of shingles is shown in the bottom picture of Figure 3.3.

### 3.2.4 Exteriors

Figure 1.1 shows stations five and six running in sequence but essentially, these two stations can run in parallel. As work is progressing with the roof on top, workers are simultaneously installing doors and windows, exterior boards, siding, and so on.

Exteriors and exterior finishes start after the walls are installed. The first activity is the exterior walls have to be covered with boards. Doors and window openings are then carefully cut out. Then the jams are installed before installing the exterior doors and windows. The last activity is siding. Figure 3.4 shows the crew installing exteriors and windows after the exterior boards have been placed. These activities can be done while the units are either attached or separate.

Figure 3.4 – Installation of Exterior Doors and Windows

### 3.2.5 Finishing

Electrical, mechanical, and HVAC work are the main activities in station 7. Certain appliances such as the fireplace are installed at this station. The breaker box is also installed at this stage. A significant amount of testing and inspection is also performed at this stage. Some of them include, gas test, plumbing tests, check for proper receptacle spacing, check for interior switches and their installation to manufactures specifications and so on.

At station 8, the extent of the interior finishes depends on whether the house needs painting or whether it is going to have wallpaper. First, the axles and the wheels are installed for transportation. Installation of axles and tires can happen on station one depending on how the houses are moved at a particular plant. Assuming the house has wallpaper instead of painting, interior finishing can go into full gear at station 9. Window curtains are installed; appliances such as dishwasher, toilets, washing machine, and dryer are fitted into place. In addition, any repair work that needs to be done also takes place at this station. If the house needs paint, then a whole day is spent on drywall finish. This is not because of the activity taking too long, but they have to wait overnight for the walls to dry up.

## 3.3 COMPARISION OF MANUFACTURED VS SITE BUILT HOUSING

Manufactured and Site-built housing have their similarities and differences. One major difference is the absences of a regular foundation in the manufactured houses. This section compares and contrasts the differences between manufactured housing and site-built housing in the areas of codes, environments in which they are built, foundations, and cost.

### 3.3.1 Code Comparison

The manufactured housing industry uses the HUD (US Department of Housing and Urban Development) code, which was developed by the housing and urban development branch of the United States government. The code was developed in 1976 mainly to raise the standards of the manufactured housing industry and increase safety. The housing industry professionals have been debating whether the HUD code is up to the same standards as that of the major site-built housing codes such as BOCA (Building Officials Conference of America), IRC (International Residential Code), and UBC (Uniform building code). Two studies will be cited that have been performed in the past to compare the HUD code and BOCA code. Another study by Mehrotra, Syal, and Senghore (2001) will be cited for comparison of the HUD code with the International Residential Code. The BOCA code is the most widely used residential building code in the United States. The first study on the BOCA and HUD codes comparison was done at the University of Michigan 's College of Architecture and Urban Planning and the second one is a Plan B paper written by Hasan Bayazit for a Master's degree at Michigan State University's department of construction management.

The Bayazit (1997) study, which is more detailed, looked at all the subparts (Planning considerations, fire safety, body and frame construction requirements, testing, thermal protection, plumbing systems, heating, cooling and fuel burning systems, electrical systems, transportation and systems) of the HUD code and compared them to the corresponding values on the BOCA code. Some of the standards were higher, some lower and some the same. For example, the planning considerations for HUD and BOCA codes were summarized as shown in Table 3.1.

| | | |
|---|---|---|
| **Ceiling Heights (Min)** | | |
| Habitable Rooms | 1.98 m | 2.13 m |
| Hallways | | |
| **Exit Facilities** | | |
| Egress Doors | 2 required | 1 required |
| Travel Distance | 10.6m | 22.8 m |
| Exit Door Size | 71.1cm by 188cm for swinging doors and 71.1 cm by 183 cm for sliding doors | 91.4 cm by 203 cm |
| Egress Window | Required in all bedrooms unless there is an exit door. 91.4 cm from the floor | Required in every bedroom unless there is an exit door. 111 cm from the floor with a net opening of 0.52 $m^2$. |
| **Interior Privacy and Toilet Compartment** | | |
| Privacy Lock | Required | Privacy Required |
| Minimum Size | 76.2 cm in width and 53.3 cm clearance in front of each toilet | 76.2 cm in width and 53.3 cm clearance in front of each toilet from the tub and the wall |

The minimum glazed and open able areas for light and ventilation are the same, the minimum room dimensions for living area are the same and that of one-person bedrooms are the same. There is little difference in the ceiling heights for habitable rooms and hallways among other things. Minimum travel distance to exit facilities is shorter in the HUD code, which shows the attention the code shows when it comes to fire safety. Similar comparisons of all the subparts are made and it consistently shows the HUD with similar standards to the BOCA code and even better in some cases.

The study performed at the University of Michigan was also very similar. The difference is, one table of summary was produced showing major subparts but not all. Thirty-two (32) elements were looked at. Of all the elements, sixty-three percent (63%) had the same requirements. Twenty-two percent (22%) of the elements looked at were more restrictive in the HUD code and thirteen (13%) of the elements were more restrictive in the BOCA code.

A paper on comparison of the HUD and the international building code is cited for Table 3.2.

Table 3.2 – Summary of Fire Safety Considerations for HUD and International Residential Code. (Source: Mehrotra and Syal, 2001)

| **FIRE SAFETY CONSIDERATIONS** | **HUD CODE/1994** | **INTERNATION RESIDENTIALCODE / 2000** |
|---|---|---|
| **Flame Spread Rating Requirement** Interior finishes of walls, columns, and partitions | Should not exceed 200. [HUD 3280.203] | Should not exceed 200. [IRC R319.1] |
| Ceiling interior finishes | Should not exceed 75. [HUD 3280.203] | Should not exceed 200. [IRC R319.1] |
| Walls adjacent or enclosing cooking range | Should not exceed 25. [HUD 3280.203] | Should not exceed 200. [IRC R319.1] |
| Kitchen cabinets, doors, countertops, backsplashes, exposed bottom and end panels, plastic bathtubs, and shower units | Should not exceed 200. [HUD 3280.203] | Should not exceed 200. [IRC R319.1] |

Table 3.2 – cont'd

| FIRE SAFETY CONSIDERATIONS | HUD CODE/1994 | IRC/2000 |
|---|---|---|
| **Carpeting** | Should not be used in Compartments for furnace and water heaters. [HUD 3280.205] | Not Specified |
| **Fire stopping** | At least 1" lumber or 5/16" thick gypsum board should be provided between concealed spaces to prevent spreading or fire. [HUD 3280.206] | At least 2" lumber or ½" thick gypsum board should be provided between concealed spaces to prevent spreading of fire. [IRC R602.8] |
| **Foam plastic thermal Insulating material** | | |
| Flame spread | Not exceeding 75. [HUD 3280.207] | Not exceeding 75 |
| Maximum smoke index | 450 [HUD 3280.207] | 450 [IRC R319.1] |
| **Fire detection equipment** | | |
| Smoke detectors/alarms Should be placed | One in each bedroom [HUD 3280.304] | One in each bedroom area, also outside, in its vicinity. [IRC R317.1] |

The flame spread rating requirements for interior finishes of walls, columns, and partitions are the same in both the HUD and IRC code. Kitchen cabinets, doors, countertops backsplashes, exposed bottom and end panels, plastic bathtub, and shower units, all have the same flame-spreading requirement of not more than 200 in both the HUD and IRC code. The flame spread rating requirement is more stringent in the HUD code when it comes to ceiling interior finishes and walls adjacent or enclosing cooking ranges. The ratings are 75 and 25 respectively compared to 200 for both in the IRC. Requirements for firestopping between concealed spaces are more stringent in the IRC code. The requirement for flame spread and smoke index are the same in both codes.

### 3.3.2 Production Environment

With the exception of the installation process on foundations, manufactured housing are strictly factory built houses. This means the houses are built in a controlled environment with no adverse effects from whether. That is one major advantage it has over site-built housing. A manufactured housing production schedule is usually not delayed because of weather if the workers can get to the factory. A second advantage it has over site-built housing is that, since it is in a very closed and controlled environment, supervision is very easy. This means, a highly skilled labor force is not necessary for production of the houses. Superintendents, foremen, and production managers can hire fairly skilled workers and still obtain desired production with close supervision.

### 3.3.3 Foundation

Foundations are also fundamentally different between site built and manufactured houses. Here are two definitions from the Manufactured Home Installer/servicer Course offered by the MMHA that can help the reader understand the process of installing a manufactured home foundation discussed below.

FOUNDATION FOOTING: Part of the support system located at or below ground level. Piers are placed on foundation footings, which are made from concrete or treated lumber.

PIER: The portion of the support system between the foundation footing and the manufactured home, exclusive of caps, plates and shims.

In a typical site built home with a basement, the footing is continuously dug around the whole perimeter of the house. Then basement/foundation walls are placed on the footing, and the house sets on the foundation walls. In a manufactured housing foundation, the footings are not continuous. Instead of one continuous footing, there are several small ones with an area of 144 square inches. The footings are placed on site and spaced based on dimensions and weight of home, the roof load zone, size and type of construction, of the footings. The figure below shows how the footings could be spaced based on the aforementioned criteria.

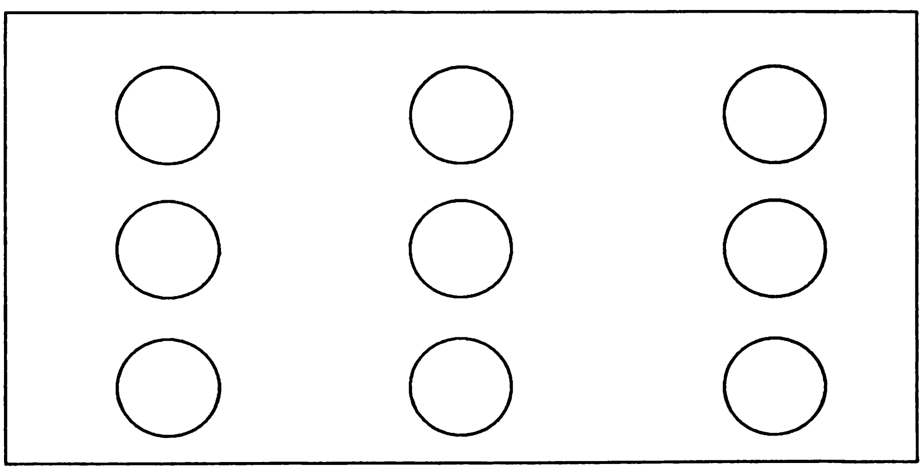


Figure 3.5 – Top View of Footing Spacing.

The footings, just like in site built houses, must be extended below the frost line or protected from frost effects. Piers are then placed on top of the footings, on which the beams under the house are placed. Below is a diagram of a single block pier sitting on a foundation footing.

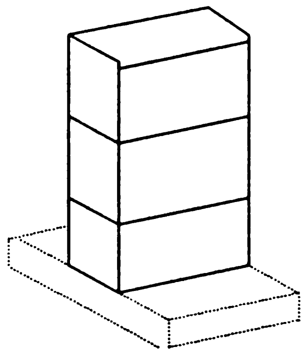


Figure 3.6 – Single Block Pier
(Source: MH Installer Course, 2000)

It is sometimes required to put piers around the perimeter of the house. Otherwise, it may lead to sagging floors, walls and roofs.

### 3.3.4 Cost Comparisons

In 1998, the U.S. Department of Housing and Urban Development published an extensive report titled "Factory and Site-Built Housing; A Comparison for the 21st Century". The comparisons include the regulatory process, code requirements, and cost. Table 3.3 shows the different contributors to the total cost that were analyzed such as construction costs, land costs, overhead/administration costs and financing costs. The original table included comparisons with modular housing but since this thesis is focusing on manufactured housing, it is vital that the scope of the cost comparisons is also focused.

Table 3.3 - Summary of Cost Comparisons
(Source: HUD Report on Cost - 1998)

| | Site-Built | Manufactured Homes | | | |
|---|---|---|---|---|---|
| Description: | Two-Story | Double-Section | Double-Section | Double-Section | Single-Section |
| Square Feet: | 1,990 | 1680 | 1680 | 1680 | 1215 |
| Foundation | | Blocks | Permanent | Permanent | Blocks |
| | Private | Private | Private | Land lease Community | |
| | | Individual Lot | Subdivision | | |
| **Construction Costs** | **$ 76,752.00** | **$ 36,150.00** | **$ 37,650.00** | **$ 37,650.00** | **$ 21,650.00** |
| Structure | $ 70,765.00 | $ 34,650.00 | $ 34,650.00 | $ 34,650.00 | $ 20,850.00 |
| Foundation | $ 5,987.00 | $ 1,500.00 | $ 3,000.00 | $ 3,000.00 | $ 800.00 |
| Cost per square ft | $ 38.57 | $ 21.52 | $ 22.41 | $ 22.41 | $ 17.82 |
| **Land Costs** | **$ 35,136.00** | **$ 34,425.00** | **$ 34,881.00** | **$ 1,167.00** | **$ 711.00** |
| Lot density | 4 per acre | 2 per acre | 4-6 per acre | 4-6 per acre | 6-8 per acre |
| Improved lot | $ 33,941.00 | $ 33,714.00 | $ 33,714.00 | | |
| Site preparation | $ 1,195.00 | $ 711.00 | $ 1,167.00 | $ 1,167.00 | $ 711.00 |
| Monthly land rent | | | | $ 250.00 | $ 200.00 |
| **Overhead/Admin** | **$ 29,232.00** | **$ 11,448.00** | **$ 20,179.00** | **$ 12,088.00** | **$ 7,035.00** |
| Overhead & Ge. exp | $ 8,325.00 | $ 1,908.00 | $ 3,363.00 | $ 2,015.00 | $ 1,172.00 |
| Marketing | $ 3,024.00 | $ 954.00 | $ 1,682.00 | $ 1,007.00 | $ 586.00 |
| Sales commission | $ 4,752.00 | $ 1,431.00 | $ 2,522.00 | $ 1,511.00 | $ 879.00 |
| Profit | $ 13,104.00 | $ 7,155.00 | $ 12,612.00 | $ 7,555.00 | $ 4,397.00 |
| **Financing Costs** | **$ 2,880.00** | **$ 477.00** | **$ 841.00** | **$ 504.00** | **$ 293.00** |
| Construction financing | $ 2,880.00 | | | | |
| Inventory financing | | $ 477.00 | $ 841.00 | $ 504.00 | $ 293.00 |
| **TOTAL SALES PRICE** | **$144,000.00** | **$ 82,500.00** | **$ 93,551.00** | **$ 51,409.00** | **$ 29,689.00** |

The table starts with a comparison of typical homes with different traits. Site-built homes are compared to manufactured homes.

CONSTRUCTION COST: The authors included labor and material for both the structure and foundations as part of construction cost. Included as part of the structural cost are additional construction of site finishes such as siding and roofing completion, interior finish of marriage walls and flooring, and site-built garages (HUD 1998).

LAND COST: Land cost consists of developed land costs, such as, cost of subdivision infrastructure (roads, sidewalks, and utilities) (HUD 1998).

OVERHEAD / ADMINISTRATION COST: These items, which also affect the cost of a home, include office space, office cost, administrative and management staff, and company vehicles. Overhead cost as a percentage of sale price is lower for manufactured housing (25%) than it is for site-built housing (22.3%) (HUD 1998).

FINANCING COST: The length of time it takes to build site-built homes is usually three months or more. On the other hand manufactured homes usually takes about five days to build after an order is received from a retailer. The financing cost of the inventory is minimal for the producer, and much of the cost of inventory is shifted to the retailer. This allows for cheaper financing cost for manufactured housing over site-built housing (HUD 1998).

All the four different categories of cost looked at, the report consistently shows manufactured housing as much cheaper compared to site built housing even if the manufactured house is on a permanent foundation, private lot, or located on a subdivision.

## 3.4 SUMMARY

This chapter dealt with two main themes. The first is the production process of manufactured housing. An effort was made to educate the reader who has never been in such a factory to have a basic understanding of how these houses come together. Pictures were used in the illustrations instead of diagrams to help the reader visualize the process. In case the reader is familiar with site built housing, a comparison was made with manufactured housing to present the similarities and differences and further help the reader understand the manufactured housing process. Cost comparisons were made to re-enforce the point made in the introductory chapter that manufactured housing is a viable option for affordable housing.

# CHAPTER FOUR

# PRODUCTION PROCESS AND MATERIAL FLOW MODELS

## 4.1 INTRODUCTION

This research project consisted of a great deal of legwork. The data collection process to the Northern Indiana area consisted of approximately five thousand miles of traveling including one trip to Cincinnati, Ohio. Data collection was conducted through plant visits with other research team members. This chapter deals with two focus areas. The first one is the data collection process and the second is the development of the production process and material flow model. In the data collection part, first, the less rigorous part of process mapping and how that was used to develop the process flow diagrams and eventually the production process and material flow model, is presented. Then, the data collection part (i.e) time data collection is discussed. Finally, the product of the data, which is the production process and material flow models, are presented.

## 4.2 DATA COLLECTION

The data collection part of the project was done in two phases for two factories in Northern Indiana. The first phase was a familiarization phase and the second was the actual data collection. Since time is the main data collected throughout the process, a portion of this chapter is dedicated to the concept of time study and what it means to this project, but first the author would like to discuss the concept of process mapping and how is was used in this project.

### 4.2.1 Process Mapping

Process mapping is a concept used in developing the process model. "The fundamental concepts of process mapping are based on the idea of structured analysis, which has produced significant payoffs in diverse business enterprise applications such as banking, insurance, manufacturing (auto and aerospace industries), pharmaceuticals, and service enterprises" (Hunt, p. 14, 1996). Another basic concept of process mapping as stated by Hunt (1996) is to:

> *"Understand a process or system by creating a "process map" that graphically shows things (objects or information) and activities (performed by men or machines). The process map is designed to properly relate both things and activities".*

The data collection process started with the process of familiarization with the factory floor from which data will be collected. This was the process-mapping phase. The factory floor is divided into stations and certain activities are performed in each station. First, all the stations were clearly identified. Each station is then visited and studied carefully. The purpose is to identify the activities taking place in each station and their relationship with one another. Feeder stations are also identified, the process that takes place in the feeder station, material used, and activities are all observed and recorded. To illustrate, after observing and mapping stations 13, 14, and 15 in one of the factories, a list of major activities was generated as follows:

- Setting the roof
- Roof Insulation
- Roof Decking
- Cover Decking with paper

- Shingles with paper
- Exterior boards
- Installation of Exterior Doors and Windows
- Siding

The activity relationship is as shown below in Figure 4.1. This activity relationship is simply in the form of a process flow diagram.

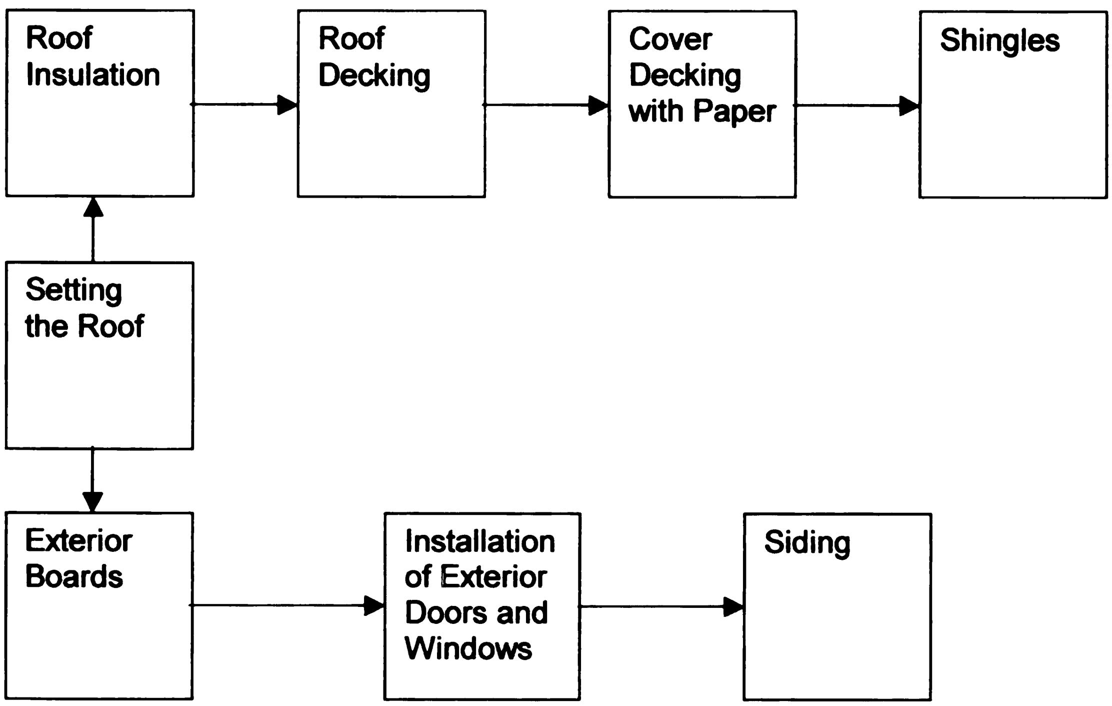



Figure 4.1 – Example Activity Relationship

Similar sketches were developed for all the stations throughout the factory and their activity relationships shown. Another product of the process-mapping phase is shown in Table 4.1 that lists the activities in each station, the crew size, and feeder names. If a feeder station accompanies a main station, then that station is also visited and mapped. With the process mapping data, the process flow diagrams can now be developed.

Table 4.1 – Process Mapping Data Sheet

| Station # | Activities | Crew Size | Feeder Name | Comment |
|---|---|---|---|---|
| 8 | Roof Setting | 3 | Roof Feeder | |
| 8 | Finish Ceiling Wiring | 1 | | Activities sometimes overlap into successive stations |
| 9 & 10 | Roof Decking | 3 | | |
| 11 | Cover Roof Deck w/ Paper | 3 | | |
| 12 | Install Shingles | 2 | Shingles Feeder | |
| 8 | Exterior Boards | 2 | | |
| 9 & 10 | Exterior Doors and Windows | 2 | | |
| 11 | Siding | 2 | Siding Feeder | |
| **Feeder Name** | **Activities** | **Crew Size** | **Main Station** | **Comment** |
| Roof Feeder | Trusses are assembled | | | |
| Shingles Feeder | Shingles package is unwrapped and Placed on moving bucket to installers | 2 | 12 | |
| Siding Feeder | Cut siding material to spectified lengths | 1 | 11 | |

### 4.2.2 Process Flow Diagrams

Process flow diagrams are also called simply, flowcharts. To fully explain what a flowchart is, let us begin with a simple analogy. A globe is a scaled representation of the earth. A flow chart is a representation of a process. The process can be a business process, a construction process, or any process that includes work tasks and activities. "Flowcharting is defined as a method of graphically describing an existing process or a proposed new process by using simple symbols, lines and words to display pictorially the activities and sequence in the process" (Harrington, p. 86, 1992). Let us consider a flowchart for the process of a simple earth moving operation. Figure 4.2, shows a simple flowchart of an excavation operation.

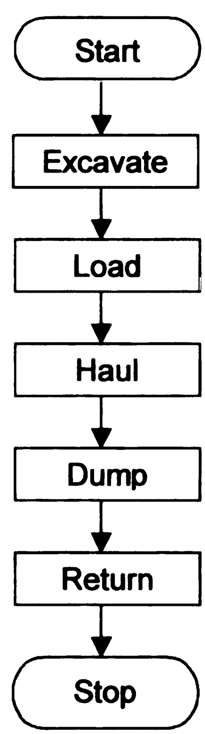



Figure 4.2 – Example Flowchart of Earthmoving Process

The process begins when the soil is first excavated and ends when the truck has returned to its original site for another load. This flow chart is typical of most flow charts in its ability to simplify a very complex operation. To be able to represent a complex process clearly is very big advantage of flow charts. Another advantage is the ease of identifying bottlenecks in the process by using flowcharts. It clearly shows how activities/work tasks are done, whether they are supposed to be done that way and help in determining how it could be done better. The author has encountered four different kinds of flow charts during the literature search phase of the project. These four different kinds of flowcharts are discussed below. Only the flowcharting techniques of the first two will be utilized in this project. Illustrations for functional and geographic flow charts can be very complex. Since they will not be used in this project, examples of them will not be shown only definitions will be provided.

BLOCK DIAGRAMS: "A block diagram, also known as a block flow diagram, is the simplest and most prevalent type of flowchart" (Harrington, 1991). Figure 4.2 above is classified as a block diagram.

ANSI STANDARD FLOWCHARTS: ANSI is an acronym for American National Standards Institute. ANSI flowchart is a more detailed form of a block diagram and deals with more detail interrelationships among activities. Figure 4.3 is a detail flowchart of the estimating process of a small homebuilding company. The estimating process mainly takes place in two different phases of a project. One is at the onset of a project when the front end needs to know the starting price for the house. The other time a thorough estimate is done, is during the project when prices and contractors change. An estimate is needed at this point to adjust the budget. A major difference between the first and second estimate is that in the second one, actual numbers supplied by the contractor is used to come up with the budget. Minor value engineering estimates are also done throughout a project. The two paths in Figure 4.3 represents the two different times estimates are performed. Only one of two paths is followed after the decision is made as to whether a new estimate is being performed or an update in being performed.

FUNCTIONAL FLOWCHART: "A functional flow chart pictures the movement between different work units, an additional dimension that is particularly valuable when total cycle time is a problem" (Harrington, 1991).

GEOGRAPHIC FLOW CHART: "A geographic or physical flowchart analyzes the physical flow of activities. It helps to minimize the time wasted while work output and/or resources are moved between activities" (Harrington, 1991).

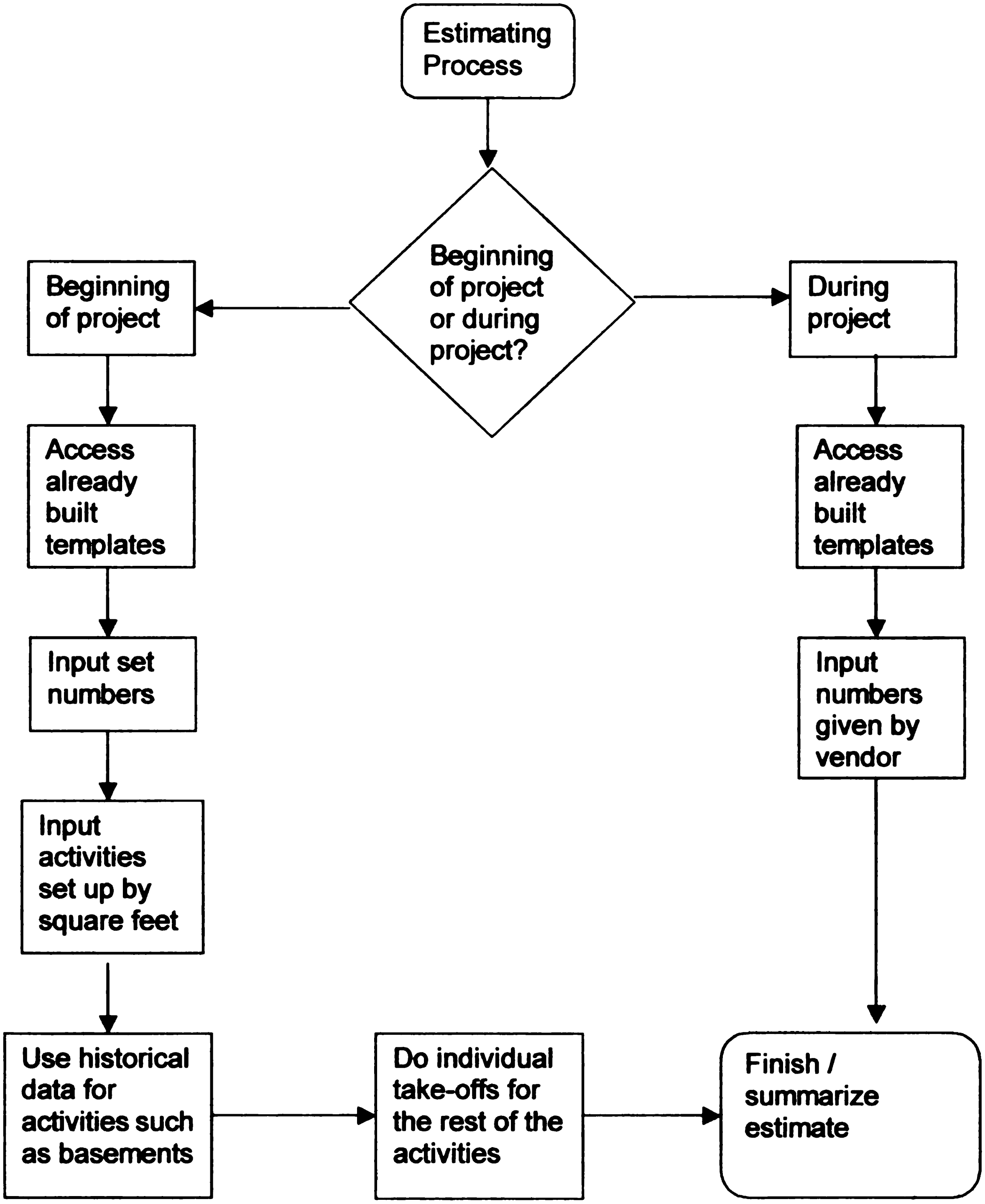
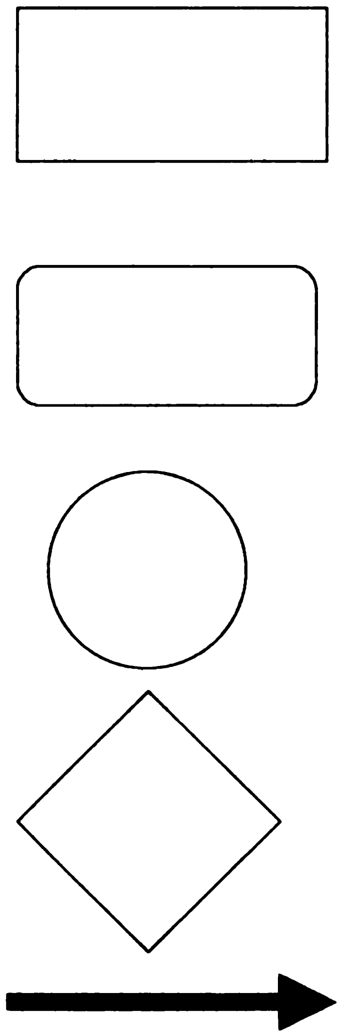



Figure 4.3 – Estimating Process Using ANSI

#### 4.2.2.1 Standard Flowchart Symbols

Several symbols are used in the development of a flowchart. The symbols shown below are just a few that will be used to develop flowcharts for the process models on this project.



*Operation: Rectangle.* Use this symbol whenever a change in an item occurs. The change may result from the expenditure of labor, a machine activity, or a combination of both.

*Boundaries: Elongated circle.* Use an elongated circle to show the beginning and end of the process. Normally, the word start, stop, or end is included within the symbol.

*Connector: Small circle.* Use a small circle with a letter inside it at the end of a flowchart to indicate that the output from that part of the flowchart will serve as the input to another flowchart.

*Decision point: Diamond.* Put a diamond at the point in the process at which a decision must be made.

*Direction of flow: Arrow.* Use an arrow to denote the direction and order of process steps. An arrow is used for movement from one symbol to another

Figure 4.4 – Standard Flowchart Symbols
(Source: Harrington, 1991)

### 4.2.3 Time Study

The primary reason for doing time study is to measure job performance; that is productivity as stated by Lawrence S. Aft in his book *Productivity Measurement and Improvement* (1992). In addition, time study according to Carroll (1972) is a way of gathering facts. The data collection for this thesis project is also concerned with gathering facts; such as the fact of how long it takes to perform a certain activity. Different companies and industries have different needs for performing time study according to Aft (1992). He mentions that use of time study to the critical operation of an organization could include;

- Developing production schedule
- Determining wage payment plans
- Estimating manufacturing costs
- Providing a base for estimating productivity increases
- Identifying employee training needs
- Appraising employee performance
- Justifying the addition of production capacity

The time collected in this thesis project, will be used to eventually identify bottlenecks and resource utilization for the manufacturing process being studied. To have a timing device is the first requirement for formulating a time study. The timing device could be a stopwatch, a wristwatch or any form of electronic device that measures time. For this project, both a stopwatch and a wristwatch were utilized. After establishing the timing devices used, it is important to understand the process that is to be studied. This was done by doing process mapping as explained above.

#### 4.2.3.1 Cycle Time

"Cycle time is the total length of time required to complete the entire process" (Harrington, 1991). This time includes the time it takes to perform the work and the time spent waiting for something, time spent chatting, or time spent waiting for resources to be available. The time that it takes to complete the process if there are no interruptions or stoppage is the actual cycle time; that is to say the time it will take to do the job in a perfect situation. Total cycle time can be thought of as actual cycle time plus idle time. Both total cycle time and actual cycle time are collected for this research project. This applies to both individual activities and combination of activities in station(s). The data sheet used for this process is shown in Table 4.2. This datasheet was used to collect data on the following parameters:

Chassis Number: Every section going through the line has a number. This number is the chassis number and it is usually written on the steel chassis. The number is the identification number for the product.

Station Number: This number is entered depending on the station that is being observed. Multiple station numbers can be used based on the activity relationship.

Table 4.2 - UC/MSU - NSF Manufactured Housing Project Data Sheet

| Station # | | Station Description: | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Chassis Number | | Duration | Sub 1 | Sub 2 | Sub 3 | Sub 4 | Sub 5 | Sub 6 | Comment |
| | Time | | | | | | | | |
| | No. of labor | | | | | | | | |
| | Time | | | | | | | | |
| | No. of labor | | | | | | | | |
| | Time | | | | | | | | |
| | No. of labor | | | | | | | | |
| | Time | | | | | | | | |
| | No. of labor | | | | | | | | |
| | Time | | | | | | | | |
| | No. of labor | | | | | | | | |
| Activity Description | | | | | | | | | |
| Activity related Material | | | | | | | | | |
| Activity Precedes/ Follows | | | | | | | | | |

| Supporting Stations Data | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Number* | Activity Description | *Duration* | *Labor Force* | *Material* | *Sub Activity* | *Sub Activity* | *Sub Activity* |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

**Activity Related Material:** Material that is being used to accomplish the task.

**Activity Precedes/Follows:** This is the predecessor and successor of the activity being observed.

Duration: The column under duration is used to enter the total cycle time for all the activities. This is from the start time of the first activity in the cycle and the finish time of the last activity.

Supporting Stations data: Supporting stations data is used for entering data on feeder stations.

A very important aspect of collecting data was to make sure idle time and actual work time are both captured in any duration of the activities. This further illustrates the point made above about the difference between total cycle time and actual cycle time. The problem was diffused by entering the actual start time and finish time of the activity cycle using a wrist watch and also using a stopwatch to record simply durations for each activity. This means that stop time for the last activity on the station could be subtracted from the start time of the first activity on the station and subcontracting lunch and break time, that will give us the total cycle time. This means durations/absolute cycle times can be gathered, and total cycle time gathered, including idle time.

For practical reasons, it was necessary to merge activities from certain consecutive stations while collecting time data. The reason for this was that activities sometimes overlap to successive stations. As a result, certain activities can occur in multiple stations especially when there is a delay of some sort. The activity is identified with the station it normally starts in, but that same activity could overlap to the next station.

#### 4.2.3.2 Data Sampling and Population

It is usually impossible to collect a large amount of data in a study to confidently say that one has data on every single scenario imaginable. More data can always be collected because there is no way of knowing if one has exhausted all possible sets of data. To get a complete data set for this research would be to collect data on every single size and design of manufactured houses produced in both factories. Doing that would qualify as a complete set of data on the whole population of houses produced. Since time and resources does not allow this, the statistical concept of sampling is used to collect the data. The concept of sampling says that the set of data collected should be representative enough to make inferences about the whole population. In this research, the eleven data points on roofing stations and exterior finishing activities, nine data points on interior finishing activities, and five data points on axle and tires were from diverse sizes and design of houses to draw inferences on the whole population of houses produced at both plants. Majority of data was collected on the most popular size in both factories but also included are the small and large extremes.

## 4.3 PRODUCTION PROCESS FLOW DIAGRAMS BY CLUSTERS

This section shows the production flow diagrams of the five main manufacturing clusters of the plant. These areas are floors, walls, roofing and exteriors, interiors, and finishing.

FLOOR CLUSTER

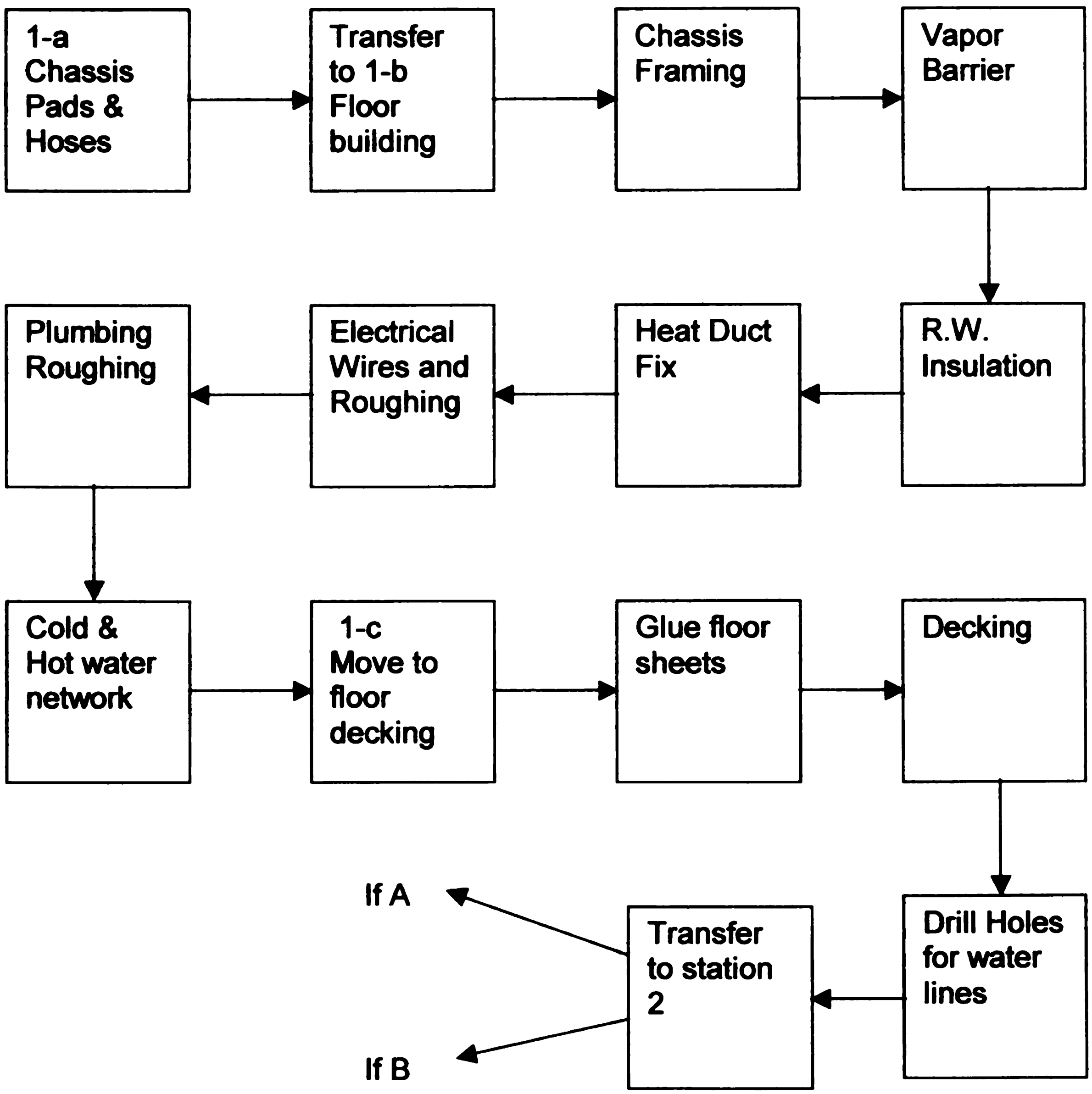



Figure 4.5a – Process Flow Diagram – Floor Cluster
(Source: Modified from UC Research Team)

Floor cluster is divided into three different parts. Station 1-a is the chassis preparation, 1-b is the floor building part and station 1-c deals with floor decking. Figure 4.5a shows activities such as chassis framing, insulation, and rough electrical and plumbing work. The floor is then moved to station 1-c were the deck is laid. The activity called holes consists of drilling holes on the floor for openings for water lines. At this point, A and B are moving in parallel as shown in Figure 4.5b.

FLOOR CLUSTER CONT'D

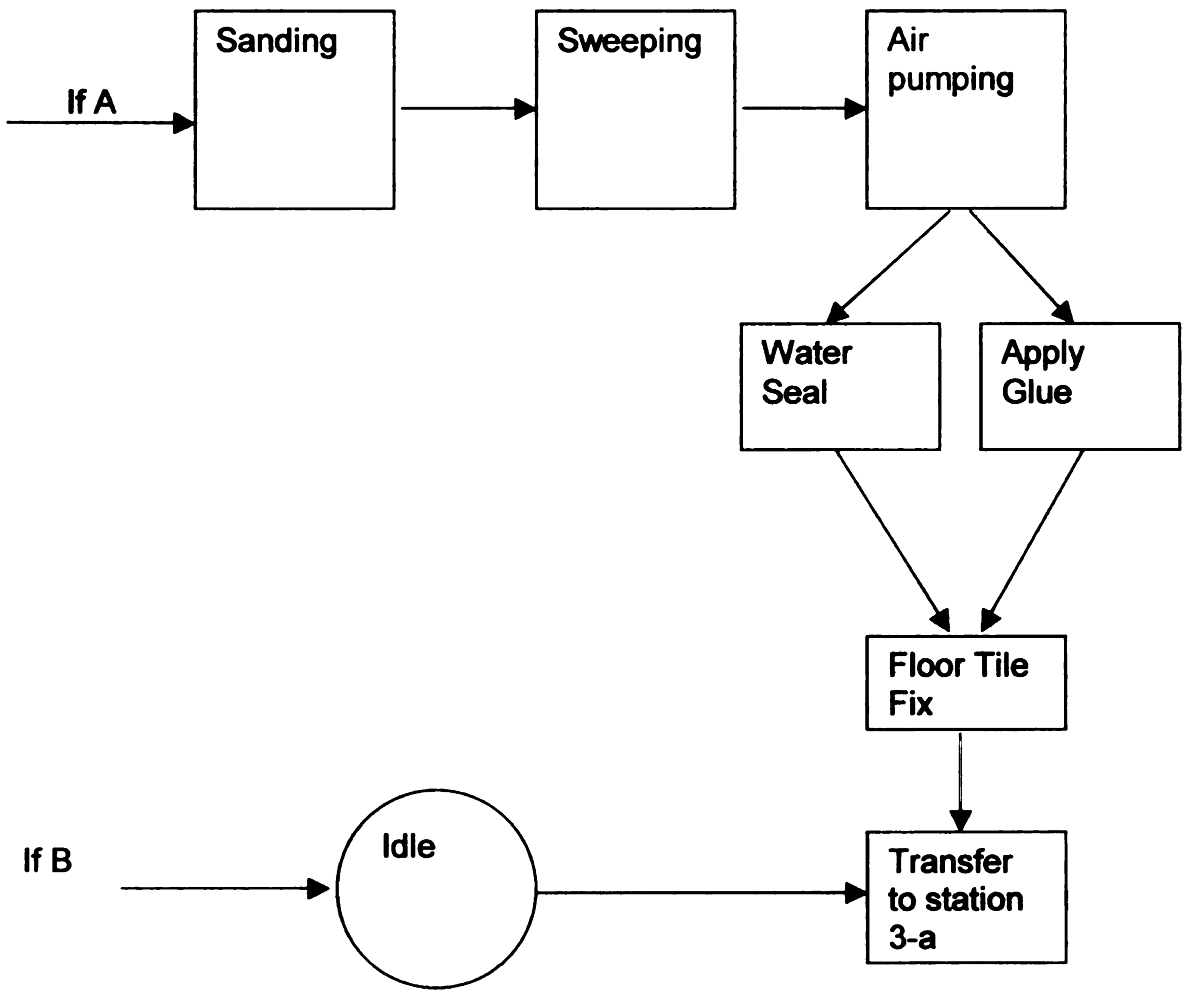



Figure 4.5b – Process Flow Diagram – Floor Cluster Cont'd
(Source: Modified from UC Research Team)

Figure 4.5b is a continuation of the floor cluster stations with tiling being the dominant activity. This activity is mainly performed on the section that contains the bathroos and is labeled as section A. Section B is mostly idle at this point because it needs carpeting instead of tiles and the carpeting activity is performed on the interior finishing station.

WALLS CLUSTER

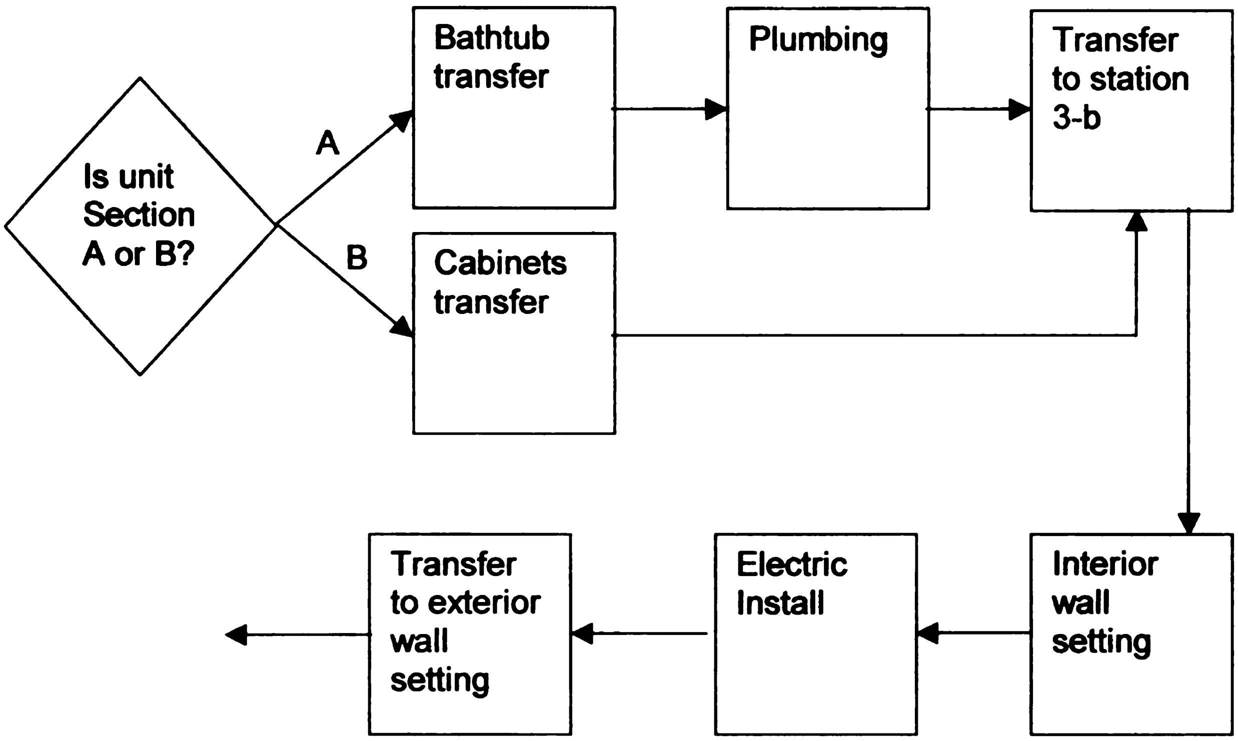



Figure 4.6 – Process Flow Diagram – Walls Cluster
(Source: Modified from UC Research Team)

The first symbol on the wall cluster diagram represents a decision point. The sections are usually divided with the bathrooms occupying one section and the kitchen the other section. The flowchart in Figure 4.6 represents section A as the one were the bathrooms are located and hence the installation of the bathtub and plumbing activities. Section B contains the kitchen and hence the cabinets transfer. Cabinet and bathtub transfer means that they are transferred from the feeder stations and installed. Not all bathroom fixtures are installed at this station. For example, both factories visited install toilets in the finishing stations. After these fixtures are installed, then the interior walls can be set.

WALL CLUSTER CONT'D – EXTERIOR WALL SETTING

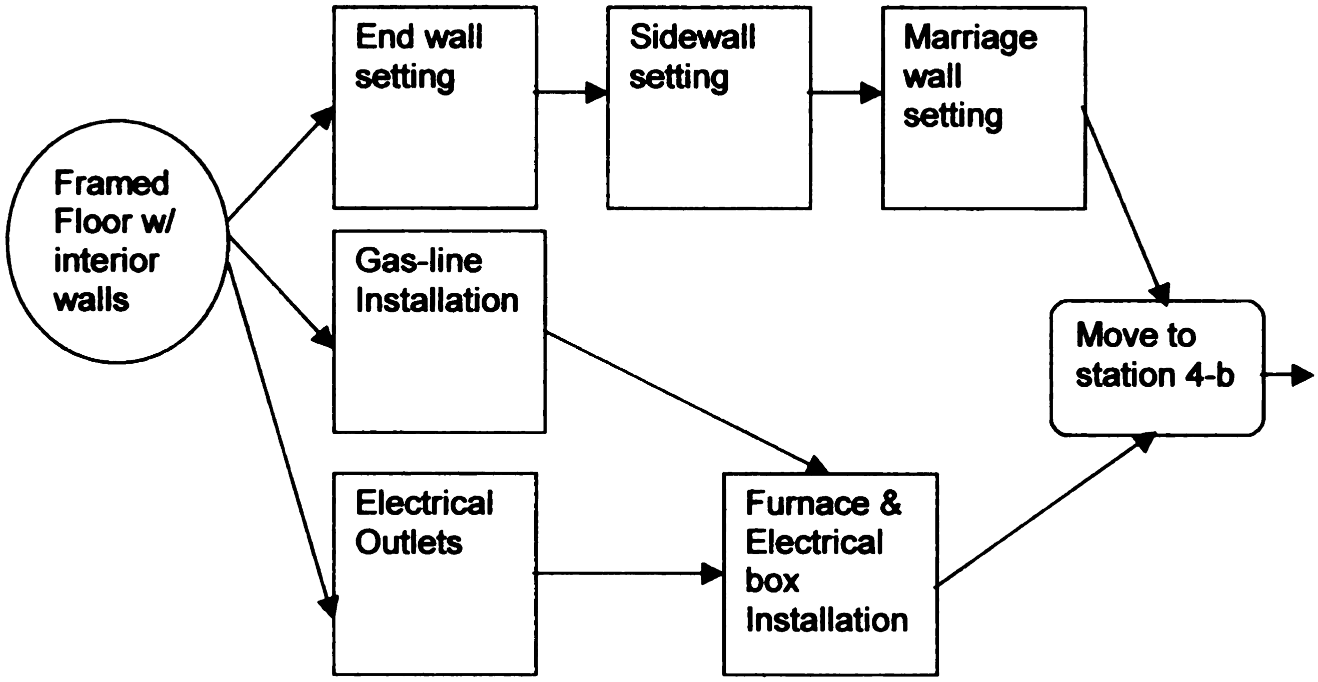



Figure 4.7 – Process Flow Diagram – Exterior Wall Setting & Fastening
(Source: Modified from UC Research Team)

WALL CLUSTER CONT'D – EXTERIOR WALL FASTENING

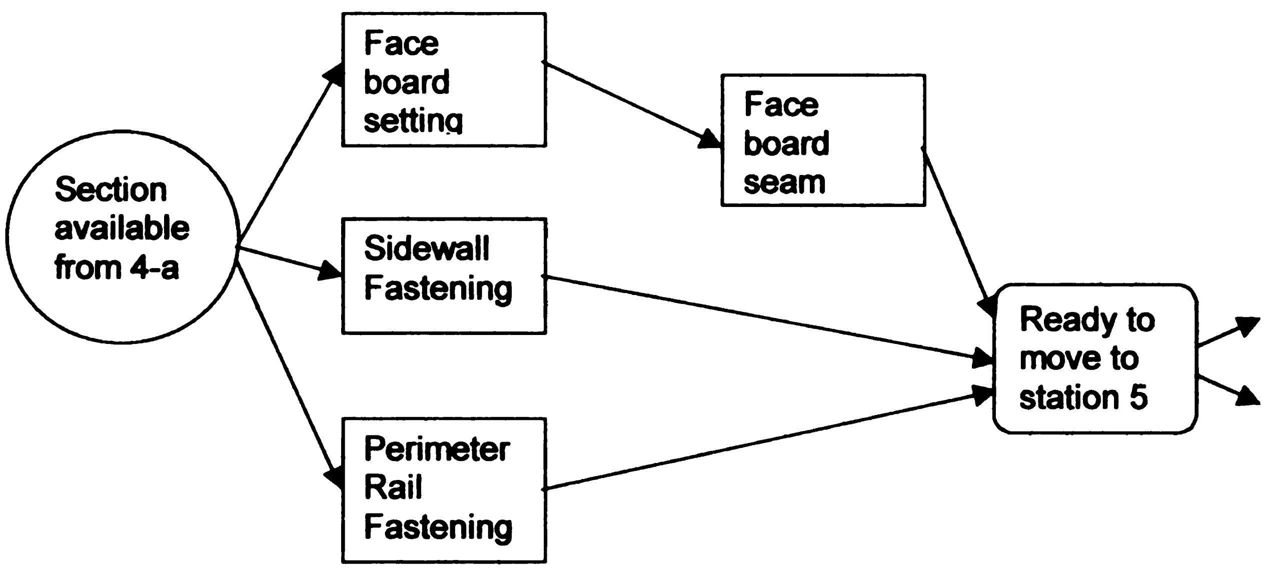



Figure 4.7 cont'd

Section 4 mainly consists of wall setting. The walls are built on a feeder station and moved via an overhead crane to the main production line. First, the end walls are set, then the sidewalls, and finally the marriage walls. Electrical work including wiring for the fixtures are performed whiles the walls are going up.

ROOFING AND EXTERIORS CLUSTER

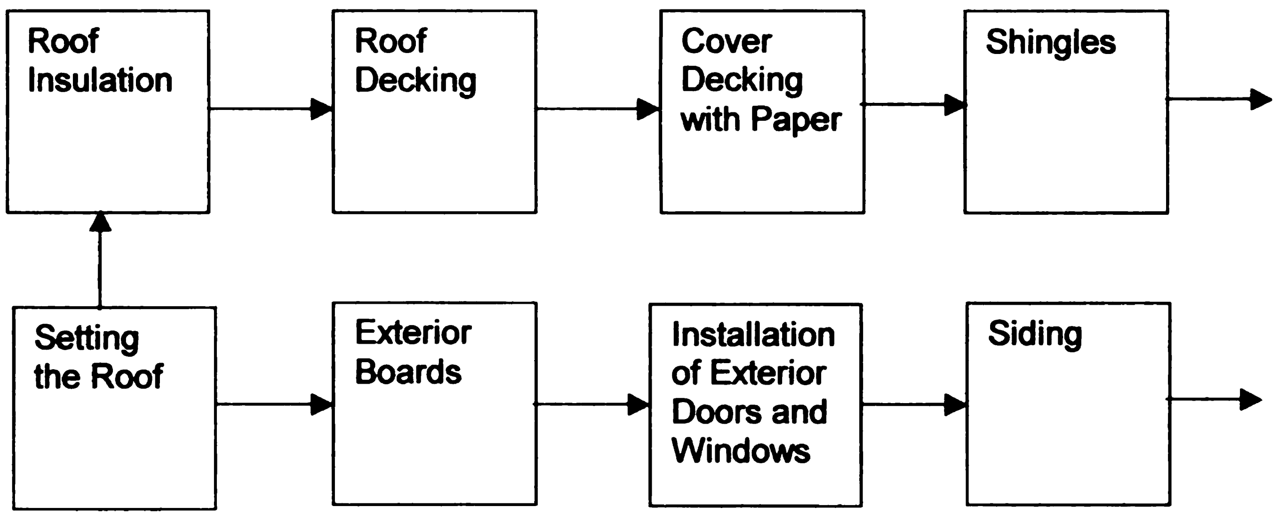



Figure 4.8 – Process Flow Diagram – Roofing & Exterior Wall Finishing

Roofing cluster starts when the whole roof structure built from the feeder station is transferred to the main line to be set on the section. From this point on two sets of activities are taking place. The roof is being worked on and in parallel so are the exterior walls. Work is also being performed inside the house but the activities are considered the major activities. After the roof is set and secured to the walls of the house, insulation is sprayed on the roof. This gives way for the trusses to be covered with roof boards. In other words, the deck on top of the roof is placed. For drainage purposes, the deck on top of the roof is covered with paper before shingles are placed. At the same time the above-described activities are taking place, the exterior walls are also being finished. First, the walls are covered with exterior boards. Door and window openings are cut so that the doors and windows can be installed. Then the house is covered with siding. These are the major activities happening in the above-described stations. After the roofing and exterior finishes have been performed, interior finishes can be started.

INTERIORS CLUSTER

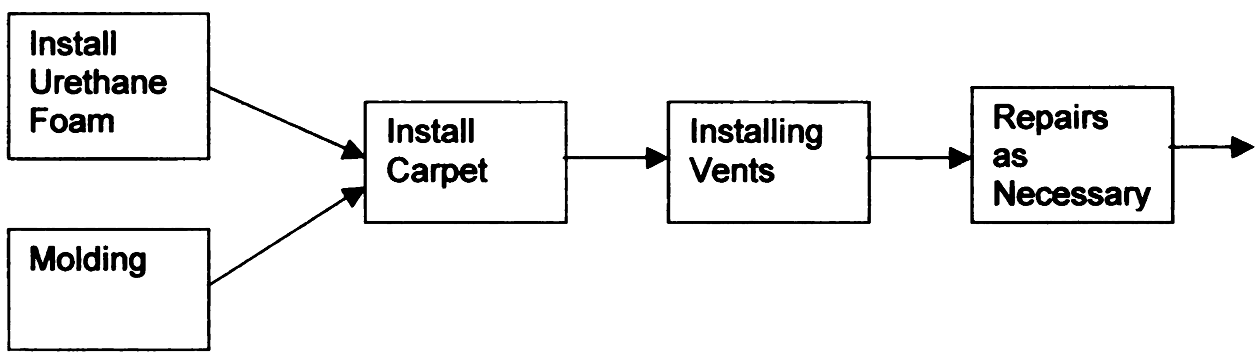



Figure 4.9 – Process Flow Diagram – Interiors

Urethane foam is the material used to pad the floor before the carpet is installed. The flow diagram shows that at the same time the urethane foam is being installed, moldings is being places on doors, windows and floor and wall linings. This does not always happen as the author has observed the two activities happening in sequence. Carpeting is then installed; the vent openings are cut and the vents coverings placed on the openings. This clears the way for the house to be moved to station six depending on how much repairs are needed. Repairs from this point on are ongoing activities but they do not affect the progress of the station unless it is something major such as a wrong bathroom fixture or a whole section of drywall to be replaced. In such cases then the work may be delayed while repairs are in progress.

**FINISHINGS CLUSTER**

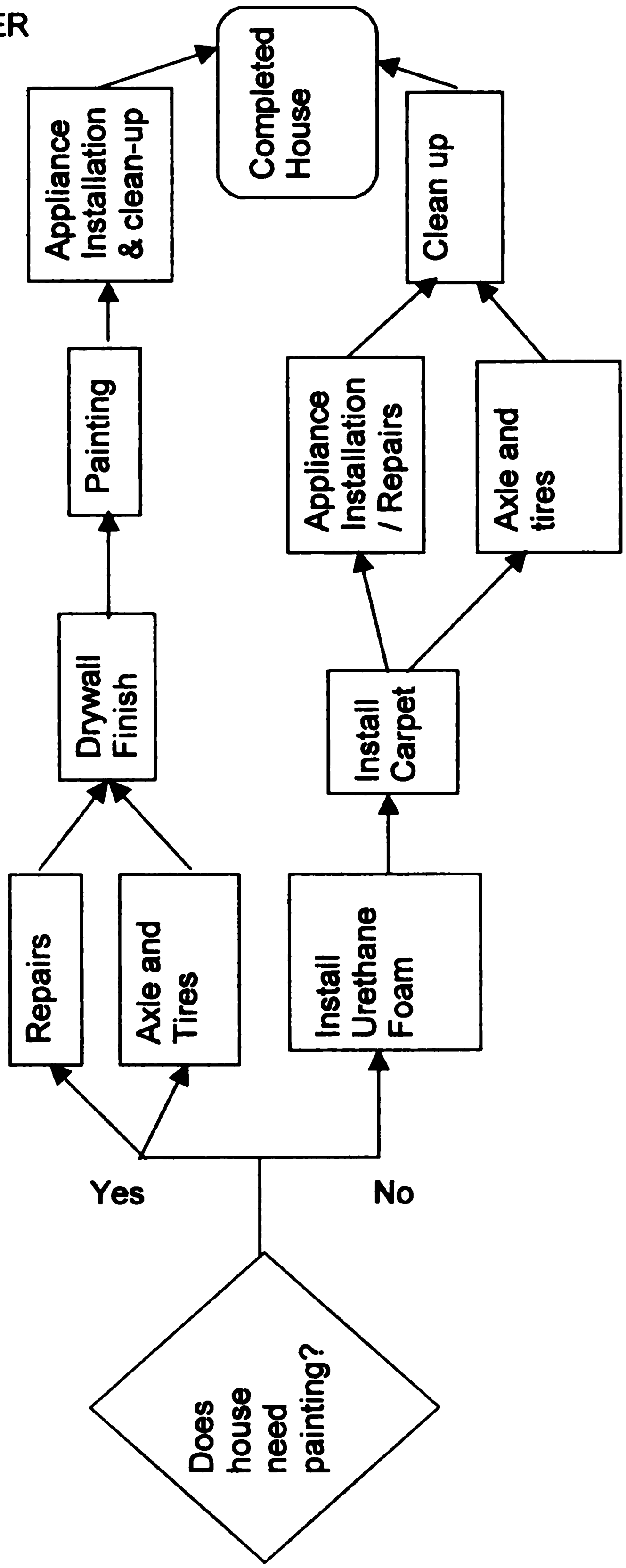



Figure 4.10 – Process Flow Diagram – Finishing Cluster

When the house moves to the finishing stations, it can go in two different directions. Some of the houses coming down the line already have wallpaper on them and others need to be painted. Whether the house needs painting or not, axles and tires have to be installed. In cases where the house needs painting, the drywall process has to be completed first. This is usually a one-day activity since the drywall has to be left overnight to dry. Painting is also a one-day process for the same reason. In cases where the house does not need painting, axle and tires are installed simultaneously with kitchen and remaining bathroom appliances. The house is then vacuumed, dusted and completely cleaned.

## 4.4 DETAILED PRODUCTION PROCESS AND MATERIAL FLOW MODEL

Over a period of several weeks of recording time data among other things, the familiarity with the process grew, coupled with the process mapping session and the process flow diagrams developed at that stage of the project. It is now appropriate to develop a detailed production process and material flow model for manufactured housing. The model will be developed in two parts. The first part starts with the chassis framing and ends at the wall stations, based on the flow diagrams above, and the second part begins from roofing and exterior up to the end. This process model is transformed into a simulation model in the next Chapter.

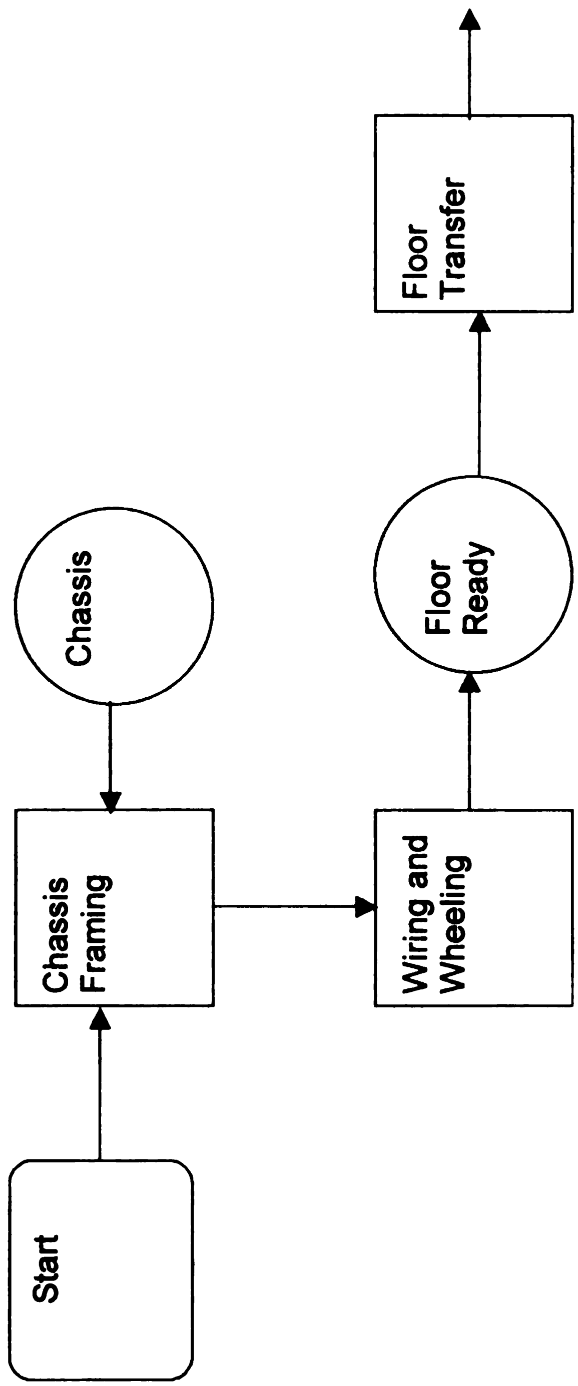



**Figure 4.11 – Production and Material Flow Model: First Half of Factory**

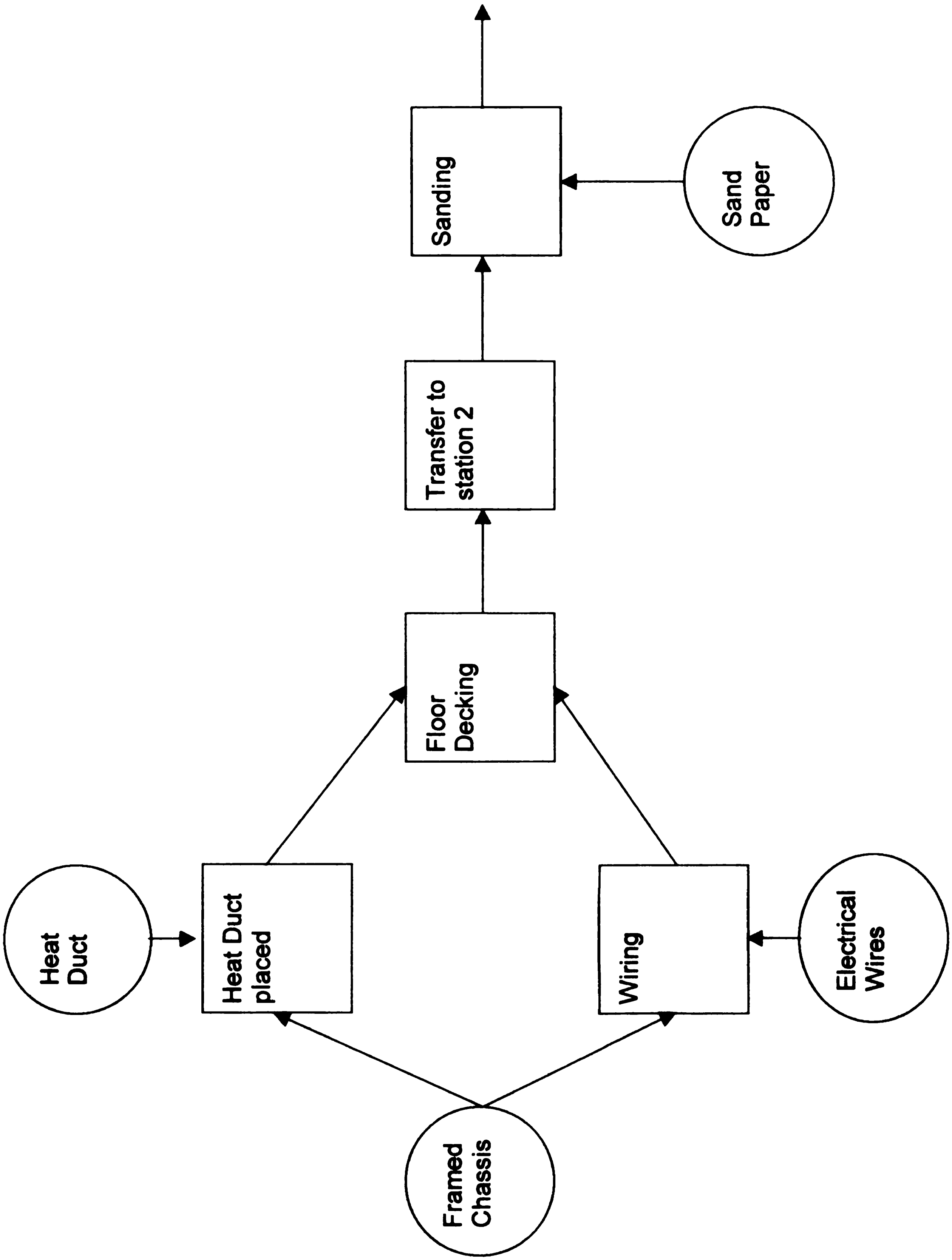
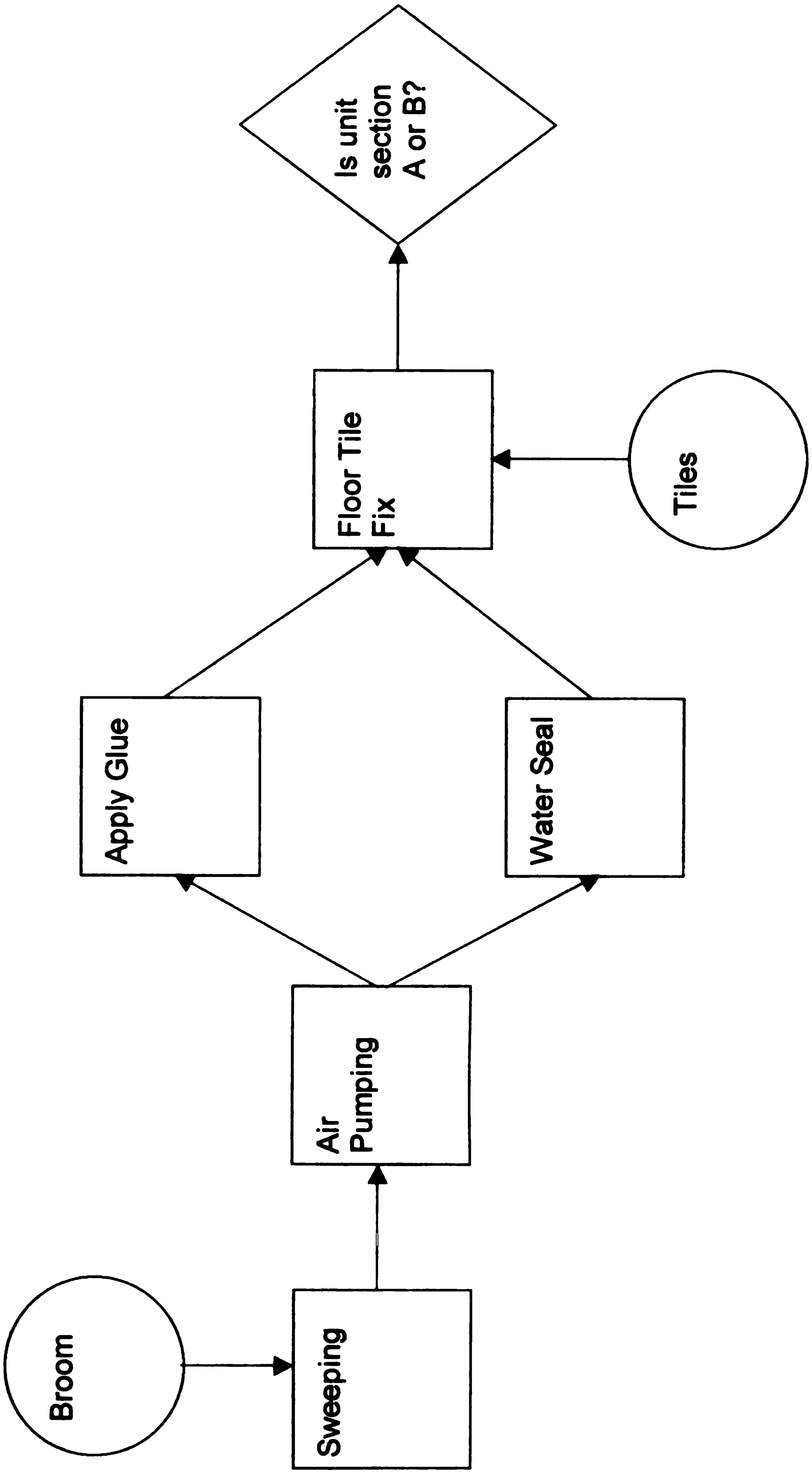



Figure 4.11 cont'd

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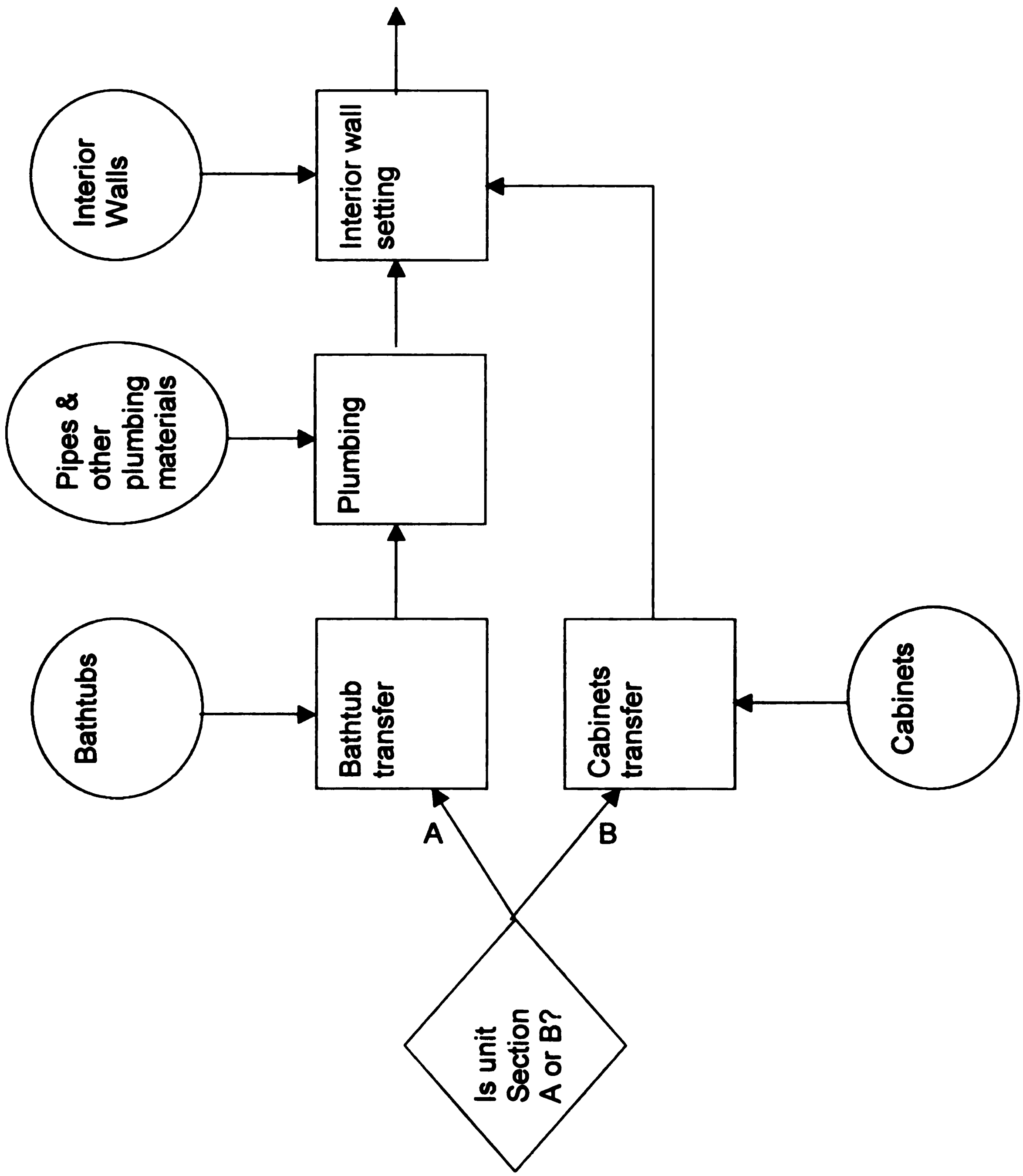


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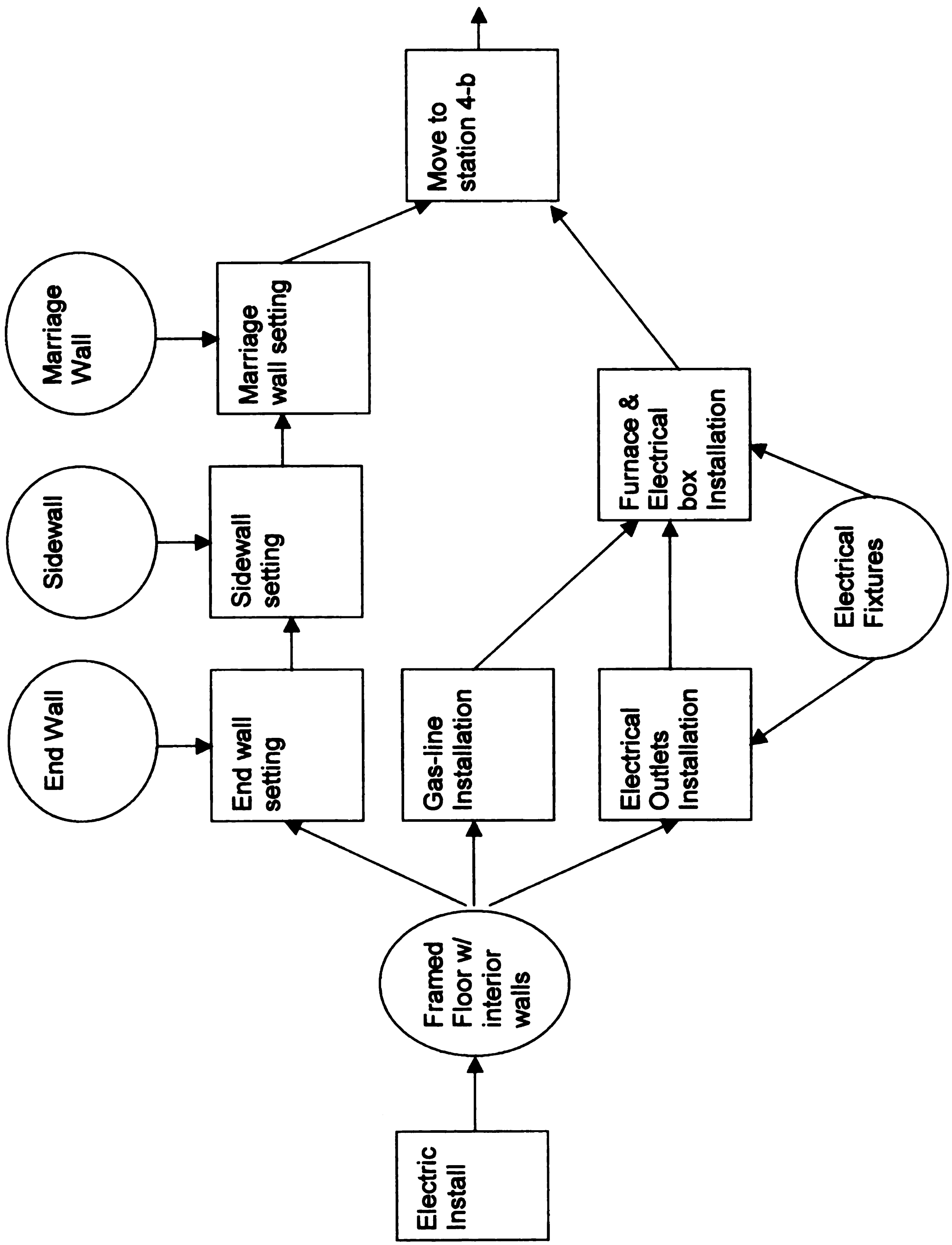


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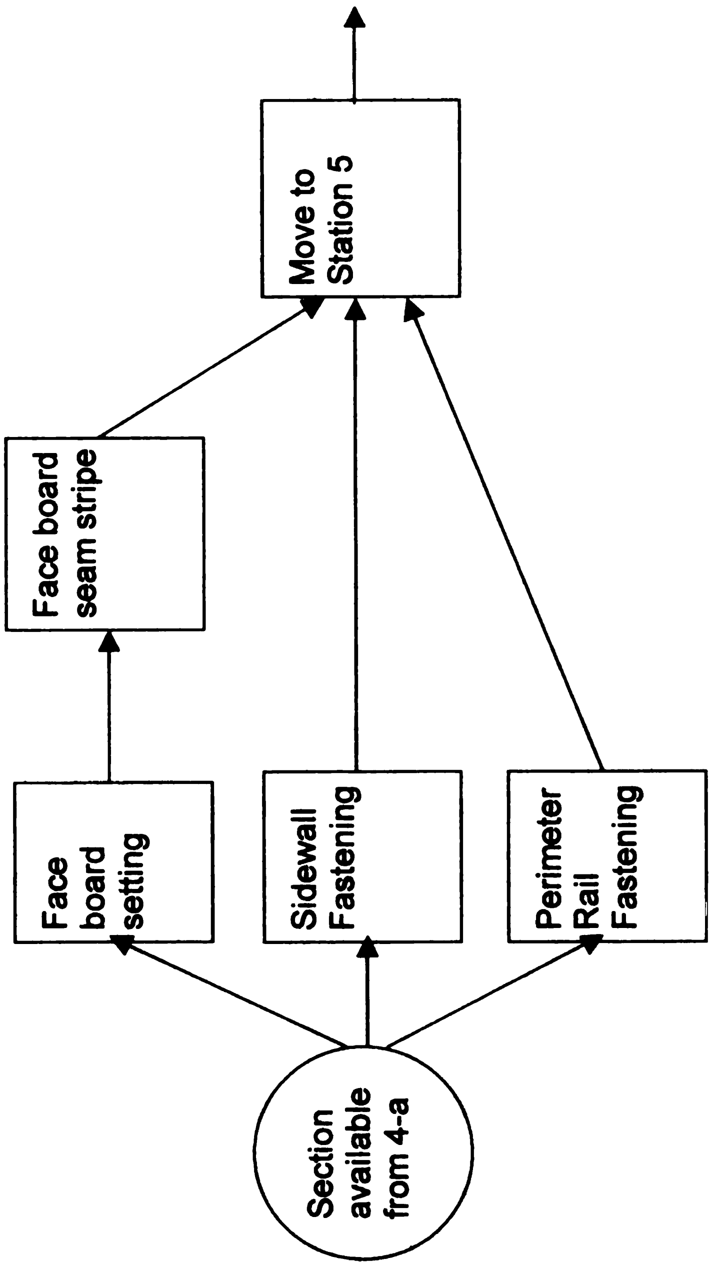



Figure 4.11 cont'd

PART 1

The first part of the model shows the chassis wheeled in with nothing on it. the floor is built with insulation, wiring and duct work all in place. After the floor has been covered, it is sanded and tiled as applicable. The floor is then installed with cabinet and bathroom fixtures. More plumbing work is performed. The wall sections are then placed accordingly, wired, and fastened appropriately. At this point, a framed house exists.

PART 2

With the frame ready, the roof structure can be moved from the feeder station to be set on top on the house, one section at a time. Insulation is sprayed on the roof, the roof covered and shingles installed at the same time doors and windows are being installed followed by siding. The major activities now consist of interior finishes such as molding around the doors and windows, pad the floor with urethane foam before carpeting the floors provided the house does not need painting but already has wall paper instead. The last finishing stations consist of installing axles and tires for transportation, installing the last of the kitchen (refrigerator, oven) and bathroom (toilet) appliances. The house is then vacuumed thoroughly and ready to be shipped out.

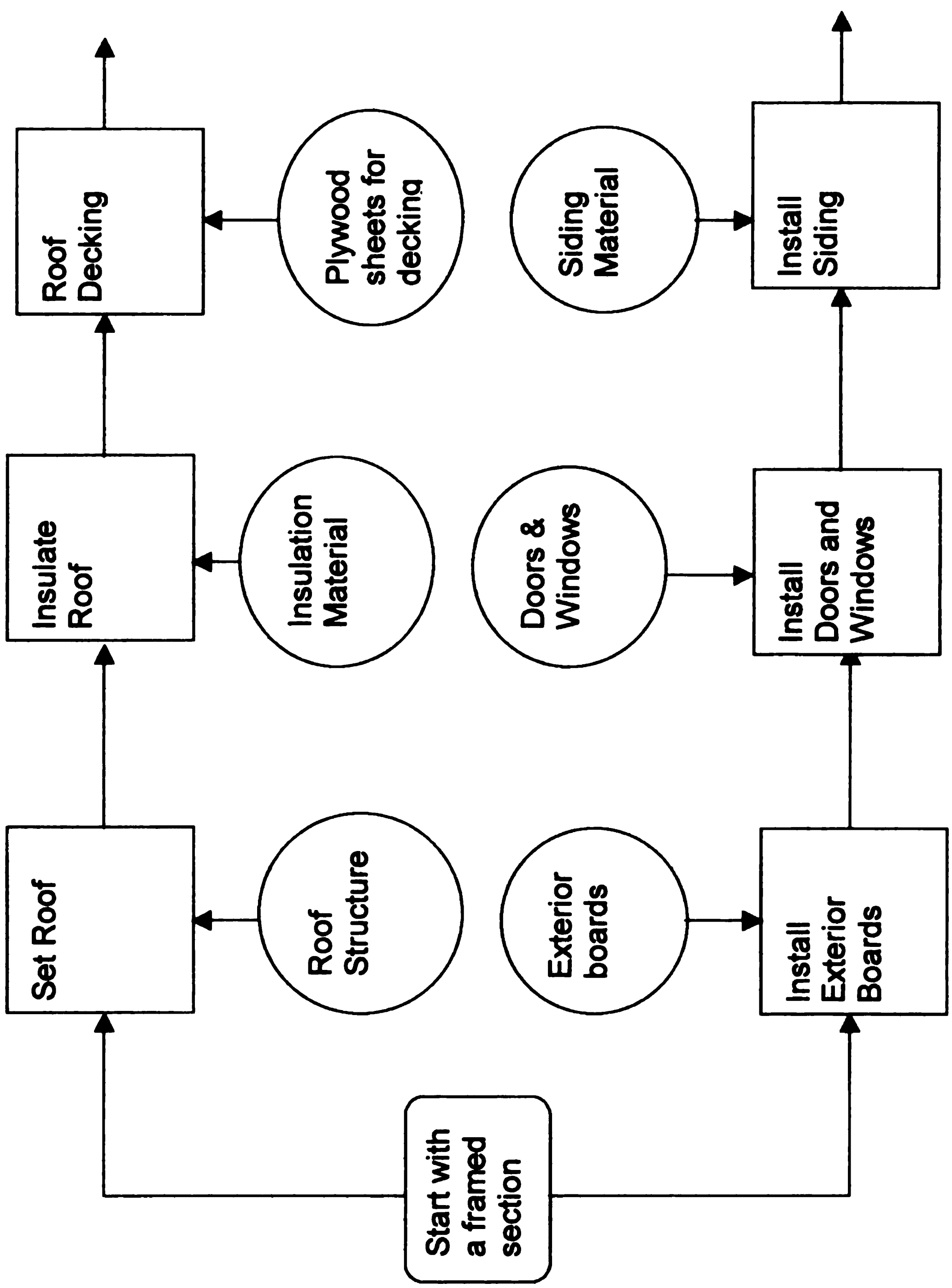



**Figure 4.12 – Production and Material Flow Model: Second Half of Factory**

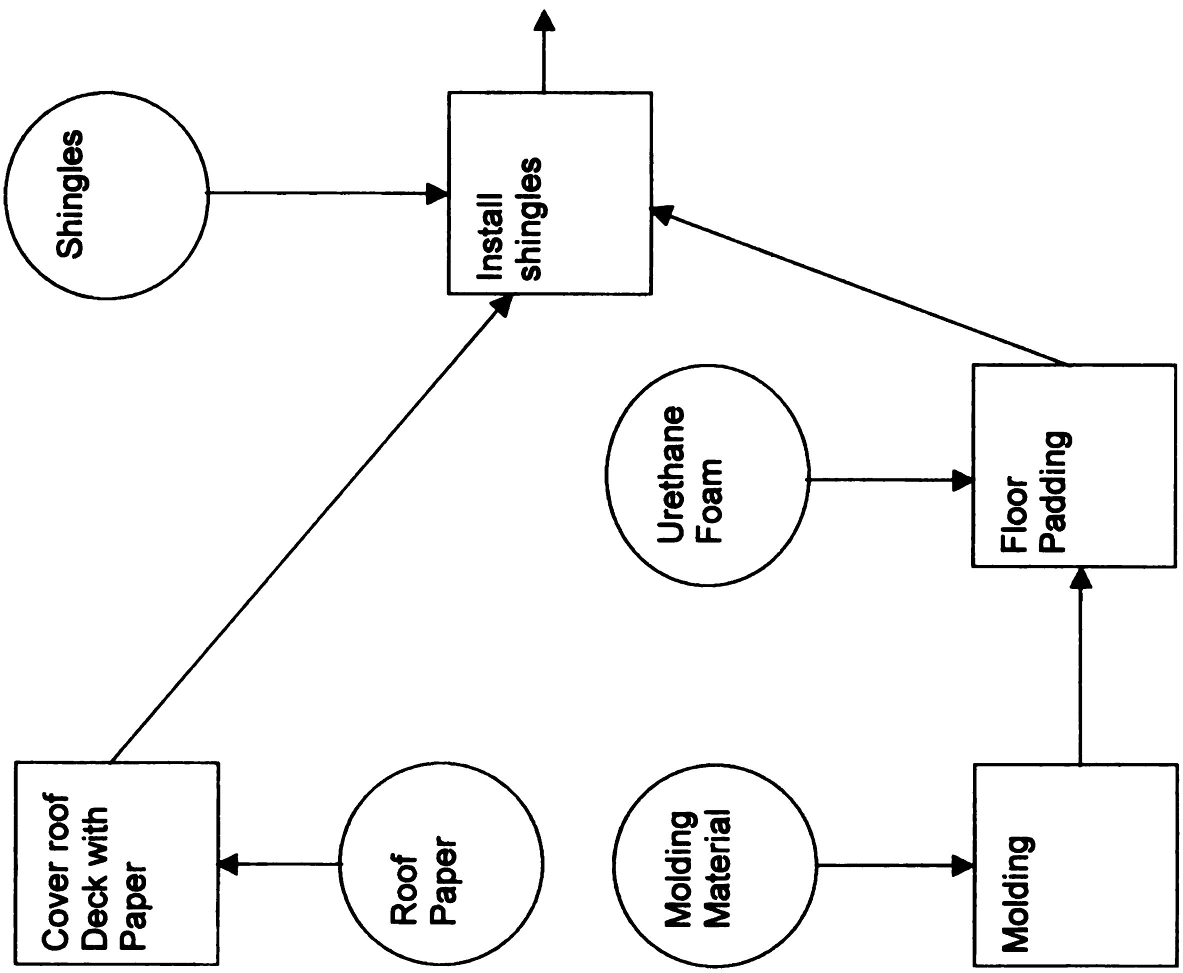
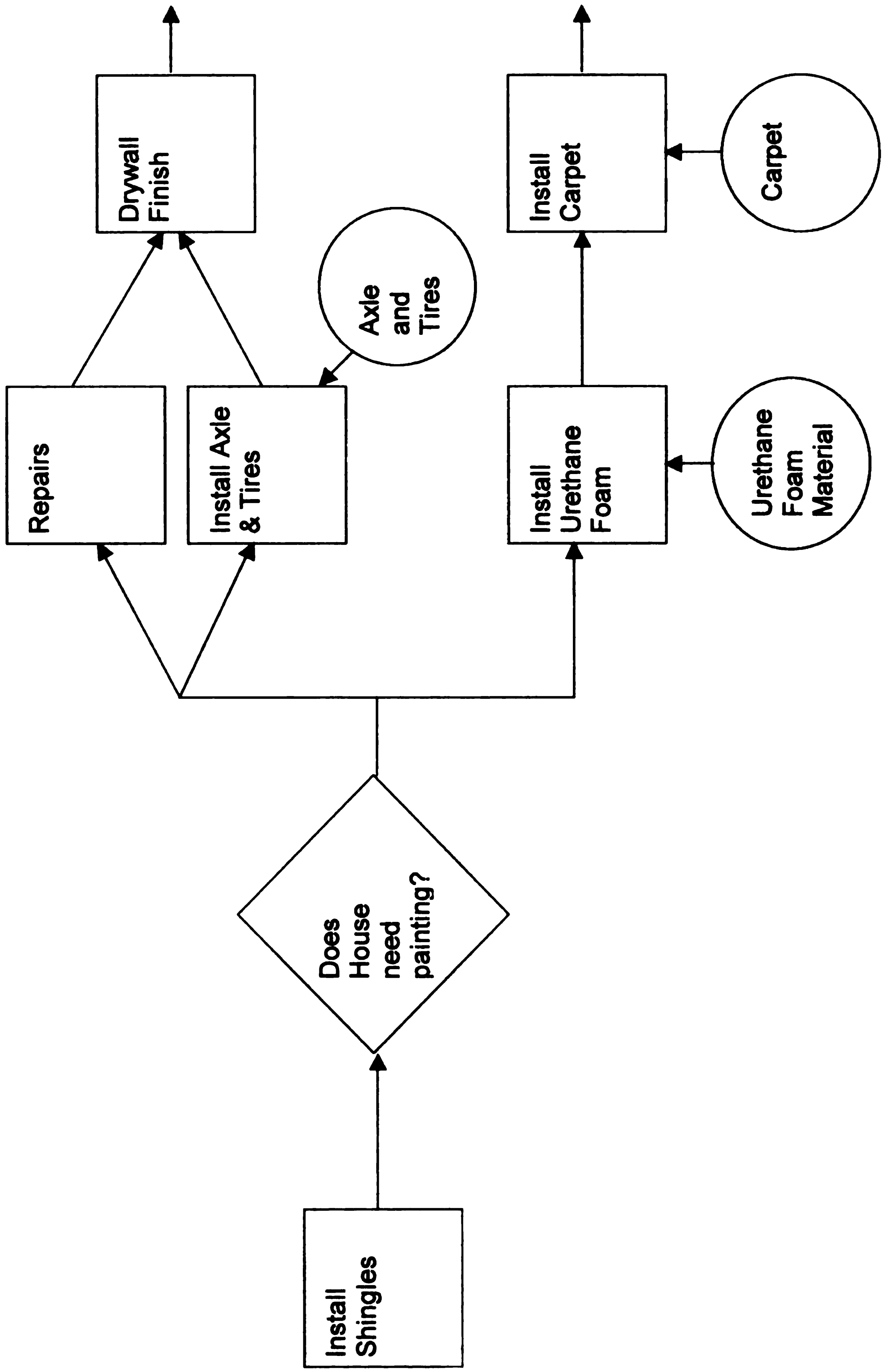



Figure 4.12 cont'd

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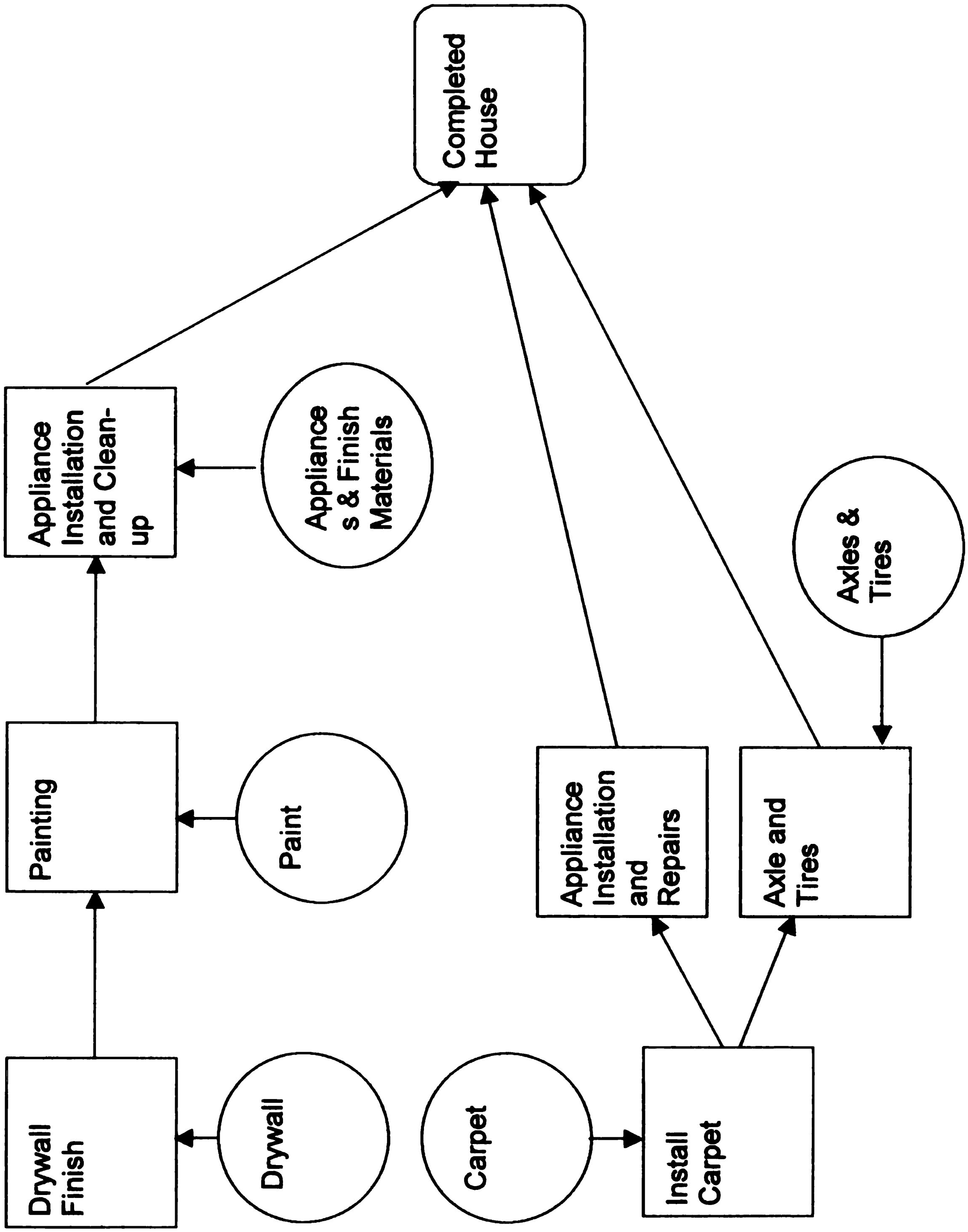


Figure 4.12 cont'd

## 4.5 SUMMARY

This chapter described the process-modeling phase of the thesis. The chapter started out by describing the concepts of process mapping and how it was utilized. Different types of process flow diagrams were discussed with examples, which emphasize block diagrams and the American National Standards Institute format. Time study background and how time data was collected followed the process mapping discussion. Process flow diagrams were then developed for different clusters such as floors, walls, roofing, exteriors, interiors, and finishing, showing activity relationships. These process flow diagrams lead to the detailed production process and material flow model. The model was divided into two parts to make the transition to the next stage, (the simulation model) much easier.

# CHAPTER FIVE

# SIMULATION MODEL

## 5.1 INTRODUCTION

In this chapter, a simulation model is developed using cycle time data collected from the manufactured housing plants and the developed process model from Chapter four. First, computer simulation will be discussed including general use and specific utilization to the manufactured housing industry. Construction simulation and its evolution will be briefly discussed. Then, simulation software used for this research will be introduced. The next step is to describe the steps used in transforming the detailed production and material flow model developed in the previous chapter into a simulation model. Finally, results obtained from running the simulation model are presented and the discussion is extended to potential uses of the simulation model to study alternatives to improving overall production efficiency.

## 5.2 WHAT IS SIMULATION

Construction simulation or any other kind of simulation is a way of mimicking reality. Simulation attempts to represent on paper what is happening in real life as close as possible. Several different definitions of simulation were encountered during the literature review phase of this project. The definition that suits this work best states: "The object of developing the model of a production system is to examine the interaction between flow units, determine the idleness of productive resources, locate bottlenecks and estimate production of the system as constituted" (Halpin and Riggs, 1992). In Chapter four, flow units have already been developed and in this chapter, idleness of productive resources will be studied along with the location of bottlenecks.

## 5.3 TYPES OF SIMULATION

There are two different types of simulation. These are discrete-event simulation and continuous simulation, both of which are briefly defined in the next two subsections. Discrete- event simulation is used for this thesis.

### 5.3.1 Discrete-event Simulation

In discrete-event simulation, the system is reproduced using activities, which start and end according to specified durations and number of attributes. According to Pritsker (1986), "the state of a system is defined in terms of the numeric values assigned to the attributes of the entities". The system is characterized by its state at any given point in time. In discrete-event simulation, the assumption is that the state of a system changes instantaneously at specific times marked by events (Martinez, 1996). An example of discrete-event simulation include cars arriving at a traffic signal involving a finite number of units (cars) or activities (arrivals), which start and end according to specified durations.

### 5.3.2 Continuous Simulation

In the case of a continuous simulation model, the state of the system is represented by dependent variables that change continuously over time (Pritsker, 1986). Examples of continuous simulation include nuclear reactions and population growth whose states are changing continuously. Continuous simulation requires differential equations to define the continuously changing state of the system.

## 5.4 WHAT IS SIMULATION USED FOR

Simulation has been in the academic and business management fields for the last several years before it came to construction. Universities have used simulation to perform research on Industrial operations. Furthermore, simulation is used because of the cost and time it takes to build a real system and run experiments on it, whether it is experiments on aerodynamics, manufacturing, or business process. Unlike manufacturing, in construction real-size full-scale models/prototypes are almost non-existent. The following are further benefits of simulation: (BCM 817 Class Notes, Spring 2001).

- Identifying needs and allocating resources
- Understand the interaction between resources
- Trade-off alternatives
- Determine the duration of operations taking into account the non-deterministic nature of things
- Determine operation costs

### 5.4.1 Use of Simulation for Manufactured Housing

The benefits of simulation to the manufactured housing industry will be discussed in the context of the benefits described above. Manufactured housing utilizes assembly-line production with activities and processes, which require the use of resource. Proper use and allocation of these resources is essential which requires a determination of operation durations and cost, and trade-off alternatives. In simulation, these issues of concern are usually studied. This section will deal with how some of these issues can be applied and used in the manufactured housing industry.

#### 5.4.1.1 Identifying Needs and Allocating Resources

The needs of all plants are unique and so are the type and amount of resources needed. Simulating the process over a certain amount of time, one can expect to find durations over which the activities in the system consume resources and deliver the product. Simulation will provide an estimate for resources needed based on what the user wants to produce or the needs of the user.

To illustrate, consider a new company in the planning stages of setting up their first plant. This particular company may have a unique product or a unique style of manufacturing, which are not well documented, making staffing decisions quite haphazard. In other words, they want to know what their needs are and how to allocate the appropriate resources. In this case, the production system could be modeled using simulation with estimated numbers on labor use. After running the system, the results could be used to find out what the labor utilization is and then changes made accordingly to the best possible scenario. Although simulation may not be able to optimize the system, it will be able to give results based on how well resources are being utilized. The plant can be staffed according to such information. Let us consider Figure 5.1. An activity requires one unit of material, one forklift, and one laborer to start, but there is a crew of three. The first laborer is pulled and after activity "A is finished, the laborer moves with the process to activity "B". The second laborer is pulled as soon as the forklift is available so activity "A" can start again. When the first laborer is finished with activity "B" it is pulled back to the queue so she could be used again. The question now is how many laborers are needed in other to maximize the utilization of both the forklift and the laborers. One does not want to have the forklift waiting for availability of laborers or a very large wait-time for the laborers either. How does one allocate the ideal number of resources (laborers) in this case to maximize utilization? Simulation will be able to help answer such a question.

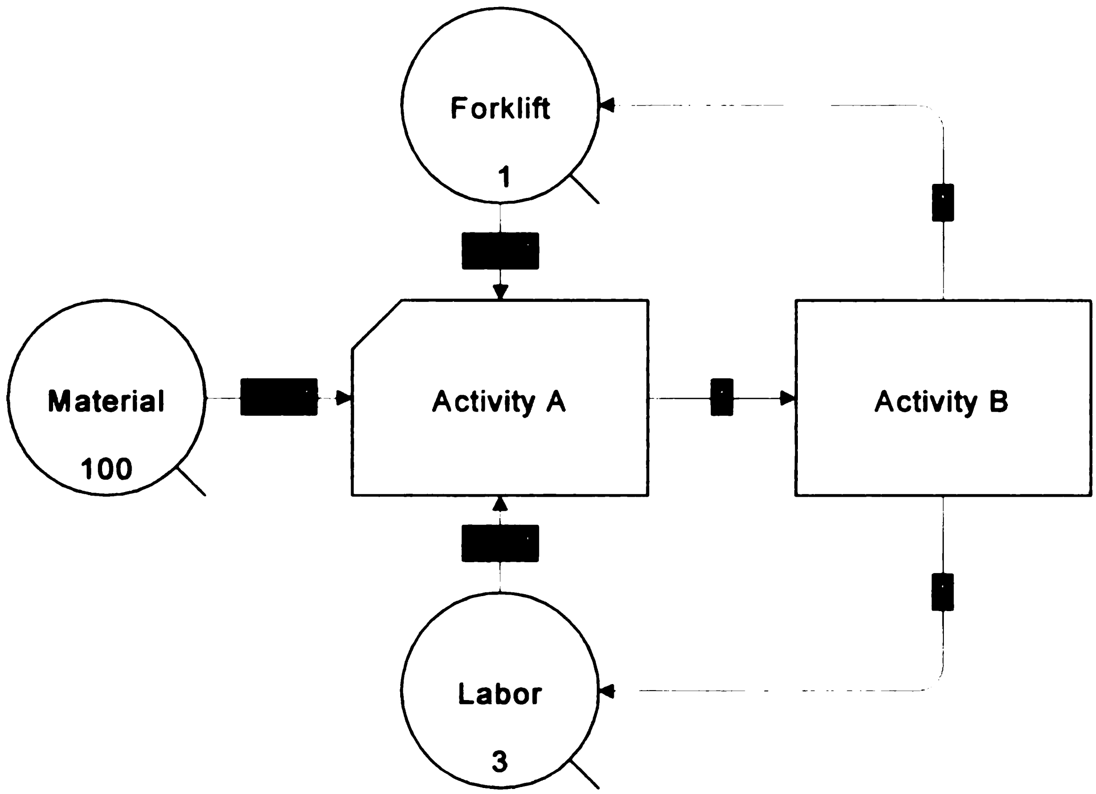


Figure 5.1 – Need and Resource Allocation Example

#### 5.4.1.2 Understand the Interaction Between Resources

Similar to real life, simulation system entities, which include all kinds of resources, come together to make an activity happen. The resources discussed in this section are those that are shared by multiple activities. The timely start or completion of activities, depend on the availability of all the applicable resources. Consider there is an existing crane that moves walls from the feeder stations to the main assembly line. When the crane is not moving walls, it is sitting ideal. Similarly, a separate crane exists for moving roofs from the roof feeder station to the main production line. When the roof crane is not transporting roof structures, it is sitting ideal. It is feasible that one of these cranes can be utilized for both activities. In both factories visited during this project, the walls and roofing stations are close enough to each other that there should not be any problems with the movement of the crane from station to station. The effect this will have on production can be answered by simulation. Simulation can show whether the crane is constantly moving, is it keeping up between the two stations, and if not, will installing a faster crane meet the criteria.

#### 5.4.1.3 Trade-off Alternatives

The process of trading-off alternatives involves trying to balance the costs and benefits of different options. A company may want to invest in new equipments to help improve the production on the floor. They may be considering two cranes with different capacities and speeds, or they may be considering pumps for delivering roof insulation with different speeds. Analysis of overall production rate on each option can be performed. In cases where cost of equipment is not known, certain simulation software can provide cost data. The above example is for comparing two new alternatives. The argument is also valid when the two alternatives are being compared and one already exists. It illustrates as to how trading one alternative for the other, affect production. Let us say a company is considering installing new overhead crane to move walls from the feeder station to the main line. The new crane has a larger capacity and faster speed. The questions the company wants answered could include: (1) how would the process be affected by installing a faster crane? (2) can we produce more houses? (3) how much more houses can we produce in a given amount of time? (4) how much will our profitability increase by increasing production? Specifically, on the interaction between resources, the company might want to know: (1) how much more wall insulation will be needed if we are to produce so much more units? (2) how will staffing be affected by changing production rate as a result of the new crane? (3) Will the ordering cycle for other materials be affected?

Simulation can help answer these questions by studying the plant with the current crane and develop a model. Based on the speed of the new crane under consideration, the time input can be changed and simulation results will show impact on the process. Answers to other questions will follow.

#### 5.4.1.4 Determine Durations of Operations and Operations Cost

This is a very important benefit to manufactured housing. Since we live in an uncertain world, durations are almost never deterministic. Approximately, how long will it take to produce so many units? Measuring duration for a whole operation can be a very tedious task. Furthermore, the non-deterministic nature of things suggests that a single measurement is not enough to determine the right duration. Simulation will allow the user to input few durations and then repeat it for a large number of times. This will allow averaging out durations, which will then be close to the actual duration. The same concept can be applied to manufactured housing since building a single house can take multiple days with many activity durations and different cost variable for slightly different options on the houses. So simulation will not only help answer the question, how long it will take, but also how much is it going to cost?

## 5.5 CONSTRUCTION SIMULATION

Construction simulation was developed over time to meet certain demands of the industry especially the highway/transportation industry. CYCLONE, developed by Daniel Halpin in 1977 has become the basis from which most simulation software has been developed (Halpin, 1977). Several attempts though have been made before that to develop a credible system of network modeling from which simulation can be performed but none of which had the impact of CYCLONE. Two of these attempts were that of Teicholz's "link node" model in 1963, and Halpin's CONSTRUCTO in 1976. STROBOSCOPE (State and Resource Based Simulation of Construction Processes) is the most recent simulation language in academia. To make STROBOSCOPE available to the less rigorous users of construction simulation a version of STROBOSCOPE called EZSTROBE, which uses a graphical user interface, was developed (Martinez, 1998). EZSTROBE is what will be used for this research.

## 5.6 INTRODUCTION TO EZSTROBE

The simulation software used for this project is called EZSTROBE. EZSTROBE is a simulation system with the following features (Martinez, 1998):

- Uses MS VISIO as the front end of the simulation system with which the user interacts and constructs an Activity Cycle Diagram of the construction operations being modeled

- Uses STROBOSCOPE Simulation Software as the simulation engine where the actual simulation is performed and results are generated
- Allows the use of variables to parameterize the modeled construction operation
- Allows the use of standard and customized results to be generated.

EZSTROBE follows the basic modeling elements developed by Halpin for CYCLONE and discussed in detail in Chapter one, section 1.5.3.1. It uses normal, combi, and queue nodes for developing Activity Cycle Diagrams.

## 5.7 STEPS IN SIMULATION MODELING

The following steps are generally used in developing simulation models (Paulson, 1995, Sawhney and AbouRizk, 1993).

1. Define Problem
2. Develop logic network
3. Determine or estimate:
    - Operations time durations
    - Production quantities
    - Cost information
4. Transfer logic network to computer simulation program
5. Run model
6. Validate model
7. Use model for decision making

These steps will now be defined as each applies to this research. Some of these steps have already been accomplished in previous chapters and will not be reproduced.

### 5.7.1 Define Problem

"In the problem definition stage the goals of the simulation experiment and the boundaries of the problem are defined" (Sawhney and AbouRizk, 1993). The problem in this research is to show how the production process of manufactured housing can be improved. A process model has been developed based on the layout of two different factories. From that model, 3-4 stations will be transformed into a computer simulation model. The computer simulation model is the focus of this chapter.

### 5.7.2 Develop Logic Network

In this stage, the complete description of the construction operation which has to be modeled is developed (Sawhney and AbouRizk, 1993). Logic network is the same as activity cycle diagram or the process model. As detailed in Chapter four, developing the process model included steps such as the process mapping, use of process flow diagram techniques like block diagrams and ANSI format. The process flow diagrams were further developed during the data collection stage when the understanding of the activity relationship was greatly improved. This finally led to the production process and material flow model shown in Figures 4.11 and 4.12.

### 5.7.3 Determine or Estimate Operations Time Durations

In this phase, the input data required for the simulation experiment is collected (Sawhney and AbouRizk, 1993). Depending on a particular goal of a project, this stage could involve: Operations time durations, production quantities, and cost information depending on what the problem is. In this research, operations durations were the main data collected. Actually, this stage translates into the data collection stage. Data collection is fully detailed in section 4.2.

### 5.7.4 Transfer Logic Network into Computer Simulation Program

In this stage, the preliminary model is converted into a form that can be easily understood by the computer (Sawhney and AbouRizk, 1993). This step is the main purpose of this chapter. To transfer the Activity Cycle Diagram into a simulation model, we need more than notations used for building process flow diagrams. At this point, instead of using block diagram notations or the ANSI format, the basic modeling elements from Figure 1.2 will be utilized. The use of Normals, Queues, and Combis is what transforms our logic network into a simulation model. Figure 5.2 shows the simulation model transformed from the production process model. The simulation model came about as such: one of the goals of this project is to develop a simulation model for the manufactured housing process. An extensive process model (logic network) was developed with the assistance of the University of Cincinnati team and the team from Michigan State University. These process models are shown in Figures 4.11 and 4.12. Time durations were collected over a period. A part of that process model is now being transformed into a simulation model as one of the authors major contribution to the research. In addition, "what if " scenarios for possible process improvements to the system will be presented in this Chapter.

At this point, the reader will be reminded that only four consecutive stations were transformed into a simulation model. The process being simulated starts from where the wall frames are installed to the station were axles and tires are installed. Before the model is explained in detail, Table 5.1 is presented to show alphabetically all the queues and activity notations used in the model. The model is then presented in Figure 5.2. A detailed explanation of the model follows.

Table 5.1 – Notations for Simulation Model

| ACTIVITY NOTATIONS | EXPLANATIONS |
|---|---|
| CoverRDWPaper | Cover Roof Deck With Paper |
| GetCarpet | Get Carpet |
| InstallCarpet | Install Carpet |
| InstallDW | Install Doors & Windows |
| InstallExtBoard | Install Exterior Boards |
| InstallShingles | Install Shingles |
| InstallSiding | Install Siding |
| InstallTires | Install Tires |
| InstallUreFoam | Install Urethane Foam |
| InsulateRoof | Insulate Roof |
| Molding | Install Molding for Interior Doors & Windows |
| RoofDecking | Build Deck on top of Roof Trusses |
| SectionControll | Dummy Activity to Control Process |
| SetTruss | Roof Truss Structure placed on Framed House |

Table 5.1 – Cont'd

| QUEUE NOTATIONS | EXPLANATIONS |
|---|---|
| CarpetReady | Carpet Ready for Installation |
| CompletedHouse | House production complete |
| Control | Dummy queue to control model |
| DoorFeeder | Material - Door Feeder |
| ExteriorBoardsFeeder | Material - Exterior Boards Feeder |
| ExteriorBoardsInstal | Install Exterior Boards |
| FramedHouse | Framed House |
| HousecoveredWSi | House Covered With Siding |
| InsulatedRoof | Insulated Roof |
| InsulationMater | Insulation Material |
| LaborDWWt | Labor for Door & Window Installation |
| LaborExtBoardWt | Labor for Exterior Boards |
| LaborInsulatWt | Labor for Roof Insulation |
| LaborMoldingWt | Labor for Interior Door & Window Molding |
| LaborRDWt | Labor for Roof Decking |
| LaborRPWt | Labor for Roof Paper |
| LaborShinglesWt | Labor for Shingles Installation |
| LaborSidingWt | Labor Siding |
| LaborTiresWt | Labor for Tire Installation |
| LaborUFWt | Labor for Urethane Foam |
| Molds | Material - Interior Doors & Window Mold |
| RoofBoards | Material - Roof Boards |
| RoofDecked | Roof Decking Completed |
| RoofFeeder | Activity Feeder Station for Building Roof |
| RoofPaper | Material - Roof Paper |
| RoofRForShingles | Roof Ready for Shingles |
| RoofReady | Work on Roof Completed |
| RoolsofFoam | Material Urethane Foam |
| SettersWt | Labor Roof Setters |
| ShinglesFeeder | Material Feeder - Shingles |
| SidingReady | Finished Installing Siding |
| Tires | Material - Tires |
| TiresReady | Tires Ready to be Installed |
| SideShingle | Material For Siding |
| SidingInstalled | Siding Installed |
| WindowFeeder | Material Feeder - Windows |

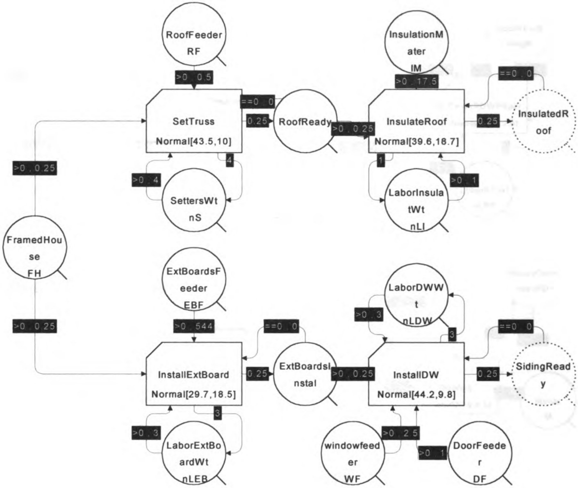


Figure 5.2 – Simulation Model of a Section of Manufactured Housing Production

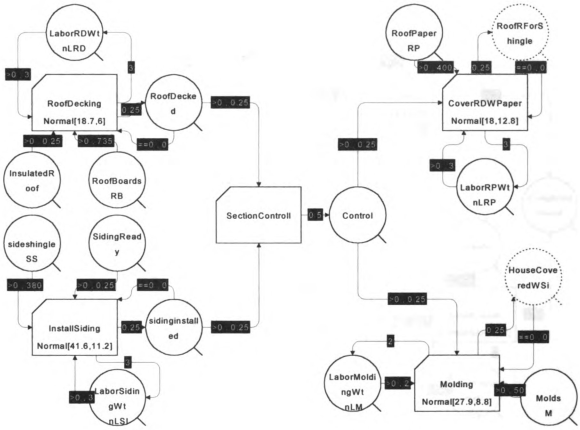


Figure 5.2 cont'd

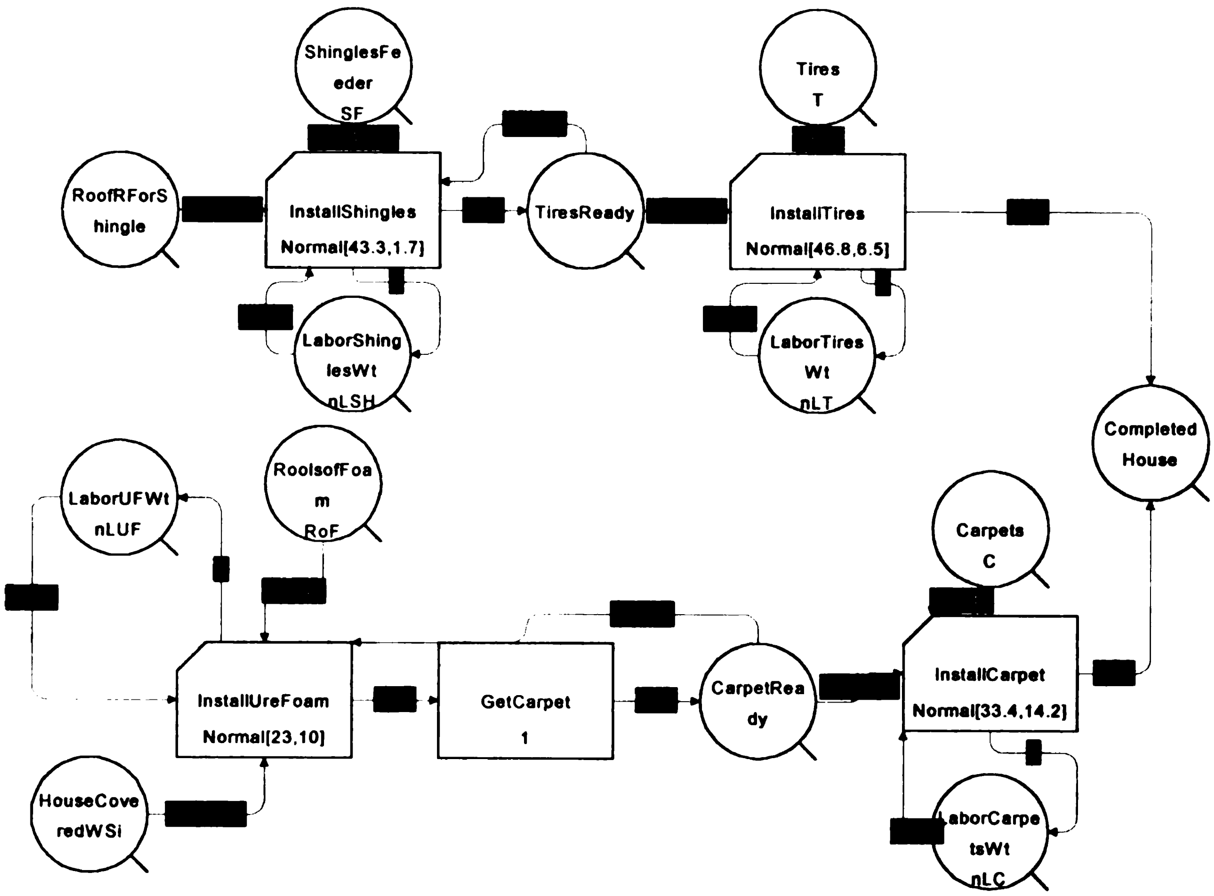


Figure 5.2 cont'd

The process goes as follows: there are two paths shown in the model. Activities on both paths are being performed on each section that passes through. The top path will first be explained followed by the bottom path.

TOP Path: a framed house enters the first station applicable; the crew starts setting the truss from the feeder station as shown in the first combi. The activity time duration has a normal duration of 87 minutes with standard deviation of 30.9 minutes. The activity needs resources from two queues to start. These are the setters and the roof from the feeder station. The activity that follows the roof setting is roof insulation. This activity takes place with one worker on top of the trusses and spraying insulation on the roof using a hose. This activity is supported by two queues, one representing the worker spraying the insulation and the other representing the insulation material. After insulation, the roof decking activity follows. Roof decking consists of laying the sheets of roof boards on top of the roof structure. The roof decking combi shows three queues feeding into it. One is for the labor, the second one is for the roof boards and the last queue represents the fusion queue from the previous page. The acitivity that follows roof decking is to cover the roof with paper. This is done for drainage purpose and to prevent freezing. Again, the activity needs labor and material. Installing shingles is the last roofing activity. From there, the tires are attached and the house is ready for interior finishes.

BOTTOM PATH: the first activity on the bottom path is the installation of exterior boards. "InstallExtBoards" represents the material feeder needed for this activity and the other queue is for labor. Installation of doors and windows follows. This activity has two separate material feeder queues one for doors the other for windows. The top queue represents labor. After the doors and windows are installed, siding is placed on the walls. After this activity, interior finishing activities are represented on the bottom path such as molding the interior doors and windows, installing the padding for the carpet represented on the model as Urethane Foam. After the carpet in laid, the boundary of the model of this research stop there.

There is a dummy combi and queue called "SectionControl" and "Control" respectively on the model. These are not activities happening on the factory floor but they were inserted on the model to serve a very important purpose. The activities on the lower half of the model, progress faster than those on the upper half. This is caused by the large duration of the roof setting activity. Install exterior boards, doors and windows, and siding crews sometimes have to wait for the assembly line to move because of space restrictions on the factory floor, they can progress only so much. The dummy combi "SectionControl" forces the lower activities to stop and wait for the upper ones since they are working on the same section. "SectionControl" needs 0.25 of a resource from both the top and bottom paths for the process to continue which in reality is the same 0.25. When the process is running and the lower path reaches "SectionControl", the 0.25 resource delivered is kept until the top portion releases the same 0.25 resource before 0.5 is released to the queue "Control". Unless both 0.25 are in the combi, the section will not be released.

Referring back to the model, quarter (0.25) of a house is removed from queue "framed house" each way which is received by the activity "SetTruss" and "InstallExtBoard". The activities on the top and bottom of the sheet are actually being performed on the section simultaneously. The quarter (0.25) of a framed house resource represents a section being sent down the line. Since quarter (0.25) plus quarter (0.25) represents half a house or one section, the model is releasing one section at a time down the production line by saying if the content of the queue is greater than zero, pull a quarter (>0, 0.25). The process continues as such down the line. The combis show the statistical distribution of the data in the form of Normal [87, 30.9] as in the case of "Set Truss" combi. This shows a normal distribution with mean 87 minutes and standard deviation of 30.9 minutes. The factory floor is limited in space. The notation (==0,0) is a constrain, which says, if the content of the successor queue is not equal to zero, then do not start the predecessor activity (combi). This is to ensure that the model does not show the houses stacked on top of each other because that is not what happens in the factory. The dotted queues are EZSTROBE's way of fusing two pages and facilitating continuity of one model.

### 5.7.5 Run the Model

Running the model is the process of getting results. This also serves as debugging and testing to find out if it behaves as expected. Tabular and graphical reports are checked to make sure the results conform to what was observed on the field.

Simulation models in EZSTROBE can be parameterized to give results in many formats. One is cost and another is resource utilization. For the purposes of this research, resource utilization will be analyzed with focus on labor resources. The labor parameterization is shown on Table 5.2. All the material and labor queues are parameterized for more efficient trial and error runs. Table 5.2 and 5.3 show a list of parameterized name and value of labor and material queues. The value on material is from the estimates of how much material it will take to build 624 houses based on the company's materials listing. The result drawing element is used to tabulate formulas for all the queues under investigation. The mathematical formula used to calculate utilization is:

Utilization = 1 – (QueueWait.AveCount) / number of resources.

The formulas for all the labor resources are tabulated in Table 5.4.

Table 5.2 – Labor Input Parameters

| Name | Description | Value |
|---|---|---|
| nS | Labor Setters | 4 |
| nLEB | Labor Exterior Boards | 3 |
| nLDW | Labor Doors & Windows | 3 |
| nLI | Labor Insulation | 1 |
| nLRD | Labor Roof Decking | 3 |
| nLSI | Labor Siding | 3 |
| nLRP | Labor Roof Paper | 3 |
| nLM | Labor Molding | 2 |
| nLSH | Labor Shingles | 3 |
| nLUF | Labor Urethane Foam | 1 |
| nLT | Labor Tires | 2 |
| nLC | Labor Carpet | 3 |

**Table 5.3 – Material Input Parameters**

| Name | Description | Value |
|---|---|---|
| FH | Framed House | 624 |
| RF | Roof Feeder | 624 |
| EBF | Exterior Boards Feeder | 678912 |
| IM | Insulation Material | 21840 |
| WF | Window Feeder quantity | 3120 |
| DF | Door Feeder | 1248 |
| RB | Roof Boards | 917280 |
| SS | Siding shingles | 474240 |
| RP | Roof Paper | 499200 |
| M | Molds | 62400 |
| SF | Shingles Feeder | 870480 |
| RoF | Rools of Foam | 61152 |
| T | Tires | 3744 |
| C | Carpets | 61152 |

**Table 5.4 – Result Formulas**

| | | |
|---|---|---|
| SettersUt | Setters Utilization - Roofing | 1-(SettersWt.AveCount)/nS |
| LabExtBoardsUt | Labor Utilization - Exterior Boards | 1-(LaborExtBoardWt.AveCount)/nLEB |
| LaborDWUt | Labor Utilization - Doors & Windows | 1-(LaborDWWt.AveCount)/nLDW |
| LaborInsulationUt | Labor Utilization - Insulation | 1-(LaborInsulatWt.AveCount)/nLI |
| LaborRDUt | Labor Utilization - Roof Decking | 1-(LaborRDWt.AveCount)/nLRD |
| LaborSidingUt | Labor Utilization - Siding | 1-(LaborSidingWt.AveCount)/nLSI |
| LaborRPUt | Labor Utilization - Roof Paper | 1-(LaborRPWt.AveCount)/nLRP |
| LaborMoldingUt | Labor Utilization - Molding | 1-(LaborMoldingWt.AveCount)/nLM |
| LaborShinglesUt | Labor Utilization - Shingles | 1-(LaborShinglesWt.AveCount)/nLSH |
| LaborUrethaneFoam | Labor Utilization - Urethane Foam | 1-(LaborUFWt.AveCount)/nLUF |
| LaborTiresUt | Labor Utilization - Tires | 1-(LaborTiresWt.AveCount)/nLT |
| LaborCarpetUt | Labor Utilization - Carpets | 1-(LaborCarpetsWt.AveCount)/nLC |

With the above formulas entered into the model, it can now be run to find out the labor utilization. Table 5.5 shows definitions of queues measured attributes. Table 5.6 shows definitions of activities measured attributes.

Table 5.5 - Definitions of Queue Attributes

| | |
|---|---|
| Cur | Content at the Time of the Report |
| Tot | Total Amount of Resource to Ever Enter |
| AvWait | Average Waiting Time |
| AvCont | Time-Weighted Average Content |
| SDCont | Time-Weighted Standard Deviation of Content |
| MinCont | Minimum Content |
| MaxCont | Maximum Content |

Table 5.6 - Definitions of Activity Attributes

| | |
|---|---|
| Cur | Current # of Times the Activity is Being Performed at Time of Report |
| Tot | Total Number of Times it has Started |
| 1stSt | Time at which the first instance started |
| LstSt | Time at which the last instance started |
| AvDur | Average Duration |
| SDDur | Standard Deviation of Duration |
| MinD | Minimum Duration |
| MaxD | Maximum Duration |
| AvInt | Average Time Between Successive Starts |
| SDInt | Standard Deviation of Time Between Successive Starts |
| MinI | Minimum Time Between Successive Starts |
| MaxI | Maximum Time Between Successive Starts |

Table 5.7 – Labor Utilization

| | |
|---|---|
| Setters Utilization - Roofing: | 0.9808 |
| Labor Utilization - Exterior Boards: | 0.3462 |
| Labor Utilization - Doors & Windows: | 0.5035 |
| Labor Utilization - Insulation: | 0.4503 |
| Labor Utilization - Roof Decking: | 0.2130 |
| Labor Utilization - Siding: | 0.4689 |
| Labor Utilization - Roof Paper: | 0.1997 |
| Labor Utilization - Molding: | 0.3195 |
| Labor Utilization - Shingles: | 0.4919 |
| Labor Utilization - Urethane Foam: | 0.2609 |
| Labor Utilization - Tires: | 0.5299 |
| Labor Utilization - Carpets: | 0.3801 |

The Future Events List is empty at simulation time = 109989

Total Number of Named Objects: 159
Total Number of Variables: 249
Total Number of Statements: 43

Table 5.7 to 5.9 shows the results of running the model with 624 houses, which is assumed to be roughly a years worth of production. Table 5.8 shows the content of each queue after the simulation run on the first column. The amount to resources passing through each queue during the entire process is depicted in the second column. Average waiting time of each queue is the third column followed by the time weighted average content, standard deviation, minimum, and maximum content of queues during the operation. The activity results Table is a detail report of durations after the operation is done. Average duration of activity is shown as well as the average interval of successive starts. Also shown is the first and last time each activity was initiated.

Table 5.8 – Queues Statistical Report

| Queue | Cur | Tot | AvWait | AvCont | SDCont | MinCont | MaxCont |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| CarpetReady | 0 | 312 | 1.13 | 0 | 0.03 | 0 | 0.25 |
| Carpets | 0 | 61152 | 55458 | 30578 | 17629 | 0 | 61152 |
| CompletedHouse | 624 | 624 | 55458 | 311.73 | 179.89 | 0 | 624 |
| Control | 0 | 624 | 55406 | 0 | 0.01 | 0 | 0.5 |
| DoorFeeder | 0 | 1248 | 0.08 | 621.45 | 359.78 | 0 | 1248 |
| ExtBoardsFeeder | 0 | 678912 | 55228 | 337526 | 195716 | 0 | 678912 |
| ExtBoardsInstal | 0 | 312 | 55139 | 0.16 | 0.12 | 0 | 0.25 |
| FramedHouse | 0 | 624 | 57.67 | 310.55 | 179.89 | 0 | 624 |
| HouseCoveredWSi | 0 | 312 | 0.15 | 0 | 0.01 | 0 | 0.25 |
| InsulatedRoof | 0 | 312 | 0.18 | 0 | 0.01 | 0 | 0.25 |
| InsulationMater | 0 | 21840 | 55344 | 10898 | 6296.1 | 0 | 21840 |
| LaborCarpetsWt | 3 | 3747 | 55.44 | 1.87 | 1.45 | 0 | 3 |
| LaborDWWt | 3 | 3747 | 45.27 | 1.53 | 1.5 | 0 | 3 |
| LaborExtBoardWt | 3 | 3747 | 57.83 | 1.95 | 1.43 | 0 | 3 |
| LaborInsulatWt | 1 | 1249 | 49.25 | 0.55 | 0.5 | 0 | 1 |
| LaborMoldingWt | 2 | 2498 | 60.61 | 1.37 | 0.93 | 0 | 2 |
| LaborRDWt | 3 | 3747 | 70.12 | 2.37 | 1.22 | 0 | 3 |
| LaborRPWt | 3 | 3747 | 70.53 | 2.38 | 1.21 | 0 | 3 |
| LaborShinglesWt | 3 | 3747 | 45.52 | 1.54 | 1.5 | 0 | 3 |
| LaborSidingWt | 3 | 3747 | 47.02 | 1.59 | 1.5 | 0 | 3 |
| LaborTiresWt | 2 | 2498 | 42.03 | 0.95 | 1 | 0 | 2 |
| LaborUFWt | 1 | 1249 | 65.7 | 0.74 | 0.44 | 0 | 1 |
| Molds | 0 | 62400 | 55404 | 31172 | 17989 | 0 | 62400 |
| RoofBoards | 0 | 91728 | 55384 | 458052 | 264440 | 0 | 917280 |
| RoofDecked | 0 | 312 | 1.81 | 0.01 | 0.04 | 0 | 0.25 |
| RoofFeeder | 0 | 624 | 55255 | 310.88 | 179.89 | 0 | 624 |
| RoofPaper | 0 | 499200 | 55404 | 249373 | 143912 | 0 | 499200 |
| RoofRForShingle | 0 | 312 | 1.38 | 0 | 0.03 | 0 | 0.25 |
| RoofReady | 0 | 312 | 1.45 | 0 | 0.03 | 0 | 0.25 |
| RoolsofFoam | 0 | 61152 | 55433 | 30564 | 17629 | 0 | 61152 |
| SettersWt | 4 | 4996 | 1.6 | 0.07 | 0.53 | 0 | 4 |
| ShinglesFeeder | 0 | 870480 | 55424 | 434998 | 250953 | 0 | 870480 |
| SidingReady | 0 | 312 | 44.65 | 0.13 | 0.12 | 0 | 0.25 |
| Tires | 0 | 3744 | 55468 | 1872.4 | 1079.4 | 0 | 3744 |
| TiresReady | 0 | 312 | 0.67 | 0 | 0.02 | 0 | 0.25 |
| SideShingles | 0 | 474240 | 55316 | 236528 | 136715 | 0 | 474240 |
| SidingInstalled | 0 | 312 | 46.04 | 0.13 | 0.12 | 0 | 0.25 |
| WindowFeeder | 0 | 3120 | 55228 | 1553.6 | 899.44 | 0 | 3120 |

Table 5.9 - Activities Statistical Report

| Activity | Cur | Tot | 1stSt | LstSt | AvDur | SDDur | MinD | MaxD | AvInt | SDInt | MinI | MaxI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CoverRDWPape | 0 | 1248 | 151.84 | 111163.11 | 18.28 | 12.14 | 0.00 | 58.99 | 89.02 | 35.36 | 21.75 | 218.00 |
| GetCarpet | 0 | 1248 | 211.48 | 111212.57 | 1.00 | 0.00 | 1.00 | 1.00 | 89.01 | 39.56 | 5.80 | 243.74 |
| InstallCarpet | 0 | 1248 | 212.48 | 111213.57 | 33.35 | 14.18 | 0.00 | 74.73 | 89.01 | 39.56 | 5.80 | 243.74 |
| InstallDW | 0 | 1248 | 26.49 | 110980.31 | 44.16 | 9.86 | 11.72 | 76.97 | 88.98 | 33.41 | 33.79 | 218.00 |
| InstallExtBoard | 0 | 1248 | 0.00 | 110807.42 | 30.63 | 17.91 | 0.00 | 93.45 | 88.86 | 33.38 | 26.49 | 218.00 |
| InstallShingles | 0 | 1248 | 173.99 | 111184.26 | 43.29 | 1.70 | 38.26 | 50.15 | 89.02 | 36.01 | 40.04 | 217.92 |
| InstallSiding | 0 | 1248 | 69.82 | 111027.26 | 41.33 | 11.51 | 7.23 | 85.30 | 88.98 | 33.90 | 33.51 | 218.00 |
| InstallTires | 0 | 1248 | 215.88 | 111226.61 | 46.29 | 6.54 | 20.76 | 68.73 | 89.02 | 35.11 | 38.26 | 220.20 |
| InstallUreFoam | 0 | 1248 | 174.78 | 111190.67 | 23.42 | 10.07 | 0.00 | 56.70 | 89.03 | 36.94 | 18.48 | 237.24 |
| InsulateRoof | 0 | 1248 | 108.47 | 111094.34 | 39.86 | 18.29 | 0.00 | 107.39 | 89.00 | 28.04 | 16.19 | 193.75 |
| Molding | 0 | 1248 | 151.84 | 111163.11 | 28.25 | 9.12 | 0.00 | 59.19 | 89.02 | 35.15 | 22.31 | 218.00 |
| RoofDecking | 0 | 1248 | 142.21 | 111137.64 | 18.54 | 5.90 | 0.59 | 35.90 | 89.01 | 37.02 | 12.89 | 215.69 |
| SectionControl | 0 | 1248 | 151.84 | 111163.11 | 0.00 | 0.00 | 0.00 | 0.00 | 89.02 | 35.42 | 21.75 | 218.00 |
| SetTruss | 0 | 1248 | 0.00 | 110975.74 | 30.35 | 0.00 | 0.00 | 193.75 | 88.99 | 28.04 | 16.19 | 193.75 |

### 5.7.6 Validate the Model

Validation of the model requires that the data that was collected and inputted, to give the same results as to what was observed on the factory. It is a process of comparing model results with reality. In this research, since the statues quo from the factory is modeled, validation is done strictly by comparison. At the time of recording time data from the first factory, the production rate of the factory as stated by management was 2.5 houses (5 sections) a day. This was also observed while collecting data at the factory. When the model was run with the eleven points (5.5 houses) collected from the factory, it showed a production rate of 4.9 sections a day. This production rate was improved to 5.4 sections a day when the model was run with 624 houses. Six hundred and twenty-four (624) is an assumed number of houses the factory can produce based on the production rate of 2.5 houses a day, under ideal conditions. Six hundred and twenty-four (624) is the product of 2.5 houses a day by 5 days a week by 50 weeks a year (2.5 * 5 * 50). The exact result is 625 but for practical purposes, an even number was needed so 624 is used. The fact that the observed production rate (5 sections a day) is close to the simulated production rate (4.9 sections a day) validates the model.

## 5.8 USE MODEL FOR DECISION MAKING / IMPROVEMENTS / WHAT IF SCENARIOS

In this sub-section, five possible scenarios will be introduced based on how they can improve production. Of these five, two will be inputted into the model and the results analyzed. All five scenarios were shown to industry representatives for their input and possible pitfalls. The scenarios are, what if:

1. Roof setting activity durations was significantly reduced.
2. Insulate roof activity was moved to the feeder station.
3. Two separate production lines running in parallel with one set of feeder station serving both lines were laid on the same factory floor.
4. A quality control team was established to do repairs during finishing stages.
5. One crane could be used for movement of wall sections and roof structures from feeder stations to main production line.

### 5.8.1 SCENARIO ONE

Table 5.7 shows low utilization of all the labor except the setters. This is consistent with what was observed on the factory floor. The roof setting activity takes so long that the other activities were always severely delayed. The future event list empty at simulation time 109989, means that it took 109989 minutes to finish the operation. The calculation for the production rate is shown below.

624 houses $\longrightarrow$ 109989 minutes = 1833.15 hrs

Production Rate = (624 house / 1833.15 hrs) = 2.72 houses per day

2.72 houses per day approximates to 5.45 sections a day. The observed production rate at the factory was 5.5 sections a day.

Referring back to the issue of low labor utilization, the benefits of simulation can now be shown because what if scenarios can be use to find a way to remedy the situation. For example, how will reducing the duration for the roof setting activity by half, affect the production? This can be done by changing the quality of roof setters by hiring more experience workers or by increasing the crew size. Input time reduction by half into the model shows different numbers on labor utilization as shown in Table 5.10.

Table 5.10 – Labor Utilization with Reduced Duration on Roof Setting Activity

| | |
|---|---|
| Setters Utilization - Roofing | 0.82801 |
| Labor Utilization - Exterior Boards | 0.59054 |
| Labor Utilization - Doors & Windows | 0.84240 |
| Labor Utilization – Insulation | 0.74489 |
| Labor Utilization - Roof Decking | 0.35723 |
| Labor Utilization – Siding | 0.78782 |
| Labor Utilization - Roof Paper | 0.35519 |
| Labor Utilization – Molding | 0.53800 |
| Labor Utilization – Shingles | 0.82771 |
| Labor Utilization - Urethane Foam | 0.43692 |
| Labor Utilization – Tires | 0.89867 |
| Labor Utilization – Carpets | 0.63806 |

Statistics report at simulation time = 65274.6

The labor utilization for the setters decreased by sixteen percentage points but that of all the other labor crews increased. The labor utilization for tires increased by thirty-seven percent (37%). More importantly, the average time between successive starts decreased from eighty-eight (88) minutes to fifty-one (51) minutes. The total operation time dropped to 65274.6 minutes. What is now the production rate with these new numbers?

624 houses $\longrightarrow$ 65274.6 minutes = 1087.91 hrs

Production Rate = (624 houses / 1087.91 hrs) = 4.59 houses per day

There is a forty percent (40%) increase in production just by solving the delay problem with the setters.

#### 5.8.1.1 Sensitivity Analysis

In this section, a sensitivity analysis will be performed to study what effect further reduction of roof setting activity duration has on both labor utilization of the activity and overall production. Figures 5.3 and 5.4 show the results of the analysis.

Table 5.11 – Sensitivity Analysis Data

| Duration(Minutes) | Utilization(%) | Production Rate |
|---|---|---|
| 10 | 34.32 | 4.59 |
| 20 | 47.1 | 4.51 |
| 30 | 59.61 | 4.44 |
| 40 | 73.53 | 4.26 |
| 50 | 83.96 | 3.97 |
| 60 | 88.91 | 3.6 |
| 70 | 94.95 | 3.21 |
| 80 | 96.57 | 2.93 |
| 87 | 98.08 | 2.72 |
| 90 | 98.63 | 2.59 |
| 100 | 99.31 | 2.35 |
| 110 | 99.6 | 2.17 |
| 120 | 99.65 | 2.02 |
| 130 | 99.79 | 1.84 |
| 140 | 99.87 | 1.71 |

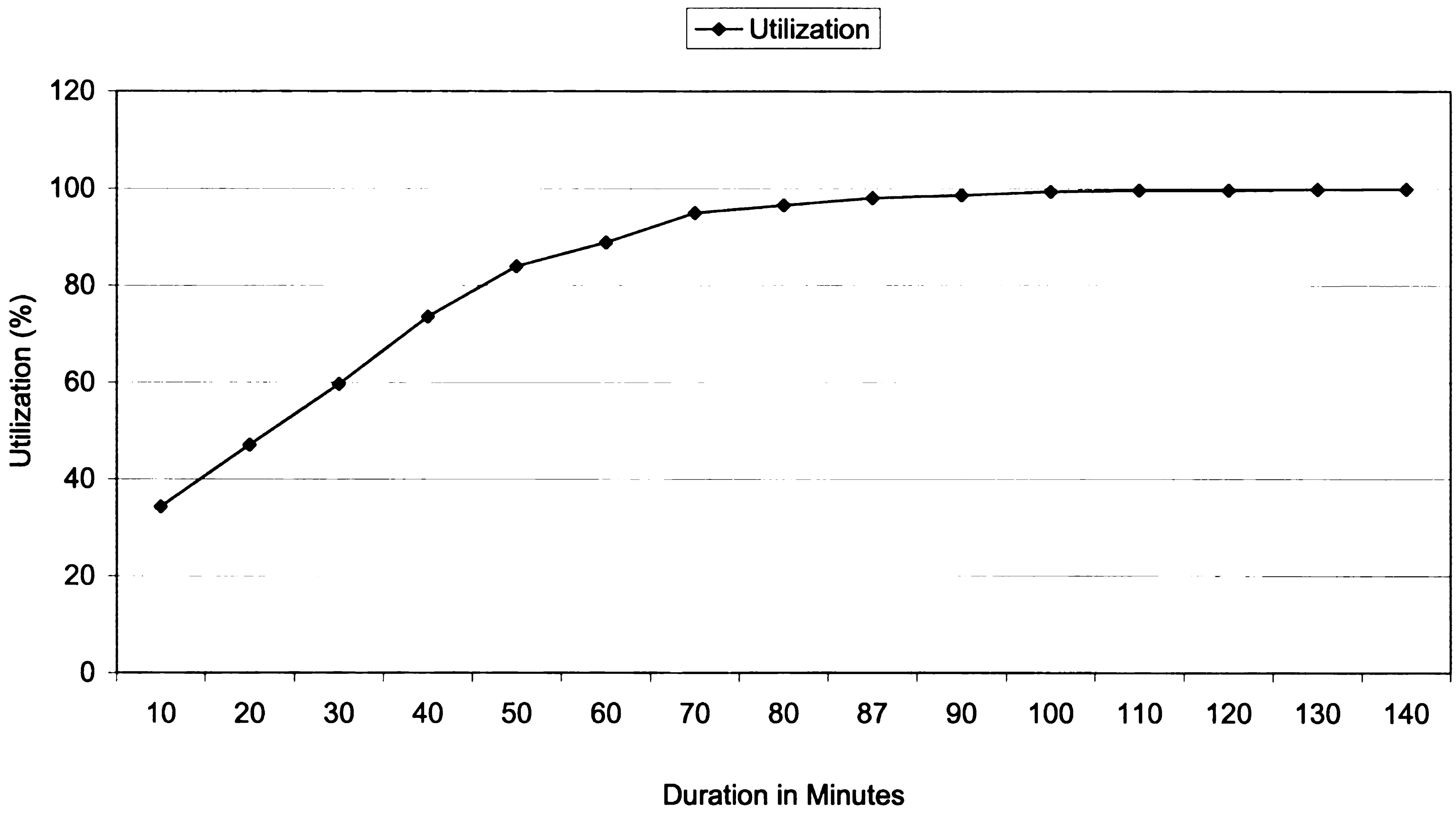


Figure 5.3 Sensitivity Analysis - Duration vs Utilization

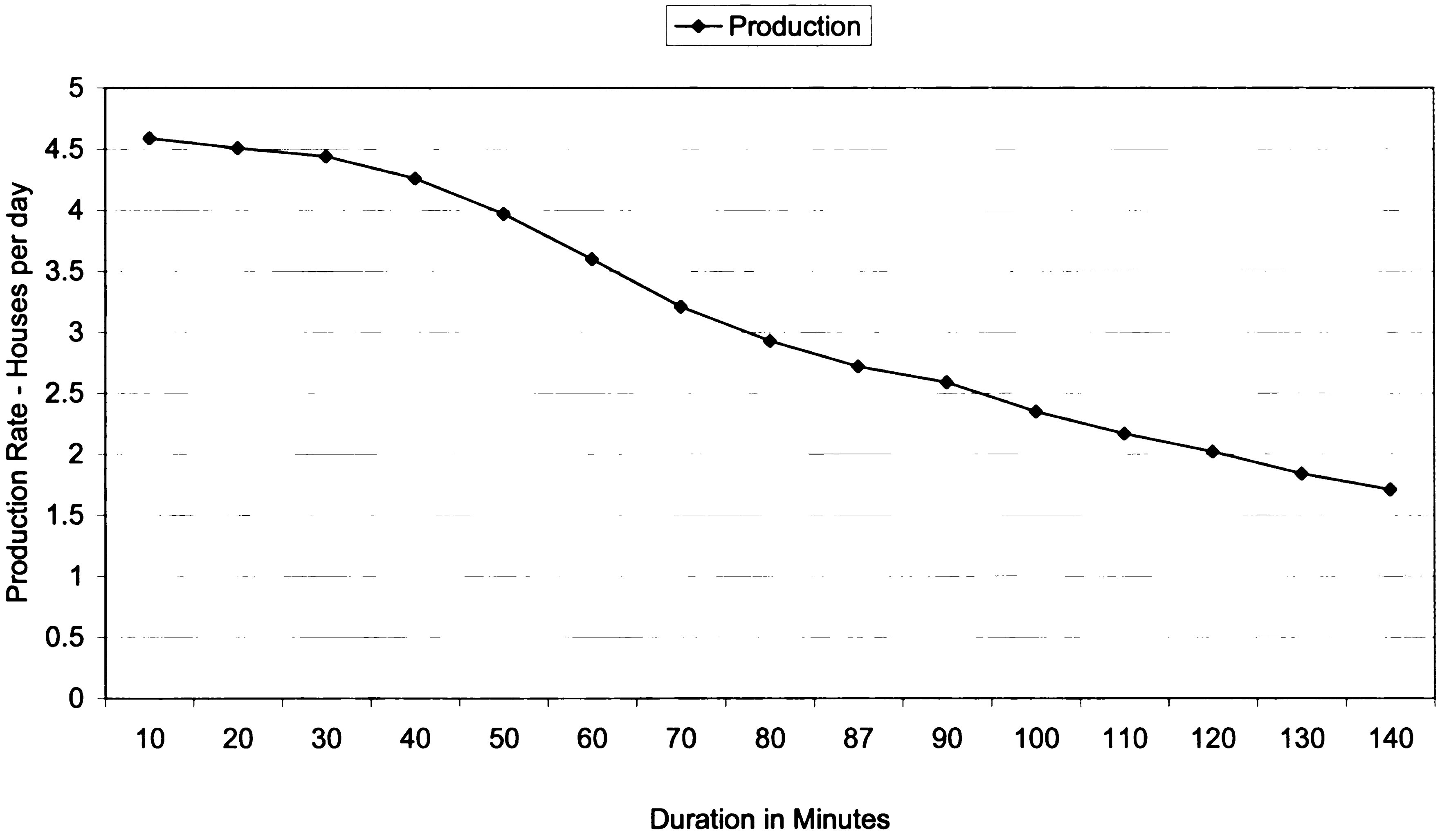


Figure 5.4 - Sensitivity Analysis - Duration vs Production

Figure 5.3 shows that as the activity duration increases, the utilization also increases, but the rate of increases becomes smaller as shown in the graph turning into a horizontal line. The production rate on Figure 5.4 keeps decreasing as the activity duration increases.

PITFALLS FROM INDUSTRY

There is no pitfall with this scenario according to the industry personnel. This is no longer a problem in the specific plant that it arose from according to the production manager. That claim though cannot be justified by the author for two reasons. The first is, the scope and timing of the research did not allow for another time study to justify the claim. The second reason is the whole plant has gone through tremendous overhaul in terms of its production rate and labor force since the initial data was collected. They currently have half as many people in the plant and produce sixty-percent fewer houses because of economic downturn.

### 5.8.2 SCENARIO TWO

The model on Figure 5.2 shows the activity roof insulation right after roof setting. Insulating the roof on the main assembly line is actually practice in only one of the factories. After the roof structure has been assembled on the feeder station, it is moved to an adjacent station on the feeder station and the ceiling boards painted. While it is being painted, roof insulation could be an activity happening simultaneously. This may require some quality control in order to avoid the paint mixing up with the insulation. The result of implementing these changes in the model gave a simulation time of 107361 minutes. The production rate is:

624 houses ⟶ 107361 minutes = 1789.35 hrs

Production rate = (624 houses / 1789.35 hrs) = 2.79 houses per day.

2.79 houses per day is a negligible improvement from the 2.72 houses per day with the insulation on the main line. This further emphasizes the point that the set truss activity is taking so long that it affects the entire top path. The author believes that for improvements to materialize anywhere on the top path, the duration for set truss activity has to improve. To show this, the insulate roof activity is moved to the feeder station with the roof set activity duration reduced by half and the model ran again. The simulation time is 64089.62 minutes. This translates into a production rate of 4.67 houses per day.

## PITFALLS FROM INDUSTRY

According to industry personnel, the above scenario would cause numerous problems. When the roof is being set, the setters need to know the location of the interior walls and mating walls looking from the top of the roof. This is so that they can screw the roof to the walls. If the roof were insulated before setting it, the setters would have a difficult time moving insulation out of the way to screw the roof to the walls. The same thing applies when the electrician is doing the ceiling wirings. Insulation again will have to be moved to get the wires on top of the ceiling panels. Another problem is that of cutting holes on the ceiling for skylights. The person doing the cutting will have the problem of insulation dropping from the ceiling on top of them.

### 5.8.3 SCENARIO THREE

Figure 1.1 shows a typical manufactured housing production assembly line. There are feeder stations on both sides of the line supporting the production process. What if two production lines running in parallel are laid out on a factory floor large enough and have all the feeder stations between the two lines serving both production lines. A schematic layout is shown in Figure 5.5. The way this system will work is that both lines will share all material and activity feeder stations. The advantage could be the savings from using one common feeder instead of two feeders for both production lines. This will require precise scheduling, and highly efficient activity and material feeder stations.

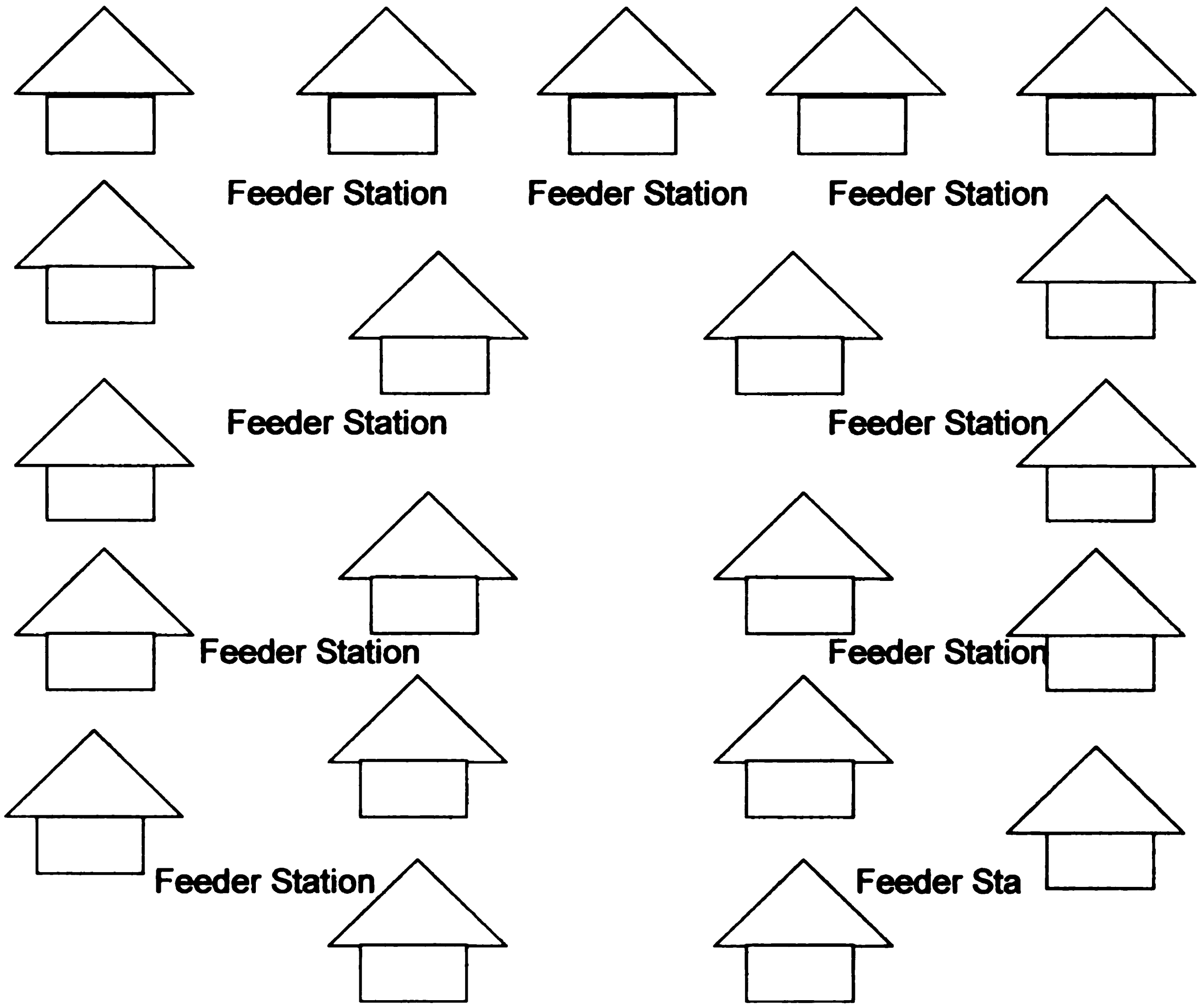


Figure 5.5 – Schematic Layout of Double Production Line Scenario

## PITFALLS FROM INDUSTRY

There were two kinds of pitfalls on this scenario raised by members of the industry during the conversations with them. The first has to deal with the actual laying out of the building itself. The building obviously has to be large enough which means the upfront building cost will be relatively large. Then one has to decide what kind of capacity is needed. The normal practice in the industry is that when more capacity is needed, a new plant is simply built on the side to accommodate that extra demand. It is easier to shut down a plant when the demand gets lower than trying to curb production in a massively large plant. Another issue is that the activity feeder stations have to be larger than the normal space required for two plants if they are to serve two lines simultaneously according to the industry personnel. For example, if a plant's roof feeder station has three substations each 20 * 80 feet, a plant with parallel production lines may need eight instead of six substations. Other kinds of issues raised deal with the process such as the moving of materials between lines during production, since the material feeder stations will be in between the two lines. This could be solved by moving all materials for a days production before or after work hours. Another process pitfall raised was the larger amount of space the outside line enjoys over the inside line. Surge stations may have to be utilized to solve this problem. The surge stations may also serve another purpose of feeding materials to the feeder stations.

### 5.8.4 SCENARIO FOUR

The fourth "what if" scenario is to implement a quality control team towards the end of the production line. Their primarily task is to do repairs. This team will consists of a dry wall person, a painter, a carpenter, electrician, plumber, and any other skilled trade applicable. Their job will be to strictly do repairs to failed inspections and damages sustained on the production line. It was observed in both factories that it takes considerable amount of time to get the skilled trades from their respective stations to the finishing stations to do repairs when needed. For example, when there is a problem with a drywall section that needs to be replaced, the drywall person(s) do not want to leave their stations for fear of causing delays on the line. It is even harder when the problem was not their fault initially. The quality control crew should be able to eliminate this problem.

## PITFALLS FROM INDUSTRY

Members in the industry suggested that this will cause sluggishness. If the skilled trades who are doing the job initially know that a repair crew is available, they will not do the job right in the first place. This was a unanimous concern among all the people I talked to. Another issue that came up is that of the labor cost. The industry usually on keeping the labor cost around twelve percent (12%) of the dollar value of the produced houses. Adding more labor may make it hard to keep the cost at the desired level. A third pitfall has something to do with the way workers are compensated. If compensation depends on the number of houses or sections built per day, a quality control team will cause the hasty processing of units in order to make the maximum amount of money in a short period. Finally, most of these pitfalls can be addressed with good management skills. If a production manger has good enough skills to make everybody do their job right and not have to depend on someone else to cover their mistakes, then the issue of quality control is a brilliant idea according to some industry members. Others countered that those management skills could be use to avoid mistakes in the first place and totally avoid the issue of quality control.

### 5.8.5 SCENARIO FIVE

A fifth scenario that could possibly save a plant large amount of money is that of consolidating cranes/hoists. There are usually two pairs of cranes on a factory floor. One is for moving walls from feeder stations to the main production line and the other for moving roofs. The cranes run on tracks anchored to the plant ceiling and their movements are usually not very flexible. These cranes spend a large amount of time waiting to move structures to the main line. The scenario proposed here is to make the tracks flexible enough that one crane or one pair can be used for both the walls and roof stations. This will reduce wait time for the cranes and initial cost of setting up a plant.

PITFALLS FROM INDUSTRY

Pitfall number one is the cost of making the tracks flexible may offset the savings on the cranes. Although no hard numbers are available, one-industry personnel does not like the idea because the initial cost benefit analysis does not favor fewer cranes. In terms of production, the issue of scheduling the production so that the wall and roof station does not need the crane at the same time is another pitfall from the industry. If this is not accomplished, the initial idea of reducing wait time is invalid. A third pitfall is the speed of the cranes. The cranes can pick up heavy material but they are very slow. The movement of the cranes over long distances may slow down production even with accompanied with a good scheduling system. This may be very costly if it causes the scheduled delivery of a house.

## 5.9 SUMMARY

This chapter dealt with the simulation part of this project. The chapter started with definition of simulation and the two different types of simulation. These are discrete-event simulation and continuous simulation. The use of simulation and its possible application to manufactured housing is discussed thoroughly. Construction simulation specifically is then introduced together with EZSTROBE. Then the steps to follow in transforming the process model from the previous Chapter to the simulation model are discussed. A detailed description of transferring the logic network developed in Chapter four was a major part of this section and consequently the Chapter. Finally, a section on what if scenarios closed the chapter. The what if scenario consists of five options which could possible increase production or save the plant money were discussed and with the help of people who work in the manufactured housing industry, the pitfalls of the options were presented.

# CHAPTER SIX

# SUMMARY AND CONCLUSIONS

## 6.1 OVERALL SUMMARY

This research presented a tool for improving the manufactured housing production process. The literature review Chapter was divided into three different subjects. Literature on manufactured housing in general was presented, followed by construction simulation literature and finally literature on both construction production planning and general business planning. In addition, an extensive list of industry terminology was presented in the literature review Chapter. In Chapter three a detailed description of the production process was presented. This was done to help the readers who are not familiar with the process of building houses in a factory. To further help those readers who are familiar with site-built housing, a comparison on codes, costs, foundations, and production environment was also presented in Chapter three.

A detailed study of the production process on the factory floor was carried out. The process was mapped out using concepts such as process mapping to obtain a process model. This process model was partially transformed into a computer simulation model. The simulation part of this project has shown how the production process can be improved. Applications of computer simulation to manufactured housing are presented and the "what if" scenarios presented a procedure for trying possible improvement ideas.

This thesis is part of a larger research project between two universities and many students have contributed both directly and indirectly to both the thesis and the larger project. The author's strict contributions to this thesis include but not limited to identifying major activities during the process mapping stage on several stations including those presented in the simulation model. Further contributions include collecting time data on major activities from the roofing stations to the start of the finishing stations. The process flow diagrams of Figure 4.8 to 4.10 were developed by the author. The production process and material flow model was developed by the author using all the process flow diagrams. The simulation model is also the work of the author with the help of Dr. Tariq Abdelhamid. Use of simulation as applied to the manufactured housing plant is the exclusive work of the author. The "what if" scenarios including the pitfalls from industry personnel, the interview process to gain those pitfalls, were also carried out by the author.

## 6.2 SUMMARY BY OBJECTIVES

In this section, each of the objectives presented earlier will be revisited. A summary of each one of them will be presented and how they were met.

### 6.2.1 To Develop a Production Process Flow Diagram for Multi-Section Manufactured Housing Production

The first step in this objective is the process-mapping phase. A factory is visited on the first day to gain the basic understanding of activity relationship among other things. Table 4.1 is an example of a data sheet used in this process. Data on feeder stations, activities, crew size, and number of stations are collected. Only major activities are identified. After this preliminary information is collected, ANSI flow charting concepts are used to represent the process observed on paper. The result is the process flow diagram of Figures 4.5a to 4.10.

### 6.2.2 To Develop a Production and Material Flow Process Model for Manufactured Housing

The data collection process continues with the time study phase. The objective in this phase is to measure activity durations of the major activities identified in the process-mapping phase. A stopwatch and wristwatch were used together with Table 4.2 to collect time data. After six months of data collection, the familiarity of the process grew greatly. With the help of the process flow diagrams developed earlier, the material listing of the housing modules, and the observed relationship of the activities and materials, a production and material flow model was developed as shown in Figure 4.11.

### 6.2.3 Transformation of Production and Material Flow Process Model into a Computer Simulation Model

Three to four stations were picked to be transformed into a simulation model. The stations start from the framed house to the beginning of the interior finishing stations. The reason for picking these stations is simply based on familiarity. The process modeling procedure discussed in Chapter one was utilized to develop a computer simulation model. The simulation software used for this project is EZSTROBE. The model was validated by comparing the observed production rate on the factory floor and the production rate obtained from running the simulation, which were comparable. The simulation showed bottlenecks in the production process. The bottlenecks were included in the "what if" scenarios section. These scenarios are possible ways of improving the production process. There were a total of five what if scenarios. Two of the scenarios were specific to the model and were inputted to find out the effect on the production process. Three of them were generic scenarios. All the scenarios were presented to personnel working in the manufactured housing industry including production managers and their input and pitfalls on the scenarios gathered. That section closed the scope of the project and provided a framework for the overall goal of showing how the production process and material flow of manufactured housing can be improved and streamlined.

## 6.3 CONCLUSIONS

After analyzing the production process in two different manufacturing plants, the author agrees with many other researchers that the manufactured housing industry is still primitive in terms of its equipment use and use of modern technology compared to other manufacturing industries. The manufacturing process is very labor intensive and the industry as a whole can benefit from use of more modern equipments such as faster cranes and a less labor intensive way of moving materials from feeder to main stations.

Based on the "what if" scenarios discussed in section 5.8, the author concludes that the manufactured housing industry can gain valuable insight by studying the process diligently. The scenarios presented in section 5.8 showed how using simulation, different options can be tested and studied for possible future implementation. The author feels that the manufactured housing industry should also adopt manufacturing technologies from other sectors. This can be achieved by studying and doing a systematic analysis of the production process in order to understand what systems will work well from other industries.

Finally, developing a production process model as was done in Chapter four should be taken to a further step of making the workers understand the process. Each worker should not only understand their responsibilities, but they should understand how their work affects the whole production process. This strategy will help alleviate errors.

## 6.4 RESEARCH LIMITATIONS

The first limitation to this research is the selection of major activities during the process-mapping phase. The major activities that were selected are not the only activities taking place in the stations. More importantly, they are not the only activities with durations taking place. Major activities are the ones that stand out the most and easily observable to the researchers. A different research team may select different major activities to represent the production process.

The second limitation deals with the changing nature of labor during the production process. When a crew is delayed, they may spread out to other stations and give assistance. This means an activity that started out with three laborers and end up with four by the time they are finished and consequently affecting the activity duration. During the simulation phase, this was not modeled because of limitations in the simulation software used. EZSTROBE cannot model changing labor force but its parent software STROBOSCOPE can model changing number of laborers.

The third limitation of this research is the variability in size of the houses observed during data collection and their effect on activity durations. The length of the houses can range from fifty to seventy-two feet long. In few activities such as siding, this difference in length was not adjusted for when considering the average and standard deviation of the activity durations.

It is the understanding of the researchers from the literature review and sampling methods that eleven data points provide sufficient data to construct a simulation model.

## 6.5 AREAS OF FUTURE RESEARCH

The first obvious point for further research is to transform the whole factory process into a simulation model. This will be more detailed and more rigorous, consequently more bottlenecks will show up.

Another area that deserves investigation is that of inputting cost into the simulation model. The cost of labor, material, and equipment can be parameterized in simulation. An investigation in this area can be very helpful to the industry especially in the area of cost benefit analysis.

The scope of this research during the simulation phase, assumed that labor was constant throughout the process and there is always enough material on the feeder stations available for use. This is obviously not what always happens on the factory floor. It has already been mentioned on the research limitations section that the number of laborers may change for any crew depending on the idleness of workers. Accounting for the changing amount of material will facilitate studying material utilization in addition to labor utilization.

Finally, another important area that can be looked at is the relationship between the skills and experience of workers and compared to the efficiency of the production process. It is of the author's opinion that the production process does not need highly skilled workers because the controlled environment makes supervision easier. This premise is worth investigating.

APPENDICES

## APPENDIX A

Roofing Station: 11 Data Points

| Chassis # | | Total | Activity Cycle Time | | | | |
|---|---|---|---|---|---|---|---|
| | | Cycle Time | Sub 1 | Sub 2 | Sub 3 | Sub 4 | Sub 5 |
| 1572B | Time | 232 | 106 | 21 | 22 | 24 | 44 |
| | No. of Labor | | 4 | 1 | 3 | 2 | 2 |
| 1566A | Time | 264 | 121 | 24 | 26 | 24 | 41 |
| | No. of Labor | | 4 | 1 | 3 | 3 | 2 |
| 1566B | Time | 268 | 115 | 26 | 25 | 18 | 43 |
| | No. of Labor | | 4 | 1 | 3 | 4 | 2 |
| 1567A | Time | 240 | 102 | 16 | 24 | 21 | 42 |
| | No. of Labor | | 3 | 1 | 3 | 3 | 2 |
| 1567B | Time | 279 | 123 | 36 | 23 | 31 | 45 |
| | No. of Labor | | 4 | 1 | 4 | 3 | 2 |
| | Time | 159 | 67 | 32 | 10 | 9 | 41 |
| | No. of Labor | | 3 | 1 | 3 | 3 | 2 |
| | Time | 193 | 51 | 66 | 21 | 12 | 43 |
| | No. of Labor | | 3 | 1 | 3 | 4 | 2 |
| | Time | 233 | 102 | 60 | 10 | 15 | 46 |
| | No. of Labor | | 3 | 1 | 3 | 3 | 4 |
| | Time | 198 | 55 | 72 | 16 | 13 | 42 |
| | No. of Labor | | 3 | 1 | 3 | 3 | 4 |
| | Time | 192 | 62 | 56 | 14 | 16 | 44 |
| | No. of Labor | | 3 | 1 | 3 | 3 | 4 |
| | Time | 192 | 58 | 59 | 15 | 15 | 45 |
| | No. of Labor | | 3 | 1 | 3 | 3 | 3 |
| Sub Activity Description | | | Set Truss | Insulation | Roof Decking | Roof Paper | Shingles |

Exterior Finishes: 11 Data Points

| Chassis # | | Total | Activity Cycle Time | | |
|---|---|---|---|---|---|
| | | Cycle Time | Sub 1 | Sub 2 | Sub 3 |
| 1567B | Time | 77 | 17 | 60 | 55 |
| | No. of Labor | | 2 | 3 | 3 |
| 1567A | Time | 96 | 13 | 56 | 85 |
| | No. of Labor | | 2 | 3 | 3 |
| 1658A | Time | 125 | 75 | 40 | 33 |
| | No. of Labor | | 2 | 3 | 3 |
| 1658B | Time | 135 | 60 | 50 | 25 |
| | No. of Labor | | 2 | 3 | 3 |
| 1657A | Time | 60 | 25 | 35 | 55 |
| | No. of Labor | | 2 | 2 | 2 |
| 1657B | Time | 100 | 35 | 55 | 45 |
| | No. of Labor | | 32 | 2 | 2 |
| 1646A | Time | 130 | 2 | 45 | 50 |
| | No. of Labor | | 3 | 3 | 2 |
| 1646B | Time | 210 | 58 | 53 | 50 |
| | No. of Labor | | 2 | 2 | 2 |
| 1521A | Time | 71 | 13 | 30 | 19 |
| | No. of Labor | | 3 | 3 | 3 |
| 1521B | Time | 82 | 11 | 34 | 26 |
| | No. of Labor | | 3 | 3 | 4 |
| 1522A | Time | 72 | 14 | 12 | 35 |
| | No. of Labor | | 3 | 3 | 4 |
| Sub Activity Description | | | Exterior Wall Boards | Door & Window Installation | Siding |

Interior Finishes: 9 Data Points

| Chassis # | | Total Cycle Time | Activity Cycle Time | | |
|---|---|---|---|---|---|
| | | | Sub 1 | Sub 2 | Sub 3 |
| 1537B | Time | 118 | 29 | 32 | 39 |
| | No. of Labor | | 2 | 1 | 3 |
| 1538 | Time | 130 | 25 | 30 | 35 |
| | No. of Labor | | 2 | 1 | 3 |
| 1539A | Time | 130 | 33 | 30 | 35 |
| | No. of Labor | | 2 | 1 | 3 |
| 1652B | Time | 110 | 25 | 60 | 35 |
| | No. of Labor | | 2 | 3 | 3 |
| 1657A | Time | 103 | 45 | 65 | 50 |
| | No. of Labor | | 1 | 3 | 3 |
| 1657B | Time | 210 | 36 | 67 | 45 |
| | No. of Labor | | 1 | 3 | 3 |
| 1645B | Time | 126 | 20 | 13 | 10 |
| | No. of Labor | | 2 | 1 | 3 |
| 1645A | Time | 65 | 20 | 15 | 42 |
| | No. of Labor | | 2 | 1 | 3 |
| 1646A | Time | 70 | 18 | 10 | 10 |
| | No. of Labor | | 2 | 1 | 3 |
| Sub Activity Description | | | Molding | Install Urethane Foam | Carpeting |

## Axles & Tires: 5 Data Points

| Chassis # | | Activity Cycle Time |
|---|---|---|
| | | Sub 1 |
| 1643B | Time | 52 |
| | No. Labor | 3 |
| 1656B | Time | 55 |
| | No. Labor | 3 |
| 1652A | Time | 42 |
| | No. Labor | 3 |
| 1657A | Time | 45 |
| | No. Labor | 3 |
| 1657B | Time | 40 |
| | No. Labor | 3 |
| Sub Activity Description | | Axle & Tires |

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