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**MATERIAL FLOW-BASED ANALYSIS OF MANUFACTURED HOUSING
PRODUCTION PLANT FACILITY LAYOUT**

VOLUME I

By

Deblina Banerjee

A THESIS

Submitted to
Michigan State University
in the partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Construction Management Program

2003

ABSTRACT

MATERIAL FLOW-BASED ANALYSIS OF MANUFACTURED HOUSING PRODUCTION PLANT FACILITY LAYOUT

By

Deblina Banerjee

Manufactured homes are built in an assembly line similar to other manufactured products. However, production process, facility layout and material handling system of the Manufactured Housing Industry in the United States is still primitive when compared to other technologically advanced manufacturing facilities like automobile etc. The facility layouts of the manufactured housing plants consist of main-stations, sub-stations and feeder stations. Visit to most of the factories reveal the fact that the stations within the plants are arranged without any prior planning and evaluation and as a result the layouts are inefficient. This has led to the necessity of incorporating the advanced technologies used in industrial engineering to help develop an efficient facility layout for a given manufactured housing plant. The goal of this research is to analyze the impact of material-flow on the facility layout of a manufactured housing production plant, and to outline the comprehensive process steps for evaluating the layout-design based on the material-flow. In order to do this, the material movement between the stations and the material handling system requirements for a manufactured housing plant is understood and a material-flow based quantitative model for the facility layout is developed. The model is then analyzed; layout alternatives are generated and evaluated in a layout evaluation software, namely FactoryFLOW, on the basis of the material movement cost, distance traveled and frequency of trips. Finally, the process steps for evaluation of the facility layout alternatives are developed in the form of a Process Flow Diagram.

Dedicated to my dear family

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Matt Syal for his continuous guidance, support and encouragement not only during my research but also throughout my time as a graduate student at Michigan State University.

I would also like to thank Dr. Tariq Abdelhamid and Dr. Srinivas Talluri for their valuable advice and support during my research.

My sincere appreciation goes to all the faculty members and the staff members at the Construction Management program for their help and encouragement. I would also like to thank my friends for their active support.

I am also very grateful to the industry personnel at the case-study factory for their help during my data collection process. A special thanks to Mr. Nick Yost (TRA) for providing information for the Manufactured Housing Factory used as the case study during this research. Many thanks to Mr. Roger Cohen and Mr. Lee Dehmlow for their time and invaluable suggestion while developing my process steps.

Finally, I offer my deepest gratitude and appreciation to my dearest husband, my loving parents and my sister Dina who have always encouraged and supported me in pursuing my dreams.

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CHAPTER ONE
INTRODUCTION

1.1 Overview

Manufactured housing has proven to be an effective alternative solution in meeting the increased demand for affordable housing. Survey results in the area of manufactured housing have shown that, in 1999, 21.4 million Americans lived in manufactured home units full-time and 88% of the home owners were very much satisfied with their selection (MHI-I). The popularity of manufactured housing can be attributed to several factors. The manufactured housing units are fully constructed in the factory and, as a result, have a price advantage over conventional on-site constructed housing that makes them affordable. In addition, the issuance of the Manufactured Home Construction and Safety Standards by the U.S Department of Housing and Urban Development (HUD) in 1976 resulted in an improvement in the quality, design and size of manufactured homes. Moreover, owing to the variety of design, appearance and flexibility, manufactured homes have found a place in privately owned lots, coming a long way from the initial mobile homes of the past. These homes have become the undisputed leader in the field of industrialized housing.

It has been estimated that the annual need for housing units typically exceeds 2 million, whereas, the annual housing supply has been around 1.75 million units during the 1980s and 1990s, and is estimated to be around 1.5 million only during the 2000s (NAHB 1992, Willenbrock 1998). Although, the beginning of the last decade had seen tremendous growth in the demand and production of manufactured homes, the last couple of years have witnessed a sharp downward trend (Mehrotra 2002).

In 1980, the federal government renamed so called “mobile homes”, “Manufactured Homes” or “HUD-Code homes”. Initially, manufactured housing was an

all-inclusive term used by the industrialized housing industry. With the passage of time, the other factory-built housing industry segments such as modular and panelized, stopped referring to their products as manufactured housing in order to distinguish them from mobile homes. Manufactured homes can be constructed, either as a single-section or in multiple-sections. The section(s) is (are) then transported to the site, installed, and connected to the required utilities. The house is built on a permanent chassis and is designed to be used as a dwelling with or without a permanent foundation. Table 1.1 shows the different types of factory built homes and their share in the housing sector. In 1998, about 22.7% of the housing sector was covered by manufactured housing, and to a lesser extent by modular, panelized and pre-cut housing sectors. However, in 2001 manufactured housing, along with all industrialized housing units, also witnessed a decline of about 3.8%, resulting in an 18.9% share of the factory-built housing.

Table 1.1: Share of Factory-Built Housing
(Willenbrock 1998, MHI 2000, AutoB, 2002)

Housing Type	1986	1993	1998	2001
Precut	3.00%	3.30%	3.30%	3.20%
Panelized	7.00%	6.70%	6.30%	6.20%
Modular	2.40%	3.30%	3.40%	2.90%
Manufactured	16.30%	18%	22.70%	18.90%

As mentioned earlier, manufactured homes are primarily of two major types, namely, single section and double sections, although there are multiple-section homes too. Typically single-section homes are 16'-0" wide with an average area of 1200 square feet and double section homes are 32'-0" wide with an average area of 1550 square feet. In 2000, 273,000 manufactured homes were installed, of which 87,200 (32%) were single-section homes and 183,600 (67.25%) were double-section homes (Census 2002).

A manufactured home is a unit that is mostly completed in a factory setting (refer to Figure-1.1). The manufactured home goes through five different stages in the assembly line within the manufacturing facility, starting from station 1(one), where the chassis is assembled, to the final station where the home is finally cleaned up and ready to be delivered at site (refer to Figure 1.2). These homes meet the HUD codes, and resemble the site-built homes to a large extent.

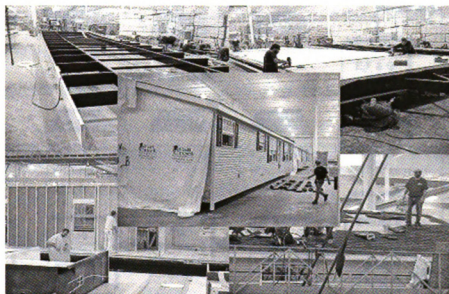
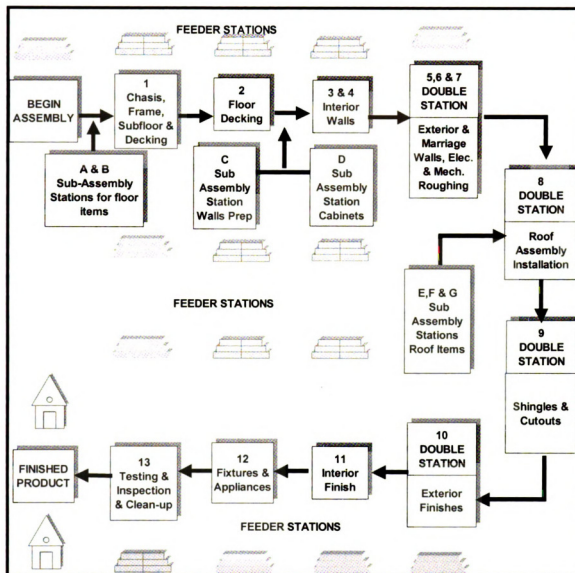


Figure 1.1: Manufactured Housing Factory
(Syal & Hastak 2002)



utilization process in order to explore the initial aspects of the facility layout design (Senghore 2001, Abu Hammad 2002, Mehrotra 2002, Barriga 2003). A developmental research work on facility layout design of a manufactured housing plant was also done, where the qualitative guidelines for designing facility layout were developed (Mehrotra 2002). Figure 1.3 presents the milestone framework for the existing, the ongoing and the proposed researches in the area of manufactured housing. This research proposes to further explore the process of manufacturing facility layout design technologies currently applied in other industries, and to introduce the basic process steps for the material-flow based quantitative analysis of the facility layout in a manufactured housing production plant.

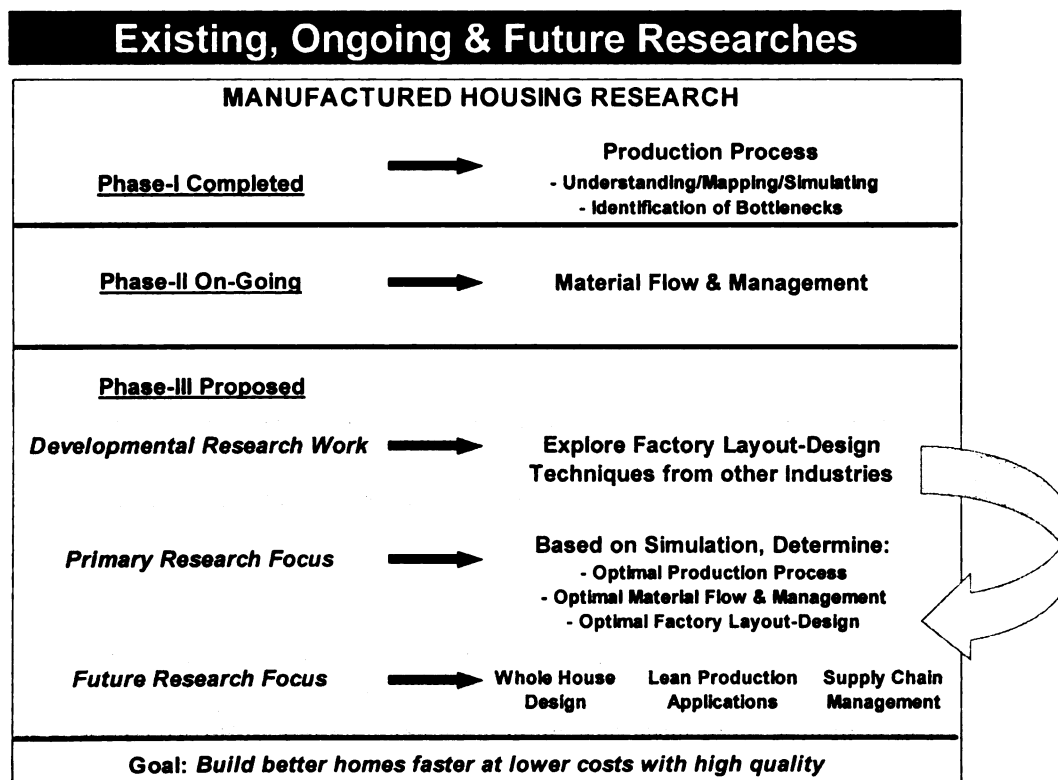


Figure 1.3: Manufactured Housing Plant: Existing, On-going and Future Research
 (Modified from Syal & Hastak 2002)

1.2 Need Statement

The study of the current market reveals that, even though there was a growing demand for the manufactured homes during the 1990s, there has been a sharp drop in the production of manufactured home units over the past couple of years. This decrease can be attributed to several factors: the present economic recession in the United States, the lack of efficient production in the manufactured housing factory at a lower cost, and the inability of manufactured housing plant to emerge as a technologically advanced industry. Several surveys and studies show that a typical manufactured housing plant fails to produce at the desired capacity and production rate because of shortcomings like the absence of streamlined assembly process, the improper flow and utilization of material in the production process (Burkhardt et al. 1996, Pheng and Meng 1997, Seidel 1999, Abu Hammad 2001, Senghore 2001), and the lack of generic guidelines and techniques to improve the existing manufacturing facility layout design (Mehrotra 2002).

The uniqueness of the construction process of a manufactured house in a factory creates a greater need for investigating innovative production, facility layout design and material flow processes for the manufactured housing industry using a different approach from that traditionally adopted for a typical manufacturing plant, as well as approaches in earlier researches.

Like most manufactured products, manufactured homes are built in a factory on an assembly line. The assembly line is made up of several spaces namely activity stations, sub-activity stations, feeder stations and storage areas. However, the facility layout-design in most of the production plants are primitive and as a result emphasizes the inefficiency in the production process and calls for detailed exploration of the various

options for facility layout design with a view to optimizing production process further. Moreover, most of the production facilities in other manufacturing industries have undergone tremendous improvement with the implementation of latest production layout technology. Somehow, the manufactured housing industry has not been technically updated with such advanced techniques. Moreover, no attempt has been made to understand the house production process alongside the problems presented by the layout of the assembly-line in the factory. Therefore, there is a need to understand the production process and to identify the problems in the layout design and to explore the possibilities of the implementation of advanced techniques in manufactured housing facility-layout. The next few sections discuss in details the various factors that have necessitated this research.

1.2.1 Increase in the Variability of Demand in Manufactured Housing

As mentioned earlier, the demand for the manufactured homes have witnessed a sharp decline over the past couple of years. In addition, the increasing requirement for multi-section manufactured homes with variability in design, as compared to single section homes of the 1970 and 1980 (Table 1.2) proved to be a major challenge to the home manufacturers. This variability in demand has given rise to the need for a flexible facility layout design for the manufacturing process which can cater to the different customized needs of homebuyers.

Table 1.2: Manufactured Housing Trends
(MHI 2000)

TRENDS	1991	1996	1999
New Home Sales	171,000	363,000	348,671
% of Total Homes	17%	24%	29.46%
Multi-Sections as % of New Homes	46.7	52.2	64.7
Av. Floor Area (SF) of Multi-Section Homes	1470	1600	1605
Av. Price/SF of Multi-Section Homes	\$25.10	\$29.56	\$31.28

There has been a growing variability in the nature of demand for manufactured homes, since, more and more people look at manufactured homes as an affordable option for site-built housing, and expect manufactured homes to be similar in size, appearance, and standards to site built homes. Initially, double-section homes, first introduced in 1969, captured a large share of the market, thereby reducing the demand for the single-section homes. Such factors as acceptance of manufactured homes as a permanent rather than transient form of housing, relaxation of restrictions regarding width of manufactured homes, and consequently the permission to transport wider sections on the highways, led to the popularity for the double-section homes (Bernhardt, 1980).

As a result, in 2000, double-section home shipments outpaced single-section home shipments, making up 70.1 percent of total shipments (MHI-1). Presently, another new trend has been noticed: the growing demand for the multi-section homes. However, the facilities in which manufactured homes are built have not been adequately changed to accommodate this ever-changing trend in the demand for the product. Originally, many of the present production plants were actually designed for single-section homes. When the demand for double-section homes grew, the same production plants were modified slightly to cater to new demands by additions to the existing facilities or use of more

external storage areas for the raw materials. Moreover, with the increase in demand for diverse types of multi-section manufactured homes, the existing facilities for housing construction have proven less efficient and, in some cases, even unusable (Mehrotra 2002).

1.2.2 Customization, Hybridization and Diversification of Product

There has been a revolutionary transformation in the field of housing, with an increase in the number of parts that are being prefabricated in a factory during the construction of the site-built houses. Consequently, the trend is now shifting more and more towards the modular and manufactured houses, making the house production a hybridized process. This calls for a flexible process and flexible facility layout design. The following part of this section explains how the various factors have affected the product design and hence the production process (MHRA 2000).

1.2.2.1 Product Customization

The manufactured housing production plants are similar to most other production plants, but they differ from them in one unique way. In most manufacturing facilities, (e.g. auto industry) the product manufactured is standard, defined by the manufacturers, and not custom-built to meet the consumers' needs. Each item produced on the assembly/production line is same as the one produced before and after it. But, this is different in the case of manufactured housing production plant, where each home produced is unique. It is a customized product and is designed according to the needs and requirements of the consumer. As a result, two homes coming down the production line are never the same. They vary in design, size, height, types, color of finish etc. Hence, the

assembly line in the manufactured housing production plant needs to be flexible in order to adjust to the requirements of each home being produced (MHRA 2000). This makes the production plant design of a manufactured housing facility a unique problem.

1.2.2.2 Product Diversification:

The downturn in the market has forced the home manufacturers to invest in product diversification. Product diversification implies that the facility producing home-units should be able to produce other forms of industrial housing elements, like modules, panel etc. This is to enable the manufacturers to cater to the fluctuating needs in an unpredictable market. Leading home manufacturers, like Champion Homes and Genesis Homes, now want to keep open the option for producing variety of products. This diversification of the product variety requires a flexible production process that can accommodate the diversified products. The manufacturing facility layout-design should be economically and technologically feasible to adopt to these changes. Unfortunately, the existing home producing plants have facility layouts that fail to meet these requirements (MHRA 2000, Mehrotra 2002).

1.2.2.3 Product Hybridization

Some of the house manufacturing plants are trying to extend their services to on-site requirements. Sometimes, the home is partly built in the factory and rest is completed on-site, according to the home-buyers' specifications. This is faster than the traditional site-built home building process, but slower than building a home completely within the factory. This procedure of product hybridization requires a facility layout design for its manufacturing process that is adaptive to variability.

However, the factory-produced houses have a constraint in their sizes, since transporting them creates another issue (CohenBrothers 2003). The full size homes are too large for centralized production and involve widespread movement to diversified locations, which involves a great deal of risk, and variability in cost. In order to solve this problem, some of the home-producing companies like *CohenBrothers Homes* are introducing the concept of *Mobile Home Factories*. The concept of manufacturing full-sized homes on a “controlled-site” gives birth to the idea of the “mobile manufacturing facilities”. The parameters required to form the template for the “mobile” factory also require the incorporation of “state-of-the-art” facility-design techniques.

1.2.3 A Shift in Focus from Product to Operation Owing to the Ongoing Economic Recession

The popularity of manufactured homes is due to the affordability of these houses, made possible by the economies of scale of the factory process, and this is directly proportional to the efficiency of the production process. As a result, manufactured home producers are able to purchase large quantities of building materials and products at a lower cost and produce homes at cheaper rates than builders of site-built houses (MHI-2). NAHB (1998) states that the average cost in 1990 per square foot (exclusive of land cost) for a double-section manufactured home was \$23.60, as compared to an average cost (exclusive of land costs) of \$ 32.78 for a modular home and \$38.57 for a site-built single family home (Mehrotra 2002).

However, the manufactured housing industry has experienced a sharp decline in sales, since peaking in 1998, as compared to the consistent demand in the site-build

housing industry. This downfall can be attributed to two factors: namely, the overall economic recession throughout the nation and financing concerns. During the mid-to-late 1990s, a number of lending firms approved many buyers with questionable credit histories to purchase manufactured homes (MHI-2003). This was followed by loan defaults and home repossessions. As a result, the financing side of the manufactured housing industry was restructured and rules for loan approval were made more stringent

This led to a decrease in the overall demand for manufactured houses across the nation, and this demand constraint has come up as a new challenge to the home manufacturing industry. As a result, the focus of the production process has shifted towards increasing the efficiency of the operation processes, instead of the earlier focus on increasing production. Home manufacturers are now forced to concentrate more on the smooth and efficient running of the production process, so that the overall “value” of the process is increased. In other words, utilization of resources should be optimal so that a home is produced faster, with better quality and at a lower cost.

One of the ways to attain this objective is to transform the facility layout design so as to improve the production process (Syal & Hastak 2002). In order to make the ideal facility layout for an existing or a new manufactured housing plant, some process steps must be followed by the manufacturers. In this thesis, the author presents comprehensive process steps for the manufacturers that can help to develop efficient facility layout for a manufactured housing plant.

1.2.4 Need to Implement “State-Of-The-Art” Facility Layout Techniques: A

Quantitative Approach

Automation and robotic technology have found wide application in many manufacturing-related industries. Most of the production facilities, such as those in the automobile industry have undergone radical transformation and have evolved as more efficient and productive facilities that are technically up to date. However, this is not true of the manufactured housing production facilities. The facility layout techniques in manufactured housing industry are still very primitive and this industry needs to learn many lessons from other industries. The highly seasonal nature of sales in the manufactured housing industry and the abundance of primarily semiskilled labor have led to a low level of mechanization in the production plants (Bernhardt 1980). The majority of equipment used in the production plants is conventional like forklifts, narrow-aisle trucks, mobile catwalks, crane systems for material handling, pneumatic hammers and staplers, power screwdrivers, and spray painters. Moreover, the placement of this equipment, and the way it is laid out or used is very ineffective; the available resources are not used to their optimum capacity. To obtain the maximum utilization of resources, the facility layout should be planned with advanced techniques used in other manufacturing facilities.

This need has accelerated the developmental research to study and understand the planning and design processes of a manufactured housing production plant and to outline the basic guidelines (Mehrotra 2002). The field of industrial design and manufactured engineering approaches the facility layout problem in two specific ways, namely, *qualitative approach* and *quantitative approach*. These are discussed in details in

the later part of this chapter and also in Chapter III. Mehrotra's (2002) work was based only on the qualitative approach. This research adopts the quantitative approach and develops an outline of a comprehensive layout design procedure for effective and efficient facility layout design of a manufactured housing plant.

1.2.5 Potential Industry Impact: Competition and Continuing Education

Manufactured housing has been one of the fastest growing housing options. A greater number of homes are being built each year. Today the manufactured housing industry share almost 25% of the total housing market, comprising the second biggest provider of the housing units in the United States. The manufactured housing industry includes 130 companies with about 300 factories throughout the nation. The top 25 companies accounted for 90.9% of total industry shipments, while the top 10 accounted for 78.8% in year 2002 (MHI-2003). The increase in strong competition among producers also highlights the need to have better and more efficient and advanced production facilities.

Although, as mentioned earlier, there is currently a drop in demand for manufactured houses, the author feels that if these houses can be made more affordable through streamlined production process and efficient layout design, the demand for the homes will increase. In order to improve the layout design techniques, manufacturers *should* be trained and exposed to “state-of-the-art” tools and techniques. Finally, there is *also* the need to educate the industry personnel with the recommended process steps.

1.2.6 Partnership for Advancing Technology in Housing (PATH) Initiative

PATH supported research in manufactured housing production industry has been done since the year 2000. Manufactured housing offers features like quality, value, and innovative designs and up-to date technology at a rate that is affordable for most homebuyers. However, in spite of its potential as a housing provider, this industry has not yet reaped the profit of the technological advances made in other sectors of housing and manufacturing. Research and innovative efforts, funded by National Science Foundation, are being carried out jointly by Michigan State University and Purdue University to improve the manufactured housing production-processes, material flow and preliminary facility layout design. However, a substantial amount of research is still required to make the industry ready to meet the goal of manufacturing better homes at lower cost and high quality. Existing researches have not only identified the means to improve process-models but have also come up with several interdependent factors that need to be streamlined in order to optimize the total production system and increase its efficiency.

Several research projects, funded by the NSF-PATH grant, have been carried out in this field with a goal of producing cost-effective, super-quality homes, by investigating the production process-flow (Abu Hammad 2002, Senghore 2001), material flow and management (Barriga 2002) within a factory. The methodology of those *research* projects primarily involved the collection of process related information from *the* factories and development of virtual process models. These process models were *simulated* in computer and the output validated with the real-world scenario. After *validating* the process models, they were subjected to further simulation with various “*what-if*” scenarios in order to find out the optimal combination of the process systems

that would ensure most efficient production. In a similar manner, the material flow and utilization within the factory was streamlined (Refer to Figure 1.3).

As stated earlier, many aspects of the complete house production process still remain unexplored. The layout design of the manufacturing facility of a home producing plant is one such area that needs focus. Developmental research work has already been initiated (Mehrotra 2002, AbuHammad 2002c) to explore theoretical advances and available facility layout design techniques used in other industries (e.g., automobile industry). Also, attempts were made to incorporate the technologies prevalent in several other areas (e.g., industrial engineering, operations research and supply chain management) into the manufactured housing process. However, the earlier research in facility layout design was exploratory and dealt with mostly qualitative aspects. As a result, there is a need for a more comprehensive analysis (e.g. quantitative) of the layout-design technologies, in order to achieve the knowledge and understanding that will help to make the manufactured house industry more competent and cost-efficient.

1.3 Existing Research

The two major sources of information for production plant design of manufactured homes are *Decision Support System for Manufactured Housing Production Process Planning and Facility Layout Design* by Abu Hammad (2003) and *Manufactured Housing Production Plant Layout Design Process* by Mehrotra (2002). These two research reports provide the existing design concepts in manufactured housing production plant and current status of the research done in this field. Although there has been little research on the layout design of house production plants, there is a larger pool of information on

production facility planning and design in the field of industrial engineering. As a result, the author has divided the areas of possible sources of information into three major categories, namely

- Production Process and Material Management in Manufactured Housing Industry;
- Contemporary Facilities Layout Design Concepts and Techniques in Industrial Engineering
- Facility Layout Design Concepts in Manufactured Housing Production Plants

Research on improving the manufactured housing production process, funded by NSF-PATH, was carried out in two main areas: improving production processes and streamlining the material flow and management. As a result of this effort three MS thesis have been completed (Senghore 2001, Abu Hammad 2001, Barriga 2002) while one Ph.D dissertation (Abu Hammad 2003d) is currently being finalized. A developmental research work on facility layout design techniques and guidelines for a manufactured housing production plant was carried out as a MS thesis (Mehrotra 2002). The other major sources are *The Manufactured Housing Industry* (Burkhardt, Mireley, Syal 1996; Syal & Mehrotra, 2001); *The Manufactured Housing Production Process* (Senghore, 2001; Abu Hammad, 2001); *Material Supply Management System For Manufactured Housing Industry* (Barriga 2003) and *Manufactured Housing Production Plant Layout Design Process* (Mehrotra 2002).

Although the manufactured housing industry lacks sufficient literature, there is **an** extensive body of knowledge related to production facility planning and design in the **field** of industrial engineering. The existing literature on this subject can be broadly **classified** into four categories, namely: material flow movement and handling systems

and facility design, modeling techniques for facility layout design, advanced facility layout design techniques, and theories and computer applications in facility design. The two major sources for facility layout design and planning that were referred extensively in this thesis are *Facilities Design* by Sunderesh Heragu (1997) and *Facilities Planning* by Tompkins et al. (1996). Chapter II of this thesis provides a detailed outline of the literature referred to during the research work.

1.4 Research Scope and Uniqueness

The scope of the proposed research is to develop a quantitative model, based on the material flow and the facility layout design of a manufactured housing production plant, and to outline the process steps for developing and evaluating layout design alternatives. The quantitative model is developed on the basis of the understanding of the house production process in a factory, detailed literature review, data collection through factory visits, and by using a software for the layout analysis. The author does not attempt to address other issues like the site design and layout; the architectural aesthetics, the information and control flow within the organization, or the design of the product (e.g. house) or the production process itself. However, it should be remembered that the intent of this research is not to propose an optimum layout design, but rather to identify the process steps that can help to design an optimum layout for a manufactured housing plant.

Existing developmental research (Mehrotra 2002) in this field deals with the **space** management and allocation issues, proximity issues and interrelationships between **the** stations but does not take into account the quantitative flow relationships (material &

sequence) between them. In this research, the author recommends a comprehensive methodology for designing the facility layout for house production plants based on material flow. The quantitative matrices can be developed for material, personnel, information, organizational, control, environmental, and process flow. However, the development of the individual matrices for each of the flows involves a huge movement of material, people, information etc and can be a very demanding process which is beyond the scope of this Master's thesis. This research focuses on the material flow aspect of the activity relationships and performs a comprehensive study of the quantitative material flow relationships that exist between the stations in the manufacturing facility, thereby developing a quantitative model for facility layout problem. The author collected extensive data from the case-study manufactured housing plant and interviewed floor managers and production engineer for developing the model, and also consulted industry personnel and facility designers for the validation of the process steps.

As mentioned earlier, a manufactured housing production plant is different when compared to most other production plants. Unlike most other production plants, they manufacture customized products to suit the customer's need. The assembly line in the manufactured housing production plant needs to be flexible in order to adjust to the requirements of each home being produced. To date, little or no work has been done in the layout design of the manufactured housing plant till. This makes the production plant design of a manufactured housing facility a unique problem. This problem is further compounded by the manufacturers' attempt to diversify and hybridize their product. Figure 1.4 provides the milestones for the facility planning process of a manufactured

housing plant, with the qualitative approach presented in the earlier research work by Mehrotra (Mehrotra 2002). The highlighted portion in Figure 1.5 highlights the scope of this research.

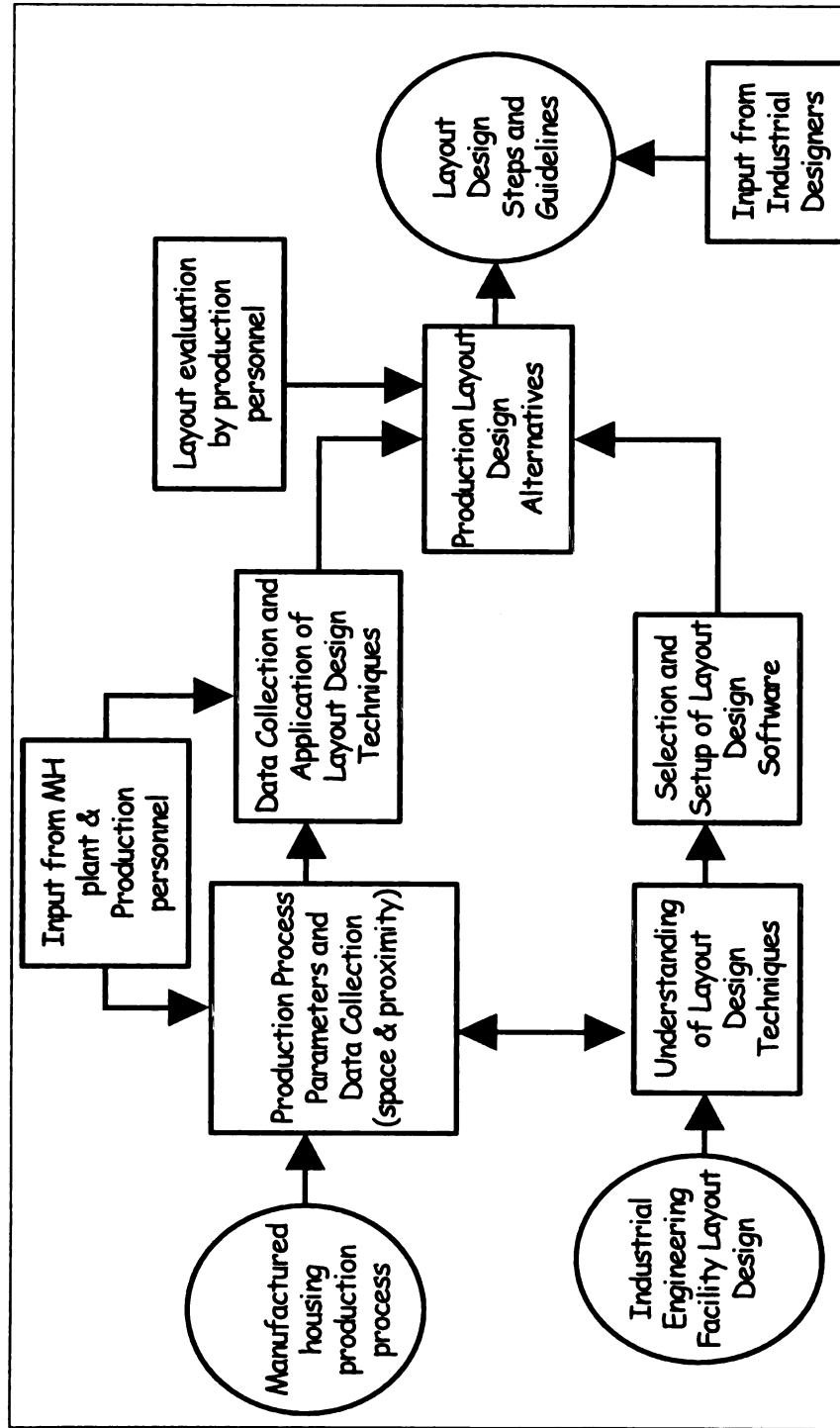


Figure 1.4: Milestone For The Facility Planning Process of A Manufactured Housing Plant
(Mehrotra 2002)

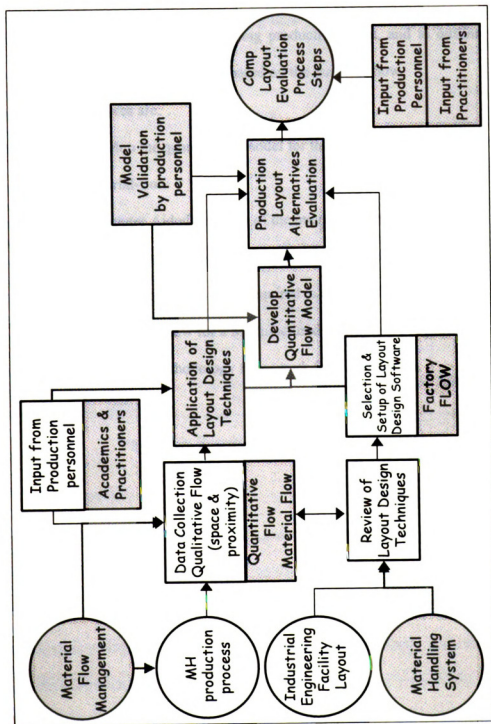


Figure 1.5: Research Scope
(Mehrotra 2002)

1.5 Goal and Objectives

The overall goal of the proposed research is to analyze the impact of material-flow on the facility layout of a manufactured housing production plant, and to outline the process steps for evaluating the layout-design based on the material-flow.

The primary objectives are:

Objective I: Develop the quantitative model for the facility layout based on the material-flow

Objective II: Computer Aided Analysis of the quantitative model, including development and evaluation of the alternatives

Objective III: Outline the process steps required to analyze the facility layout based on the material flow for a Manufactured Housing Production Plant.

Figure 1.6 represents the methodology framework for this research.

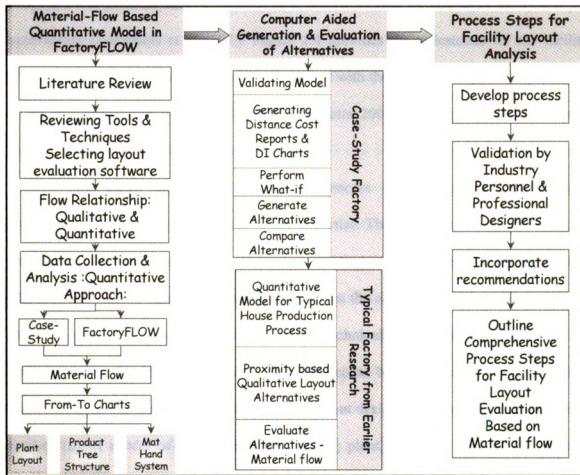


Figure 1.6: Research Methodology Framework

1.6 Methodology

Although it is difficult to state a meaningful objective for facility planning, it may be broadly defined as: “to achieve the stated purpose while satisfying several other objectives.” For example, a facility is designed only once, but it is in a constant phase of reorganization owing to rapidly changing objectives. According to the existing literature in this field, some typical facilities design objectives are: to support the organization’s vision through improved material handling, material control, and good housekeeping; to effectively utilize people, equipment, space, energy; to minimize capital investment, be

adaptable and promote ease of maintenance; and to provide for employee safety and job satisfaction (Tompkins et al 1996). Figure 1.4 provides the milestones for the facility planning process of a manufactured housing plant with the qualitative approach presented in the earlier research work by Mehrotra (Mehrotra 2002). The highlighted portions in Figure 1.5 specify the scope of this research.

As stated earlier, the production process of the manufactured housing production plant needs new perspective and expertise. The significant advances that have occurred in the past decades in the manufacturing industries, especially in facility planning and layout design, can be incorporated in the manufactured housing factory to make its production process more efficient and technically up to date. In this thesis, the author reviews the tools and techniques implemented by other industries, and utilizes them in redefining the comprehensive facility-layout design procedures for a quantitative facility layout model of a manufactured housing plant. The later part of this section provides a detailed outline of the methodology steps adopted during research.

1.6.1 Objective I: Develop the quantitative model for the facility layout based on the material-flow

In order to develop a comprehensive material-flow-based quantitative model for the facility layout of a manufactured housing plant, the following steps were adopted.

Step-1: To understand the facility layout design and production process of the manufactured housing production plant

Step-2: To review existing literature and to acquire information about the latest theories and technologies implemented during layout planning and designing of other manufacturing facilities.

Step-3: To acquire and understand appropriate designing, modeling and evaluating techniques and software for the analysis of facility layout problems

Step-4: To collect data by visiting the case-study factory and to analyze the data in order to compile the process details of the manufactured housing production plant

Step-5: To develop a comprehensive quantitative model of the facility layout based on the material flow using FactoryFLOW software.

The above noted steps are discussed in the following section.

Step-1: To understand the facility layout design and production process of the manufactured housing production plant

The author reviewed existing literature, and research works (Abu Hammad 2001, Senghore-2001, Mehrotra 2002, Barriga 2003, Abu Hammad 2003), based on design and production of manufactured homes to understand the details of identifying ways of improving productivity of manufacturing process and formulating simulation models for this process.

Defining the product to be manufactured:

A complete housing module is the final product of a manufactured housing plant. Manufactured homes can be primarily classified into two types: the single section home which is usually 16'0" wide, and the double section home, which is usually 32'0" wide. However, multi-section homes are also available. The houses differ in length, design, layout, and finishes, according to the manufacturer's or the customer's specifications.

Understanding the manufacturing process required to produce the product:

Manufactured homes are built in a factory on an assembly line. The author reviewed existing research work, like the research report written by Ayman Abdullah Abu Hammad, (2001) “Simulation Modeling for Manufactured Processes in Construction,” which provides details on identifying ways of improving the productivity of the manufacturing process. This research work deals with the complete production process, taking all stations into account. A report prepared by Omar Senghore (2001), “The Production and Material Flow Process Model for Manufactured Housing,” deals with the documentation of the production process and material flow in the manufactured housing factory and comes up with a simulation model for this process. This research focuses on a few critical assembly stations and subassembly stations. In addition, during the visits to the manufactured housing production plants, the author observed the systematic production process. The production process at different production plants were compared and a typical process model was developed.

The steps described above are followed to develop a systematic, detailed description of all the activities involved in the production of a manufactured home. These activities are grouped into five major clusters: floors, walls, roofing, exterior, and finishes. Each of the clusters of activities takes place in one of the main assembly stations, which are in turn supported by subassembly stations, feeder stations and internal and external storage areas. The major activities included in each of these clusters are as outlined in the following section.

Floors cluster: The floors cluster mainly consists of two to three stations where the installation of floor joist, HVAC systems and waterlines in the floor on the chassis

assembly with the wheels and axles, takes place. The floor is also insulated in these stations.

Walls cluster: This cluster mainly consists of installation of both interior and exterior walls with insulation. Some of the bathroom appliances are also installed in this cluster.

Roofing cluster: This cluster mainly consists of a substation where the roof truss is fabricated (in some factories pre-fabricated roof trusses are used) and two main stations where the roof is placed over the house and roof deck, and insulation and shingles are installed.

Exterior cluster: The exterior finishes are usually carried out simultaneously with the roof decking. The major activities that happen at these stations are installation of doors and windows, exterior boards and siding.

Finishes cluster: This cluster mainly consists of three to four stations. Electrical, mechanical and HVAC installations and inspections are carried out in the first two stations. At the next station, carpeting is installed and the interior of the house is painted or wallpaper is put up. Finally window curtains and appliances are installed at the last station.

Understanding the Material Management in Manufactured Housing Production Facility

The author studied the material management system of the manufactured housing plant in order to understand the material flow process and reviewed the paper on *Material Supply Management System for Manufactured Housing Industry* by Edgar Barriga, 2003. This research presented the existing material management system commonly prevalent in the manufactured housing industry and also addressed the material flow issues and proposed

the improvement of the material requirement planning (MRP) system so that the reflected production rates will be cost efficient and better.

Understanding the Facilities Layout Design Concepts in Manufactured Housing Factory

The facility layout design of the manufactured housing factory is a critical factor that affects the efficiency of the production process; it depends mostly on factors like the assembly line design, the product built, the material flow movement and the material handling system. The layout style that is normally found in manufactured housing factories is a U-shaped layout (Mehrotra 2002) because of the increasing demand for double-wide sections. Linear layouts are more suitable for factories that construct single-wide housing units, while U-shape layouts work better for factories that produce double-wide units alone or a combination of single and double-wide units (AbuHammad 2001).

Step-2: To review existing literature and to acquire the information about the latest theories and technologies implemented during layout planning and designing of other manufacturing facilities.

The existing literature on facilities planning and design in industrial engineering can be broadly classified into four categories, namely, material flow movement and handling systems and facility design, modeling techniques for facility layout design, advanced facility layout design techniques and theories and computer applications in facility design. The author reviewed the existing literature (summarized in Chapter II) in order to understand and present the new perspectives, expertise and significant advances in facilities planning. The later part of this section briefly describes the basic concept

implemented for designing the facility layouts based on the relationship between the stations in the facility.

Step-3: To acquire and understand appropriate designing, modeling and evaluating techniques and software for the analysis of facility layout problems

Along with the literature review, the author also attempted to learn the tools and techniques implemented in the field of industrial engineering for facility layout evaluation purposes. Several of the methods used are illustrated below.

Factors affecting facility layout designs: Flow relationship

To develop good layout alternatives for the facility layout design the designers must consider several factors like measure of interaction between the stations (e.g. frequency of trips or flow of material between the stations), shape and sizes of the facilities, available and required space, material handling system design, location restrictions for stations and the adjacency requirements between the pair of facilities (Heragu 1997). The data collected for the above factors are collectively known as the flow data. The *flow process chart* and *flow diagram* depicts various steps of the process and sequence of the process respectively (Heragu, 1997). The formulation of alternative layouts is the most critical step in facilities planning as the layout generated will cater to *establish the physical relationship between the activities*. The relationship between the departments or activities is determined with the help of following factors:

- **Flow** is determined by lot sizes, unit load sizes, material handling equipment and strategies, layout arrangement and building configurations.

- **Space** is a function of lot sizes, storage systems, production equipment, type and size, layout arrangement, and material handling equipment
- **Activity Relationships** is defined by material or personal flow, environmental considerations, organizational structure, process requirements.

Flow process can be defined in terms of the subject of flow, the resources that bring about the flow, and the communications that coordinate the resources. A variety of flow patterns can be utilized in layout design determined by the product being manufactured and the production process being used; and flow planning revolves around the effective combination of the flow patterns (Tompkins et al 1996). The details of flow patterns are provided in the later chapters. The flow is the major factor that affects the layout of stations within the facility, and measure of flow is required to

- 1) View alternate flow arrangement and
- 2) Evaluate alternate flow arrangements.

Flow data may be specified in quantitative measure or qualitative measure (Tompkins et al et al., 1996). A home manufacturing industry has both large volumes of materials, information, and people moving between department; and significant communications and organizational interrelations. Hence it will require both measures of flow to evaluate the layout alternatives.

Quantitative Flow

This measure of flow indicates the level or extent of interaction between two facility pairs. The pairs with greater interaction between them should be placed closer to each other than those with limited interactions (Heragu, 1997). This measure of flow involves

the measurement of large volumes of materials, information or people moving between the stations (e.g pieces per hour, moves per day). Flow may be measured quantitatively in terms of the amount moved between the departments and expressed in From-To charts, in the form of a matrix displaying the distances that the material moves between stations. Steps used to construct a From-To chart are illustrated below (Tompkins et al., 1996):

- ◆ Following the overall flow pattern, list all departments down the first row and across the top column.
- ◆ Establish a measure of flow for the facility that indicates equivalent flow volumes. If items vary in size, weight, value, etc., then items may be established so that the quantities recorded represent the appropriate relationships among the volume of movement.
- ◆ Based on the flow path for the items to be moved, establish the measure of flow volumes in the From-To charts.

Table 1.3 shows a basic From-To chart depicting the major clusters in a manufactured housing production plant. The values represent the Euclidian distance between the clusters. Table 1.4 is an example of the From-To charts developed based on the material flow between the stations.

Table 1.3: Example of Distance based From-To Chart
(Modified from: Tompkins et al., 1996, Mehrotra 2002)

	to	Station 1A	Station 1B	Station 2A	Station 2B	Station 2C	Station 2D	Station 2E
Station 1A			25	150	125	150	100	175
Station 1B	25		125	75	100	125	150	
Station 2A	150	125		150	100	100	50	
Station 2B	125	75	150		50	75	125	
Station 2C	150	100	100	50		50	100	
Station 2D	100	125	125	75	50		75	
Station 2E	175	150	75	125	100	75		

Table 1.4: Example of Material Movement Based From-To Chart
(Based on the data collected from case study)

Part Name	Parts/ Product	From	To	To
House	7	Station 35	Station 36	
Part A (Toilet & Kitchen)	1	Station 34	Station 35	
Final Finish Assembly - A	1	Station 32	Station 34	
Fasteners	1	Receiving Dock-9	Storage 26	Station 34
Trim - A	1	Station 30	Station 32	
Electrical Assembly - A3	1	Station 32	Station 32	
Gypsum Vinyl Moroccan Sand	231	Receiving Dock-9	Storage 28	Station 30
Support Shelf	8	Receiving Dock-9	Storage 28	Station 30
Shelving-Wire Closet	26.3	Receiving Dock-9	Storage 28	Station 30

Qualitative Flow

Space and proximity relationship between two departments may range from an absolute necessity that the two stations be close to each other, to a preference that the two departments be distant from each other. In facilities having very little movement of material, information, or people, qualitative measure is the basis of arrangement of departments. A relationship chart is one of the common ways of presenting the qualitative

measure of flow. It describes qualitatively the degree of closeness that should exist between various workstations (Sule, 1988).

Following are the steps used in creating a relationship chart (Tompkins et al et al. 1996, Mehrotra 2002):

1. List all the stations on the relationship chart.
2. Conduct interviews and surveys with persons from each station listed and with the management responsible for all departments.
3. Define the criteria for assigning closeness relationships and itemize and record criteria used as reasons for relationship values on the relationship chart.
4. Establish relationship values and the reason for the values for all pairs of department.
5. Allow everyone having input to the development of the relationship chart to have an opportunity to evaluate and discuss changes in the chart. Figure 1.7 shows a basic relationship chart presenting the different clusters in a manufactured housing production plant.

	1	2	3	4	5	6	7	8	9	10	11	12	13	A	B	C	D	E	F	a	b	c	d	e	f	g	h	i	k
1	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
2	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
3	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
4	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
5	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
6	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
7	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
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9	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
10	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
11	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
12	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
13	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
A	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
B	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
C	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
D	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
E	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
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a	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
b	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
c	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
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h	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
i	\	\	\	\	\	\	\	\	\	\	\	\	\	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
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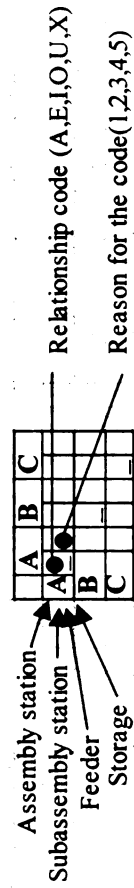


Figure 1.7: Relationship Chart
(Modified from Mehrotra 2002)

Simultaneously the author has also investigated the advanced technologies in the form of techniques (modeling techniques) and software and identified the appropriate one that is suitable for the research purpose (i.e quantitative analysis of the facility layout problems) and that can help in developing and analyzing the facility layout alternatives.

Modeling Techniques for Developing Optimal Facility Layout Design in Manufactured Housing Industry

Models are the imitation of real world. They may be classified as physical, analog or mathematical. The physical models are the models that have same shape and appearance as the real system but of smaller size, e.g. models of buildings, airplanes etc. Analog models provide necessary information of the real system, however they need not resemble the real system, e.g. graph showing the increase in population over time. As for mathematical models, there are two types: descriptive (predicting performance of a system) and prescriptive or normative (provides values for a set of decision variables) (Heragu 1997). After the models are generated, the techniques developed to solve the models are known as the *Algorithms*. Most of the facility layout design and planning problems are computationally difficult. As a result, several generic tools are implemented for modeling design and planning problems. These generic tools use the three modeling techniques, mathematical programming, queuing, and simulation modeling in right sequence, in order to get feasible and optimum solutions for design and planning problems (Ragsdale 2002).

Layout Evaluation Criteria

Based on quantitative flow of the production process the basic measurement criterion model that explains layout problem and identifies critical factors is developed. The equation below explains the following objective function.

$$\sum_a \sum_i \sum_j c_{ij} f_{ij} d_{ij}$$

Where c_{ij} = cost of moving a unit load of material distance between stations i & j per
unit distance

f_{ij} = Frequency of trips between stations i and j

d_{ij} = Distances between stations i and j

a = Material type

The following paragraphs outline the some of the various kinds of the mathematical models commonly used to develop the facility layout problems.

Traditional Models

The traditional models are used for determining the type and quantity of required production equipment. These are very simple models and can be used for simple analysis of facility layout problems (Shubin & Madeheim 1951).

ABSMODELs for the single-row and multi-row layout problems

The layout problem is primarily classified into two types for the purpose of modeling.

- ♦ Single row layout problem/ One dimensional (Refer Figure 1.8)
- ♦ Multi row layout problem/Two dimensional (Refer Figure 1.8)

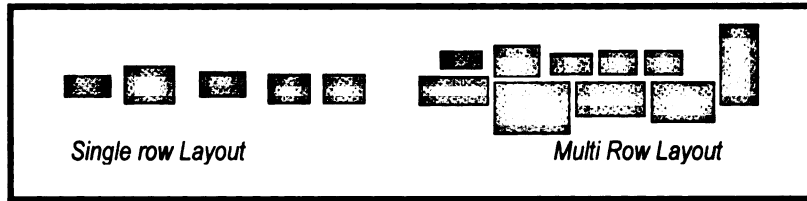


Figure 1.8: Types of Layouts
(Heragu, 1997)

As the name indicates, in the single row layout problems, the facilities are arranged linearly in one row and in multi-row problems the facilities are arranged in two or more rows. The layout of machines on one side of an automated guided vehicle (AGV) on a factory floor is an example of single row facility layout problem. The single-row and multi-row layout problems are modeled, and they have absolute terms in objective functions, the constraints, or both.

ABSMODEL 1 and ABSMODEL 2

This model is used to formulate single-row facility layout problem. Assumptions made for this model are as follows:

- The facilities are square or rectangular and their sizes are known apriori
- The facilities are arranged in a straight line
- The orientation of facilities is known apriori
- There is no restriction on the shape of buildings where facilities are to be placed

Parameters

n = number of stations in the problem

c_{ij} = cost of moving a unit load of material distance between i and j

f_{ij} = number of loads or trips required between stations i and j
 l_i = length of horizontal side of station i
 d_{ij} = minimum distance by which stations i and j are separated horizontally

Decision Variables

x_{ij} = distance between the center of station i and the Vertical Reference Line (VRL)
 (Refer Figure-1.9)

Objective Function

The parameters and decision variables pertaining to the single-row layout problem are illustrated in the Figure 1.9. Since we are considering only the single-row layout problem, the vertical dimensions of floor plan and vertical side of the facilities are not considered. The following equation represents the ABSMODEL 1.

Minimize

$$\sum_i \sum_j c_{ij} f_{ij} |x_i - x_j|$$

Subjected to:

$$|x_i - x_j| \geq \frac{1}{2}(l_i + l_j) + d_i \text{ where } i = 1, 2, \dots, n-1, j = i+1, \dots, n$$

The objective function of the model minimizes the total cost involved in making the required trips between stations and constraint ensures that no two facilities in the layout overlap. ABSMODEL 2 model can be used to formulate multi-row facility layout with facilities having equal square area. This is similar to ABSMODEL 1 and have following notations used in addition.

Decision Variables

x_{ij} = distance between the center of station i and the Vertical Reference Line (VRL)
 (Refer to Figure: 1.10)

y_{ij} = distance between the center of station i and the Horizontal Reference Line (HRL)

Minimize Objective Function $\sum_i \sum_j c_{ij} f_{ij} (I |x_i - x_j| + I |y_i - y_j|)$

Subjected to $|x_i - x_j| + |y_i - y_j| \geq 1$ where $i = 1, 2, \dots, n-1$ $j = i+1, \dots, n$
 $x_i, y_i = \text{integer}$

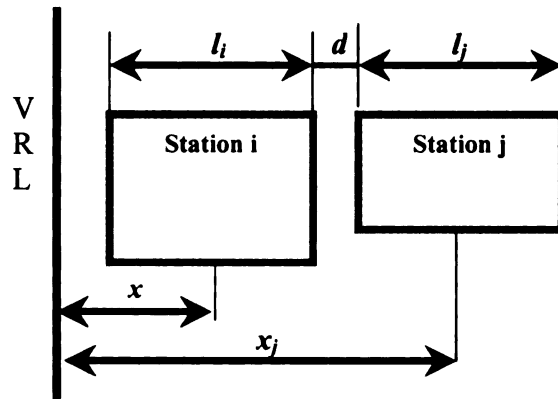


Figure 1.9: Illustration of parameters & decision variables for the single-row layout problem- ABSMODEL 1
 (Heragu 1997)

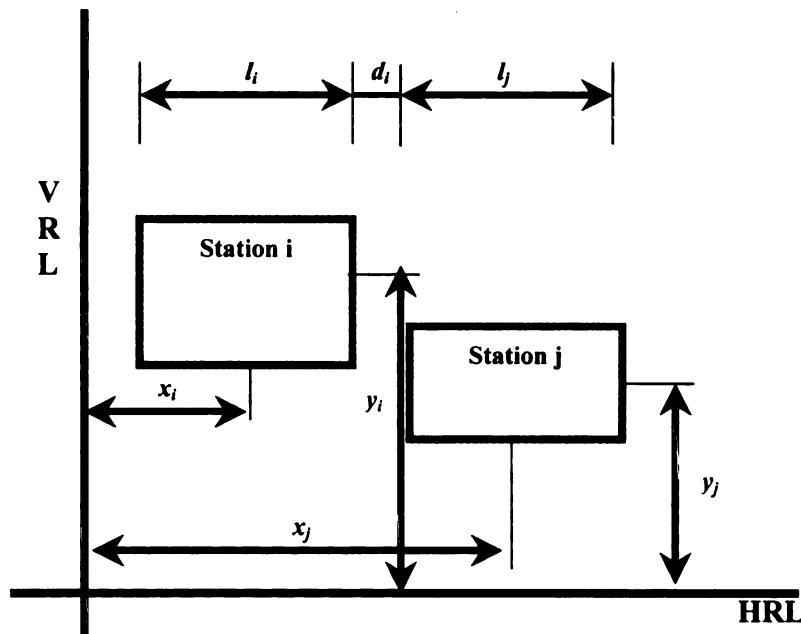


Figure 1.10 : Illustration of parameters & decision variables for the multi-row layout problem- ABSMODEL 2
 (Heragu 1997)

Constraints ensure that no facilities in the layout overlap and impose integrality. In both the above models the facilities were assumed to have equal areas, and

this assumption is not very realistic. For multi-row layout problems the same formulation procedure is adopted by introducing the vertical “y” co-ordinates as the variables. Modeling a facility layout helps to clarify the problem and identify the factors that affect the solution. However, a model by itself does not provide the solution to a problem. Algorithms or step-by-step procedures are developed to solve the model. An algorithm therefore is a systematic procedure that finds the solution to the model, and hence to the problem in a finite number of steps.

Limitations of ABSMODELS

ABSMODELS are not specific but general models. They can be solved using simple heuristic techniques. These models assume that the facilities have equal areas; when facilities have unequal areas, the models have to be modified suitably and, as a result, the models become more complicated in both formulation and computation. Moreover, the models are non-linear and the solution produced by the software may be sub-optimal. To remove the non-linearity in ABSMODELS, the mixed integer formulations of the ABSMODELS are introduced. Such models may be solved optimally by using branch and bound methods and other general techniques available for solving mixed-integer problems. The Linear Mixed-Integer Models for the Single-Row Layout Problem (LMIP) is a modified form of the ABSMODELS to overcome the limitations and are described in details in the Chapter III.

The ABSMODELS are the basic modeling techniques used in the quantitative analysis software solution FactoryFLOW that has been used for the quantitative analysis in this thesis.

Software for layout design, planning and evaluation

Production plant layout design software programs have come a long way from the traditional layout design solutions first developed in 1960s. The following section first describes a few of the layout design software solutions for qualitative analysis and then goes on to cover FactoryFLOW in details. These software solutions are discussed in detail in Chapter III.

Software for Qualitative Analysis

Some of the major software implemented to evaluate facility layout alternatives qualitatively are described below.

ALDEP & CORELAP:

Both of these software programs use the Relationship-Chart to determine the importance of station proximity and evaluate the layout design alternatives qualitatively. CORELAP also requires Relationship-Charts as an input. However, weights must be assigned to the ratings in the Chart. These weights are called "closeness ratings" (CR). CORELAP computes a total CR (TCR) for each station by summing all the CRs associated with that station. CORELAP does not consider the building shape. The final shape of the facility created depends on the placement of stations that CORELAP has selected. The procedure begins by placing the first department in the center of the layout. Each subsequent department is situated according to already-placed departments in the position that gives the best placement rating. The arrangement with the best placement rating is selected.

After the layout is completed, CORELAP calculates a numerical score for the layout. A small layout score indicates a good layout (Palekar 1998).

BLOCPLAN :

This program accepts data input from both From-To-charts and Relationship-charts, i.e. both quantitative and qualitative data are accepted. The major purpose of BLOCPLAN is to generate and evaluate block type layouts in response to the user-supplied data. BLOCPLAN also uses relationship codes specified by Muther in Systematic Layout Planning (Donaghey, 2000).

AUTOCAD based tools:

These tools can be utilized for the purpose of layout design. The factory products group at Engineering Animation, Inc. (EAI, 1999) developed software that simplifies designing a new factory or improving an existing one. Three programs (FactoryCAD, FactoryPLAN, and FactoryFLOW) run inside AutoCAD and allow for both qualitative and graphical analysis, as well as providing valuable tools for creating a layout (Owen 2002). FactoryPLAN is a qualitative layout design tool, which like BLOCPLAN uses Muther's Systematic Layout Planning for design process. It allows the user to position stations based on different flow patterns and does not restrict the positioning of stations as other software programs do. FactoryPLAN was used for preparing layout design alternatives for the manufactured housing production plant in the earlier research work (Mehrotra 2002).

Software for Quantitative Analysis

Some of the software packages that use optimization modeling techniques and algorithms, and quantitatively analyze facility layout alternatives are SPIRAL, LayOPT, Factory Modeler and FactoryFLOW. Among these available packages, the FactoryFLOW software is used for this research due to its powerful capacity to analyze material flow and good AutoCAD based graphical interphase.

FactoryFLOW

FactoryFLOW is the software which is used in the proposed research and it provides an integrated material handling system in visual environment. It is a software that is mainly used for the quantitative analysis of the facility layout alternatives. It can be defined as a post-processor to evaluate layouts, as it requires an existing layout that is to be generated by an Autocad software. However, the user can make minor changes based on the “what-if” analysis performed by this software and can try to improve the previously developed layout (E-Bundle 2003).

Moreover, it also enables the designers to analyze factory layouts by using part-outing information, material storage needs, and material handling equipment specifications. It is used for optimizing layouts based on material flow distances, frequency and costs. FactoryFLOW requires information on each move for each part: quantity moved, material-handling device used and unit load. The information about these factors can be loaded into the software by using spreadsheets or word processing software. Based on the data entered and the Autocad layout file the software calculates

total move distance and cost (Heragu 1997). FactoryFLOW analyzes the layout alternatives on the basis of material movement and material flow cost.

Step-4: To collect data by visiting case-study factory and to analyze the data in order to compile the process details of manufactured housing production plant

The author accumulated details of the material flow by visiting a home manufacturing plant in northern Indiana over a period of six weeks. The observations are documented to arrive at a systematic and detailed description of the process in order to develop a quantitative model of the case study based on the material flow.

Data Collection Process

The author followed a sequential step-by-step approach for gathering the relevant data from the case-study housing plant to develop the quantitative model for the facility layout. The basic data were obtained by watching the production process, videotaping the material movement and material handling activities, noting down the timings, interviewing the factory-floor personnel like production managers, supervisors, workers and maintenance division people. Types and volume of products manufactured, components required for building the product, name and code of each of the components, space requirements, material handling devices and their cost were some of the data collected. Once the basic data were obtained, the relevant data were extracted and were developed in the required format for documentation.

Data Collection Formats

The data collected were developed in the formats described below.

Layout Drawing in AutoCAD: The development of layout drawing was based on the measurements of the plant layout. The layout drawing provided the required information about the space needed for each station, location of the stations, distances between the stations, and aisle network for the movement of materials.

From-To Charts: The from-to charts as described in the Tables 1.3 and 1.4 were developed on the basis of the *Production Quantity Information* and *Parts Routing Information*. Production quantity information is the list of the type and quantity of all the materials/components or parts that are used for building a house. For example, the case-study plant produces six houses per day or 12 units of floors per day and each unit requires six tires for chassis assembly. Similar kind of information was noted and charts were developed for each of the components. This information was collected from the, *Bill of Materials* provided by the purchasing department, interviewing production personnel, and continuous observation of the construction process during the factory visits. Table 1.5 gives the production quantity information of the Frame Assembly of the houses produced in the case-study factory. Similarly charts for part-routing information were developed, based on the sequence in which each part visited each stations or each activity points. The examples of these charts are described in detail in Chapter IV.

Table 1.5: Product Quantity Information for Frame Assembly-A
(Based on the case study)

Frame Assembly			
	Part Description	Parts/Assy	Units
1	Frame	2	EA
2	Axle, idler,	4	EA
3	Axle, brake	2	EA
4	Tyre	12	EA
5	Bolt shackle	24	EA
6	Lock- nut	24	EA
7	Wire-primary red	116	LF
8	Wire-primary white	116	LF
9	Wire-primary black	116	LF
10	Wire brake	64	LF
11	Lug ground	2	EA
12	Wire-Bare Copper	6	LF

Step-5: To develop a comprehensive quantitative model of the facility layout based on the material flow using FactoryFLOW software.

Once the data collection formats were completed the following steps were adopted to develop the quantitative model in the FactoryFLOW software.

- Understanding the FactoryFLOW software data structure and getting started with the software
- Preparing the existing layout design in AutoCAD software and identifying the location of the activity points
- Developing the product tree structure, based on product volume, and part routing information,
- Defining the material handling equipments and system, based on the case study in the FactoryFLOW
- Generating Distance-Intensity Charts and Distance-Cost Reports.

- Validating the quantitative model with industry personnel

1.6.2 Objective II: Computer Aided Analysis of the quantitative model, including development and evaluation of the alternatives

In order to do a quantitative analysis of the facility layout and develop and evaluate alternatives the following steps were performed.

Step1: To identify the critical factors from the reports generated and develop alternatives based on “what-if” analysis.

Step II: To formulate a quantitative model of a typical production process model based on the earlier researches and evaluate various design layout alternatives proposed by Mehrotra (2002) in her developmental research work.

The details of the process steps are provided below.

Step1: To identify the critical factors from the reports generated and develop alternatives based on “what-if” analysis.

Once the quantitative model in software is evaluated by producing the distance cost-reports and distance intensity charts, the critical factors like cost-incurring material movements, large number of trips etc , are identified. Then the alternatives are developed, either by changing the layout distance or replacing the equipment for material-handling between the stations. The alternatives are evaluated to find the increase or decrease in cost or the distance traveled, and the variation in the results are analyzed.

Step 2: To formulate a quantitative model of a typical production process model based on the earlier researches and evaluate various design layout alternatives

In the next step, the author developed a generic quantitative model of the facility layout problem, considering a typical house as a product and a typical production process as the generic production process, based on the earlier researches on a manufactured house production process (Senghore 2001). The quantitative model is integrated with the design layout alternatives (based on qualitative flow) proposed by Mehrotra in her developmental research work (Mehrotra 2002). The design alternatives are analyzed quantitatively in FactoryFLOW software, and results were compared on the basis of the total material flow cost and the distance traveled by the materials between the stations.

1.6.3 Objective III: Outline the process steps required to analyze the facility layout based on the material flow for a Manufactured Housing Production Plant

The following steps were carried out to achieve objective III.

Step1: Develop an outline of comprehensive process steps for the facility layout design of a manufactured housing industry

Step 2: Collect feedback/recommendations from the manufactured housing industry personnel

Step 3: Collect feedback/recommendations from the professional design consultants

The objectives are discussed in the following paragraphs.

Step1: Develop an outline of comprehensive process steps for the facility layout design of a manufactured housing industry

Once the quantitative model is developed, the alternatives are generated and evaluated through the software analysis, and the designer for the facility layout of the manufactured housing plant can come up with an optimum layout for a given manufactured housing plant. The problem of facility layout design can be initially studied at a macro-level, where there is a need to produce both the qualitative and quantitative models for the layout problem. The qualitative alternatives can be better understood by the efficiency scores, while the quantitative alternatives based on the material flow are analyzed by the total cost of material movement. Based on the efficiency scores and cost, the optimum layout can be chosen, which can be further analyzed in a micro-level by changing the layout design or redesigning the material handling system. The proposed methodology will provide the outline of the major process steps required to design the facility layout of a manufactured housing industry. Figure 1.6 provides the structural framework of the important steps involved in this research.

Step 2: Collect feedback/recommendations from the manufactured housing industry personnel

The author interviewed the manufactured industry production managers for comments and suggestions on the method of generating and evaluating the layout design alternatives and also discussed the proposed recommendations with the industry personnel. The final process steps recommended in this thesis were proposed after incorporating their suggestions.

Step 3: Collect feedback/recommendations from the professional design consultants

The author also visited a professional design consultancy firm, which designs mobile factories for building homes, and collected their input on the procedures proposed to come up with the design for a house manufacturing facility. The recommended process outlines were refined based on the feedback from these consultants.

1.7 Research Limitations

The drawback/limitations of the research are as follow:

- The intent of this research is not to propose an optimum layout design, but rather to identify the process steps that can help design an optimum layout for a manufactured housing plant.
- The quantitative model in the proposed research is developed according to the material flow and material handling system of a manufactured housing factory. It does not take into account the information, organization, and control flow as part of the quantitative analysis. The quantitative model developed takes into account only the material movement that takes place between the stations, not the movement within the stations. The material movement within the station is classified as a part of the process.
- The quantitative analysis of the qualitative layouts of the earlier research (Mehrotra 2002) is based only on information of the production process and the layout of the previous case study plants. Since the details about the product and material handling system were not available, the author assumed the information

about the product-structure and material handling system, based on the personal knowledge and present case study factory details.

- FactoryFLOW software used in this research, is an optimization tool that can only evaluate alternative layout scenarios based on material flow, but cannot suggest the optimal solution.
- The research, owing to the thesis scope and hardware limitations, has focused on the 2-dimensional (*e.g. length and width*) analysis of the layout alternatives. The author has not taken into consideration the 3-dimensional (*e.g. length, width and height*) aspects of layout planning. However, FactoryFLOW software has the capability of analyzing 3-dimensional layout alternatives, and this can be an area for future research.
- The cost reduction shown during the analysis of various layout alternatives in FactoryFLOW in this research is based only on material flow, and does not take into account the effect of the productivity and throughput in the complete production process.
- The research does not take into account the supply chain management aspect of manufactured housing production process.
- The author also does not address the effect of the application of Lean construction principles in the operations.
- Implementation of the proposed processes for layout-design in a real factory condition is not within the scope of the research.

1.8 Expected Outcome/Deliverables

This research defines a comprehensive facility layout design process for developing the facility layout of a manufactured housing layout plant, based on material flow.

The other expected deliverables will be:

- Documentation of the complete production process of the case-study manufactured housing plant including the material flow, process flow, layout-design, space and proximity requirements, and material handling system design.
- Description of appropriate layout design techniques and software implemented during the research work.
- Description of the matrices and techniques in the software to analyze the quantitative data, and the process of quantitative modeling of the facility layout problem of the case-study factory.
- Development of layout alternatives and generation of reports to evaluate and analyze the alternatives.
- Quantitative modeling of the typical production process in software and evaluation of the layouts developed in earlier research on the basis of material flow.
- Comprehensive process steps for developing layout design alternatives based on quantitative model and evaluating the alternatives.

1.9 Conclusion

The manufactured housing industry, despite of its critical role as a supplier of affordable homes has been facing a setback due to the economic downturn. Moreover, the production process and facility layout for the manufactured homes are still primitive. Even though research efforts have been made towards exploring processes and improving the process model as well as streamlining material flow, the area of facility planning and layout design is still in a developmental phase. Initial introductory work has been done to introduce new techniques in facility layout design guidelines, considering the space and proximity relationship between the stations. However, a comprehensive procedure based on the quantitative as well as qualitative analysis remains to be done.

The author in this research outlines the comprehensive process steps for the facility layout design of a manufactured housing factory based on the material flow and quantitative model of the facility layout of a manufactured housing plant. The data relevant to the material flow relationship (e.g. material, material handling devices, material handling system) between the stations and within the departments are collected through factory visits and video recordings. The quantitative charts e.g. from-to matrices, and product-tree structures are developed, according to the information collected from the case-study factory, and are used for quantitative modeling in the FactoryFLOW software. The software model is analyzed using FactoryFLOW and various results are generated. Based on the results obtained, the alternative layout designs and material handling system designs are generated and evaluated on the basis of minimum cost. In addition, the quantitative model for the facility layout problem based on a typical production process of a manufactured house is developed, and the S-shaped, Z-shaped, L-shaped, U-shaped

and straight-line layouts, which were outlined in the earlier research, are quantitatively evaluated. The analysis reports of the “what-if” scenarios and layout alternatives are used to recommend the processes that can be followed while preparing the facility layout design of a manufactured housing plant.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Existing research and literature relevant to the proposed research can be broadly classified into three categories, namely, Production Process and Material Management in the Manufactured Housing Industry; Contemporary Facilities Layout Design Concepts and Techniques in Industrial Engineering; and Facility Layout Design Concepts in Manufactured Housing Plants. However, the evolution of facility planning concepts in the manufactured housing industry is still in an exploratory stage. Although literature exists in the areas of the manufactured homes design and production process, there is very little literature related to manufactured housing plant layout design process.

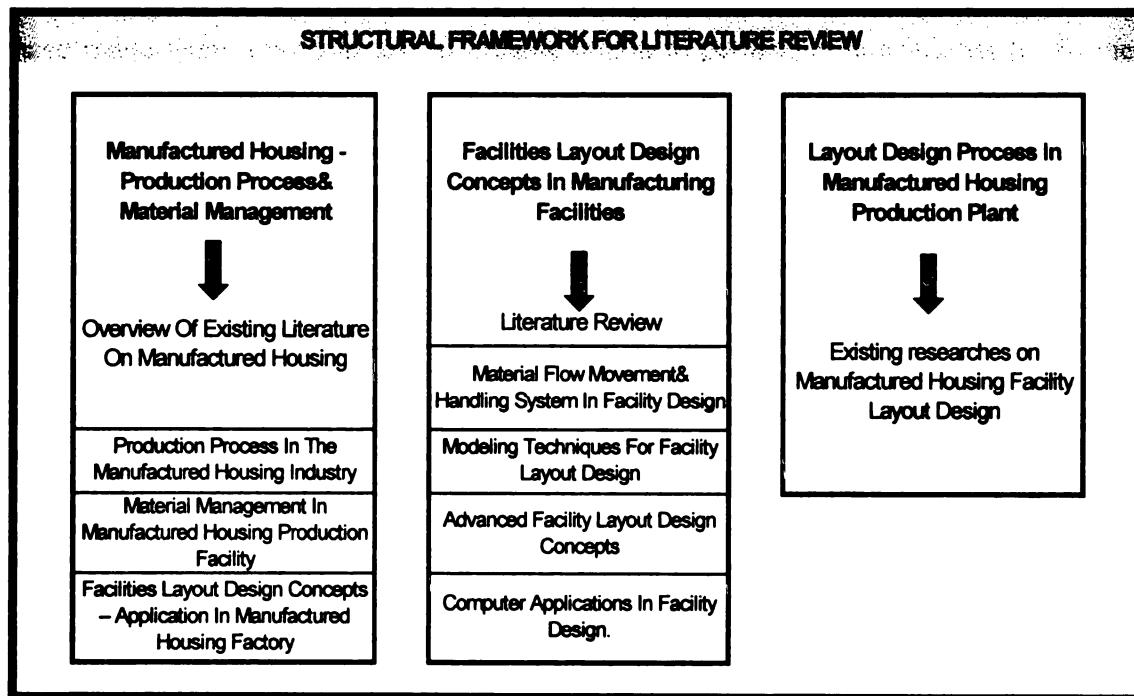


Figure 2.1: Framework For Literature Review Process

In the developmental research work on facility layout design in the Manufactured Housing Industry, the author N. Mehrotra has given a broad outline of the

state-of-art techniques in the context of layout planning process adopted in other manufacturing facilities (Mehrotra 2002). This chapter presents the overview of some of the existing work in the form of research papers and articles in the field of facility layout design, material handling systems design and material flow in manufacturing facilities. Some of the definitions presented in earlier research papers on manufactured housing have been repeated in this chapter for the convenience of the readers. Figure 2.1 is the structural framework that describes the classification behind the literature review.

2.2 Manufactured Housing - Production Process And Material Management

The acceptance of manufactured homes as a permanent rather than transient form of housing and the relaxation of restrictions regarding width of the manufactured homes have made them a popular and affordable option to permanent housing needs. To meet the increase in demand and shift to double-section housing, more production plants are being set up. But this has not really given rise to better designed and efficient home-producing plants. The earlier researches conducted through the NSF (National Science Foundation)-PATH (Partnership for Advanced Technology in Housing) grant identified the bottlenecks in the production process and formed a generic model for the material movement in the manufactured housing factory. The following paragraphs of this section give a brief summary of the background literature of the manufactured housing industry and existing and ongoing researches in this field.

2.2.1 Overview of Existing Literature on Manufactured Housing

A manufactured home is a housing unit that is completely built in a factory and has a price advantage over conventional site-built housing unit. It can have one or multiple

sections (2, 3 or more sections). The lower first cost of manufactured homes makes them economically attractive to starter families, elderly and retired people, and low income households (Lee and Englin 1989).

The *Building Tomorrow: The Mobile/Manufactured Housing Industry* (Bernhardt, 1980) is one of the many books available which discusses manufactured homes as a product, as well as reporting the industrial organization and cost and price structures in different associated areas, like the manufactured home production system, distribution system, the Community parks, and the supporting and regulatory environment. Bernhardt, as a part of two major industrialized housing related research projects, examined the status of the industry and became convinced that, "... *unless the building industry on its own initiative undertakes strategic restructuring of its own business organization as well as of its supporting, regulatory and political environments, it will attain no major performance improvements.*" He maintains that low cost and high quality shelter can be produced in high volume.

In the book *Manufactured Homes – Making Sense of a Housing Opportunity* (Nutt-Powell 1982), the authors express their views on manufactured housing policies covering market demand and need, design and construction, costs, legal issues and public acceptance of housing recommendations.

A report prepared by the National Association of Home Builders (NAHB) Research Center, Inc., for the U.S. Department of Housing and Urban Development, Office of Policy Development and Research, titled *Factory And Site-Built Housing A Comparison For The 21st Century* (NAHB 1998), offers information on several important dimensions in the area of manufactured housing. The information is categorized under

the following headings: overview of the housing industry and recent trends; characteristics of conventional and manufactured homes; household characteristics; design and material characteristics; comparison of the regulatory processes; approval, design, and inspection; code requirements; and finally the cost analysis. Based on the recent growth of the HUD-code approved manufactured housing sector, the report also suggests strategies which, when used by home builders, can improve efficiency, reduce production costs and help deliver affordable homes to buyers.

Another report prepared by NAHB Research Center, called *Home Builders' Guide to Manufactured Housing* (PATH 2000), is basically a guidebook that provides conventional builders and land developers with information on manufactured housing, and primarily focuses on differences between manufactured and conventional homes that are likely to be encountered in practice. The sections of the report describe a variety of options for using these homes. The report also covers issues related to finding a manufacturer, developing product specifications, arranging potential contracts, working with local zoning and land-use planning, considering installation and foundation options, improving the building on-site, and understanding regulatory issues and consumer financing.

The College of Architecture and Urban Planning at the University of Michigan, published their findings on a project called the *Manufactured Housing Research Project* (MHRP 1993), in the form of six reports describing 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 a form of alternative ownership with innovative uses.

Another report published by the Construction Management Program, Michigan State University (Syal & Mehrotra 2002) introduces the different factory built housing options available and describes trends and terminology related to the housing industry both nationally and in Michigan in the first part. The second volume of the report is an assessment of the site regulatory requirements that impact the use of manufactured housing (Mrozowski & Sambhare 2002).

As mentioned in Chapter I, the primary issues that are essential for understanding and determining the current status of the manufactured housing industry consist of (1) the Production Process, (2) the Material Flow and Management System, and (3) the Facility Layout Design process. These key factors are strongly dependent on each other, and their background information is provided in the later part of this chapter.

2.2.1.1. Production Process In The Manufactured Housing Industry

According to Partnership Advancement of Technology in Housing (PATH), the manufactured housing industry has been lagging behind in technological innovations as compared to site-built housing.

In 2000, a joint research team from Michigan State University and the University of Cincinnati was funded by the National Science Foundation (NSF) on the *Modeling Of Manufactured Housing Production And Material Utilization*. As a part of this project, two masters theses have emerged (Senghore 2001; Hammad 2001). Both theses described production process models of construction of a manufactured house

were and utilized simulation-based tools to streamline the production process and examine “what if” scenarios. The remaining part of this section is devoted to the brief explanation of these theses. The first part provides a brief overview of the production process and the later part summarizes both theses.

A manufactured housing factory’s production is primarily evaluated in terms of housing floors, whether it is a single bay or a double bay housing unit. Each factory has its own production rate that generally changes in a seasonal pattern, with lowest demand during the winter months. The production line of a manufactured housing factory consists of several stations organized in a logical way, taking into account the different products they produce. The number of stations varies from factory to factory, but the generic assembly line is composed of four main operations: (1) Floors, (2) Walls, (3) Roof, and (4) Finishing’s Appliances & Testing. Each of these operations can consist of one or more stations, feeder stations and sub-stations (see Figure 2.3). Each manufactured housing factory creates its own scenario to transform the generic operations into an efficient production line (Senghore 2001). Each activity needs to be coordinated at each station, and the interrelationships between stations must be well organized in order to obtain a smooth production flow. The efficiency of a well designed production line can be measured by observing the delay and waste of resources that occurs when one floor does not arrive at a station on time. These delays must be minimized or even eliminated to obtain a smoother and more efficient process flow.

The design of any production line must consider several factors: (1) Activities & sub-activities at each station, (2) station cycle time, (3) feeder station cycle time, (4)

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activity & sub-activity cycle time, (5) time between arrivals, and (6) transfer time of floors between stations (AbuHammad 2001).

The first thesis prepared by Omar Senghore, (Senghore 2001), at Michigan State University, was titled *The Production and Material Flow Process Model for Manufactured Housing*. This report contributed to the improvement of the production process of manufactured housing. The overall goal of the report is to show how the production process of manufactured housing can be improved, and resource utilization streamlined. To achieve this goal, the following objectives were identified. First, process-flow diagrams were developed for multi-section manufactured housing production, and then production and material flow process models were developed. Finally, three to four stations were selected and the process model was transformed into a simulation model in EZSTROBE (Martinez, 1998). The simulation model for example, suggested that the productivity at the roofing station was less than that at other stations. “What if” scenarios were developed by adding the requisite quantity of resources, and a solution to the poor productivity was provided by adding specific numbers of resources. Though, Senghore describes the complete production process in detail using the flow charts, he finally selected a few of the major stations on the production line and prepared, ran, and validated the simulation model.

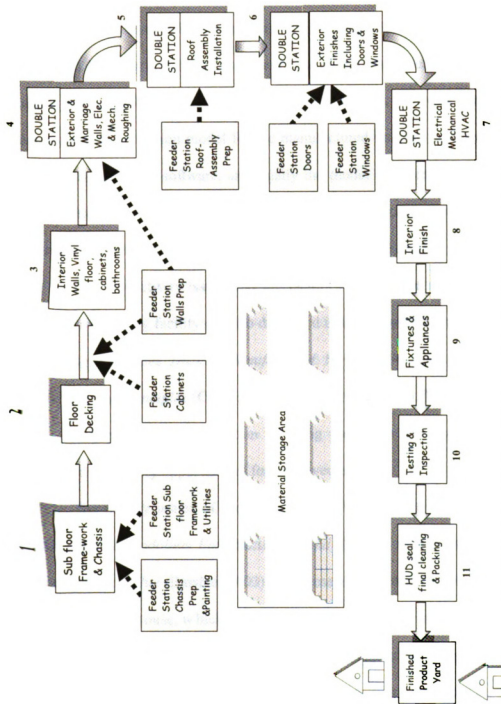


Figure 2.2: Manufactured Housing Production Process and Material Flow.
(Syal and Hastak 2000)

The second thesis was written by Ayman Abdullah Abu Hammad, of the Civil and Environmental Engineering Department, University of Cincinnati, and was titled *Simulation Modeling For Manufactured Processes In Construction* (Hammad 2002). This dissertation also identified ways of improving the productivity of the manufacturing process in a housing factory, so as to lead to a more cost-effective and efficient system utilizing the following procedure: First, the entire factory plan was mapped and then a computer-based simulation model for the manufactured housing production process was developed using Arena software, and finally the model was verified and validated with real performance measures in the factory. Hammad documented and simulated the complete production process of a manufactured home in a factory at a macro level.

The productivity issues and the factors affecting the production process of a manufactured housing facility are also discussed in the research *Performance Assessment Of Planning Processes During Manufactured Housing Production Operations Using Lean Production Principles* (Chitla 2002) in the third research. The goal of this research was to evaluate the plant production planning process in the manufacturing housing industry and to identify opportunities for improvement.

The quality issues of the manufactured homes were addressed in the fourth research titled *Methodology For Evaluating And Ranking Manufactured Houses Based On Construction Value* (Barshan 2003). This research focused on the construction value of a manufactured house, which was defined in terms of the proportion of the overall value of the house, primarily obtained from the construction materials; the processes involved in putting them in place and the post construction assurances against structural or functional damages caused by materials and/or poor craftsmanship, excluding normal

wear and tear. In order to make the decision-making approach more realistic, the research provided a framework for evaluation of manufactured houses based on a goal, which was its construction value, and utilized numerical scoring that translated the qualitative information into a quantitative approach. The proposed scoring model helped to facilitate the decision making process which was used on a case study for comparing and ranking five manufactured homes of different brands, but of the same level.

2. 2.1.2. Material Management In Manufactured Housing Production Facility

The **third** phase of this joint research was on *Material Supply Management System for Manufactured Housing Industry* by Edgar Barriga, 2003. This research addressed the **material** flow issues and proposed the improvement of the material supply efficiency that would **be** reflected in better production rates as well as cost effectiveness and quality.

The primary players in the material management system, as recognized by the **industry**, are the material handlers, material supervisor or head receiver, and the **purchas**ing manager. Each of them has his/her responsibilities well defined and forms an **essential** part of the current material management system. The material handlers move **and store** the material; the material supervisor checks quantities and quality of the **material** upon delivery and decides if the material is needed at the station; while the **purchasing** manager is in charge of the cycle counts, the tracking of inventory levels and **records**, and the quantity estimation and order of different materials. The material is **placed** either in the bulk storage or at the proper station. Due to this strategy, the material **needs** to be moved several times before it is used, creating waste of resources. The

material estimation is done manually, and therefore involves extensive time and resources and also creates an excessive amount of paperwork, making it very difficult to keep track.

The overall goal of the research was to develop an efficient material supply management system that can be considered as an alternative to be applied in the Manufactured Housing Industry. Initially the research examined and analyzed the current material management system in the manufactured housing industry to detect its shortfalls *such* that proper recommendations can be proposed for improvement. In addition to this, it *provided* a more efficient material management system by combining different *successful* management techniques used in other manufacturing industries and field data *obtained* from several visit to different factories. The proposed methodology took into *account* the material requirement planning (MRP) and integrated the use of available *technology* to make it more efficient. The methodology also recommended the use of a *computer* database, developed using Microsoft Access, to replace the physical database that is *primarily* used in the manufactured housing industry, for improving the quality of *management* of information.

2.2.1.3. Facilities Layout Design Concepts – Application In Manufactured Housing

Factory

The facility layout design of the manufactured housing factory is a critical factor that *affects* the efficiency of the production process. It depends mostly on factors like the *assembly* line design, the product built, the material flow movement and the material *handling* system. Primarily, three layout styles can be found in a manufactured housing *factory*: Linear, U-shape, and Serpentine (see Figure 2.4). Linear layouts are more

suitable for factories that construct single-wide housing units, while U-shape layouts work better for factories that produce double-wide units alone or a combination of single and double-wide units (AbuHammad 2001).

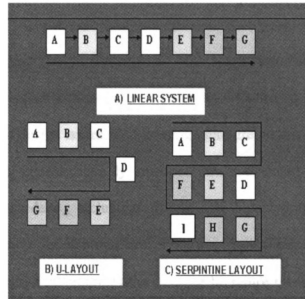


Figure 2.3: Alternative Layouts for Manufactured Housing Factories.
(Hastak and Syal 2002)

Moreover, research attempts have also been made to incorporate advanced concept of facility design in the layout development process of other factory-built housing sectors, e.g. modular housing production facilities (Mullens 2002). The researchers provided technical assistance in the design of the new modular production facility by incorporating lean manufacturing principles and making the new factory more flexible, responsive, and efficient. To test these concepts, researchers developed a computer simulation model of the proposed new factory innovations.

As already discussed earlier, the Manufactured Housing Industry is a relatively new area for research, and that is the reason why few technical articles can be found. As a continuation to the PATH Initiative, a developmental research work on *Manufactured*

Housing Plant Facility Layout Design was carried out by Namita Mehrotra (2002) and is summarized in the later part of this chapter. The initial part of the following section discusses the existing literature and research works carried out in the field of facilities planning and design in manufacturing facilities.

2.3 Facilities Layout Design Concepts In Manufacturing Facilities

This section of the chapter presents a brief summary of some of the recent research on *facilities* planning and design issues. The existing literature on this subject can be broadly *classified* into four categories, namely, material flow movement and handling systems and *facility* design, modeling techniques for facility layout design, advanced facility layout design techniques and theories, and computer applications in facility design. The *initial* part of this section summarizes the existing literature on facilities layout design, while *the* later part presents the various strategic, practical and academic concepts of *facilities* design, and how they are affected by other factors in manufacturing systems and *facilities* planning strategies in other industries, such as electronics, polyester, etc. Moreover, the research based on computer application oriented facility layout design is also briefly presented.

2.3.1. Literature Review

In this section, the author presents the new perspectives, expertise and significant *advances* in facilities planning studies by summarizing existing literature and academic *textbooks* that deal with the facilities design and planning theories and concepts. *Definitions* of some of the frequently used technical terms related to facilities planning *concepts* that are often used are provided for the convenience of the readers.

(i) Facility Planning

The concept of Facilities Planning is a complex and broad subject that cuts across several specialized disciplines. "Facilities can be broadly defined as buildings where people, material and machines come together for a stated purpose-typically to make a tangible product or provide a service" (Heragu 1997). Facilities planning, in general can be defined as "*how an activity's tangible fixed assets best support achieving the activities' objectives*"(Tompkins et al. 1996).

In the specific case of manufactured housing facilities planning, the definition of **Facility Planning** as discussed in Chapter II can be modified into the "*determination of how a manufacturing facility best supports production of manufactured houses*" (Tompkins et al. 1996) and, since the techniques used in facilities design come from the larger domain of manufacturing facilities planning, it is important to understand the concepts in this area first.

(ii) Models

A **model** can be defined as the purposeful representation of the essential features of a real world system which can be used to analyze the effectiveness of an existing system or the feasibility of a proposed system (Chung 1989). Based on the level of abstraction, a model can be classified into physical, analog and mathematical (Heragu 1997).

(iii) Algorithms

An **algorithm** is a step-by-step procedure that finds a solution to a model and hence to a problem in a finite number of steps (Heragu 1997). Based on the nature of input the algorithms can be classified into two categories, namely, (1) Algorithms accepting qualitative "flow" data from relationship charts, (2) Algorithms accepting quantitative

flow matrix expressed as From-To charts. The formulation of the charts is described in Chapter III of this thesis (Tompkins et al 1996).

(iv) Quadratic Assignment Problem (QAP) Objective

Layout algorithms can be classified according to their objective functions, namely, (1) Aims at minimizing the sum of the flow times distances, and (2) aims at maximizing adjacency scores. The “distance-based” objective is similar to the classical Quadratic Assignment Problem (QAP) and accepts data from the quantitative “From-To” charts. The objective function can be expressed mathematically as the following:

$$\text{Minimize } Z = \sum \sum f_{ij} c_{ij} d_{ij} \quad i=1 \dots n, j=1,2\dots,n$$

Where:

m = number of departments

f_{ij} = flow from dept i to dept j (expressed in number of unit loads moved per unit time)

c_{ij} = cost of moving a unit load one distance unit from dept i to dept j .

d_{ij} = distance from dept i to dept j .

(v) Constraints

The constraints in an optimization problem can be represented in a mathematical model in a number of ways. Three ways of expressing the possible constraints in an optimization problem are:

A less than or equal to constraint: $f(X_1 X_2 \dots X_n) \leq b$

A greater than or equal to constraint: $f(X_1 X_2 \dots X_n) \geq b$

An equal to constraint: $f(X_1 X_2 \dots X_n) = b$ (Ragsdale 2002).

(vi) Genetic Algorithm

A genetic algorithm (GA) is a search algorithm that is based on biological process of natural selection. It belongs to a class of randomized parallel search heuristics (Rongliang, 2001).

(vii) Objective Function

The objective in an optimization problem is represented mathematically by an objective function in general format:

$$\text{MAX (or MIN): } f(X_1, X_2, \dots, X_n)$$

The objective function identifies some function of the decision variables that the decision maker wants to maximize or minimize (Ragsdale, 2002).

(viii) Decision Variables

The decisions in an optimization problem are often represented in a mathematical model by the symbols $X_1, X_2, X_3, \dots, X_n$. $X_1, X_2, X_3, \dots, X_n$ (and are referred to) as variables or decision variables in the model (Ragsdale 2002).

In the U.S, approximately 8% of the gross national product is spent on new facilities, with about 3.2 % spent on manufacturing facilities specifically (*Over 250 billion dollars are spent on the planning and re-planning of facilities*). It has also been estimated that 20-50% of the total operating expenses for a manufacturing plant is attributable to material handling (Tompkins et al. 1996). However, various case studies reveal that, with effective facility design, the cost of material handling can be reduced by at least 30%. (Tompkins et al. 1996). Facilities planning is one of the most promising areas for improving the rate of productivity, since the layout and configuration of the facilities are very strongly related to the production process and the material flow

movement and, as a result, continue to be the most significant part of manufacturing process. In addition, economic considerations force a continuous re-evaluation and up-gradation of existing systems, personnel and equipments. The facilities planning and design of a manufacturing facility should have the capability to adapt to these new developments and changes.

In 1954, the literature available on plant layout was in the form of papers and articles in periodicals. The book *Factory Planning and Plant Layout* (Ireson 1954) was an attempt to organize the literature available along with the author's own ideas about planning and design of layouts. The author suggested that the final measure of the effectiveness of a factory plan lies in the cost of manufacturing the product in the plant; therefore, cost must be an important measure to be applied in the design procedures. The design problems used small and medium size plants. In doing so, the author reasoned that any complicated product consists of a number of smaller problems of planning facilities from the production of component parts and subassemblies to the final assembly line. Hence procedures described in this book are simple and direct.

Plant Layout and Materials Handling (Apple 1963), another one of the earlier books on plant layout and design, is presented from an engineering standpoint without becoming too involved in the technical features of equipment design and construction. Apple emphasizes the major issues of the coordination between plant layout, materials handling, methods engineering and production planning and control. One of the major goals of the book was to take advantage of all the different interrelated techniques so as to develop a satisfactory and practical layout. These layout design techniques can be used

for several facilities, such as manufacturing plants, warehouses, offices, or other industrial and business facilities

In *Facility Layout and Location- An analytical approach* (Francis & White 1994), the authors suggest that studying facility layout and location offers considerable potential for the application of operations research. A few of the major objectives of this book are:

- To provide the facilities analyst with new techniques, approaches, and philosophies for the solution of facility layout and location problem.
- To stimulate interest in facility layout and location problems within a wide variety of academic disciplines.
- To provide an opportunity for a shift in the emphasis on quantitative and qualitative aspects of facility layout and location.
- To provide a classification of the rapidly expanding body of literature on facility layout and location problems and attempt to treat a selected portion of the literature in a unified manner.

One of the recent books in this field, *Facilities Design* (Heragu 1997), deals with the proper design, layout, and location of facilities. The author suggests, “*poor facility design can be costly and may result in poor-quality products, low employee morale, and customer dissatisfaction.*” (Heragu 1997). The author provides information on types of layout problems, traditional approaches to layout design, tools and techniques for layout design, generic modeling tools, algorithms and group technology. Basic and advanced models are also available for plant location problems.

Facilities Planning (Tompkins et al. 1996), has been and is being used as a textbook for facilities design in several industrial engineering schools in the country. The book is divided into five parts. Part one focuses on the determination of the requirements for people, equipment, space, and material in the facility. Part two presents concepts and techniques to facilitate the generation of alternative facility plans. Part three continues the focus on producing alternatives but focuses on the functions of the organization. Part four presents a variety of quantitative approaches that can be used to model specific aspects of facilities planning. Part five concludes the treatment of facility planning and deals with evaluating, selecting, preparing, presenting, and maintaining the facility layouts.

The author also discusses the major objectives of facility planning. Although it is difficult to state a meaningful objective for facility planning, it may be broadly defined as the ability to achieve the stated purpose (*goal*) while satisfying several other objectives (*constraints*). For example, a facility is designed only once, but it is under a constant phase of reorganization owing to the rapidly changing objectives. Some typical facilities design objectives are to (Tompkins et al. 1996):

- (i) Support the organization's vision through improved material handling, material control, and good housekeeping
- (ii) Effectively utilize people, equipment, space, energy
- (iii) Minimize capital investment
- (iv) Be adaptable and promote ease of maintenance
- (v) Provide for employee safety and job satisfaction.

Nevertheless, one must go beyond the theoretical knowledge, principles, guidelines and techniques and develop on-hand understanding of often-interconnected

objectives that are in cross-purpose with each other and affect the overall outcome. As a result, the process of planning facilities becomes both scientific (*numerical*) and personal experience (*expert-system*) based. This book also presents a vivid and detailed analysis of various facility layout and design software, and algorithms to solve facility design issues, which are described in the Chapter III of this thesis.

Apple (1963) defines the objectives of plant layout as:

- *Facilitates manufacturing process*: The layout should be designed such that the manufacturing process can be carried out in an efficient way. This objective can be attained by (a) arranging machines, material, and work areas so that material moves smoothly, (b) eliminating all delays possible, (c) planning the flow in such a manner that work passing can be easily identified, and (d) planning for maintenance of conditions.
- ♦ *Minimizes material handling*: In an efficient layout, material handling can be reduced to a minimum by using mechanical equipment (automated guided vehicles etc.) and the distances continually traveled by the parts in transit and towards the shipping area can be shortened.
- ♦ *Maintains flexibility of arrangement and operation*: The layout design should be flexible enough to respond to the changes in the product design or the design process.
- ♦ *Maintains a high turnover of Work-In-Process*: By reducing the in-process storage of material, the overall material turnover time is shortened, and thereby the operational cost is reduced.

- ♦ *Holds down investment in equipment:* In a good layout with a proper arrangement of machines and departments, the number of pieces of equipment used can be reduced.
- ♦ *Makes economical use of floor area:* Only if each square foot of floor area in a plant is used to attain maximum advantage (the space constraint being an inherent problem in facility designing issues), the layout would be efficient.
- ♦ *Promotes effective utilization of manpower:* Proper layout can increase the effective utilization of labor.
- ♦ *Provides for employee satisfaction:* This objective can be met only if attention is given to items such as, light, heat, ventilation, safety, removal of moisture, dust, dirt etc.

2.3.1.1 *Material Flow Movement and Handling System In Facility Design*

The design of the material handling system is an important component of the facilities design problem. Material handling occupies 25% of all employees, consumes 55% of all factory space and 87% percent of production time, and represents between 15 and 70% of the total cost in a typical manufacturing facility (Heragu 1997). Researches and improvements in various material handling system design resulted in the reduction of the total manufacturing costs through reduced inventories, improved safety, reduced pilferage and improved material control (Tompkins et al 1996).. The *Material Handling Handbook* (Kulweic, 1980) defines material handling as the “..art and science of moving, storing, controlling and protecting material.” Another definition of material handling is provided by Tompkins as “..Material handling means providing the right amount of right

material, in right condition, at the right place, in right position, in the right sequence for the right cost, by using right methods” (Tompkins et al, 1996).

The factors that need to be taken into account while analyzing the material handling problems include the type of materials, their physical characteristics, quantities to be moved, the sources and destination for each move, the frequencies and rates at which the moves must be made, equipment alternatives and the units to be handled. The integration of above mentioned material characteristics and move or flow requirements is developed as *material flow* (Tompkins et al, 1996).

Selection of material handling equipment is another inherent aspect of material handling system design. The type of the material handling equipments can be divided into four categories: (1) Containers and unitizing equipment, (2) Material transport equipment, (3) Storage and retrieval equipment, and (4) Automatic identification and communication equipment. The containers and unitizing equipment category includes pallets, skid boxes etc. The conveyors, industrial vehicles, monorails, cranes and hoists comprise the basic material transport equipment. Storage and retrieval equipment is used to store and retrieve large and small loads. Barcode readers, radio frequency data terminals, light and voice directed communication devices are some of the automatic identification and communication equipment commonly used.

In *Scheduling and Control of Manufacturing Systems with Critical Material Handling* (Taghaboni & Fataneh 1990), the authors focuses on the evolution of the manufacturing systems from mass producing systems to low volume and highly flexible production systems that have compelled the material handling systems also to change. Because of this change in production systems, the material handling systems along with

the facility layout should be more adaptive to the low volume and highly flexible manufacturing system. With the advent of Automated Guided Vehicle Systems (AGVS) the researchers lay more emphasis on the material handling systems interaction with the machine layouts and machine centers so that the production shop performance is improved. The research proposed a control strategy for facility layout and material handling system of a shop floor that will take advantage of the flexibility that the AGVs have to offer to the production system.

Similarly, in *An Integrated Framework for the Design of Material Flow Systems* (Rembold & Bernard Frank 1993) the authors projected the material flow system as a multifaceted problem where the designer is required to process a large amount of information and make complex decisions concerning the layout design objectives. The research developed an integrated design framework for building material flow system models (object-oriented) as key steps towards the management of design philosophy. The model is built, evaluated and improved, using a collection of distributed software applications that have been developed to address partial problems in the material flow system design process. This framework also helps in diagnosing model performance problems and selecting improvement actions and implementing them in design tools.

The authors in *A Framework for the Design Justification of Material Handling Systems* (Noble & James Stewart 1992) restate the proposition that modern manufacturing systems are complicated, dynamic, integrated combinations of people, information, materials and machines that should function as a whole to attain the system goals and objectives. The research had two objectives:

- ♦ Explore the economic objectives of design generation and design evaluation

- ♦ Address the design of robust material handling systems, capable of supporting a dynamic, product life-cycle induced integrated system design.

The issues that were addressed during the process were, namely, to identify an integrated design approach to overall manufacturing system design; to develop a structure for conducting performance analysis of the system; to develop cost models to measure the economic performance; and to explore the impact of various design factors on the selection and specification of material handling systems.

Ananth K in *Analytical Performance Models for Material Control Strategies in Manufacturing Systems* (Ananth, 2002) states that the flow of jobs in manufacturing systems and the determination of what and when to produce at the different manufacturing stations, are regulated by material control strategies. The research developed a new approximate methodology for analyzing the queuing models of a large collection of material control strategies for multi-stage manufacturing systems. The output of the analytical framework was achieved through simulation and had the advantage of being simple and scalable.

Quantitative Methodology and Applications in Measuring Supply Chain Complexity (Luke, 2002) is a paper that presents entropy-based methodology for measuring and analyzing the material and information complexity across organizational interfaces. The paper defines a complexity analysis that can be used to emphasize several issues that are crucial to efficient material management and internal control. The methodology proposed by the author is based on dynamic and static characteristics of the flows that contribute to the overall complexity of the supply chain. The methodology

provides a quantitative insight into the transfer of complexity along the material flow and movement.

In S. Yang's *Decision Support System for Machine Re-Layout Planning* (Yang 2001), facility layout and re-layout activities have been defined as recurring activities in most of the manufacturing facilities. The re-layout process is almost unavoidable owing to the uncertainty of product demands and variable consumer behavior. According to the survey conducted during the thesis, it was observed that the frequency of the major re-layout of facility designing occurs once every 1.7 years. However, the existing layout models do not consider the re-layout constraints and hence there is a need to develop a model that specifically suits the re-layout process. The material handling system should be designed according to the layout and the interaction between any two stations. The author integrated both of these design criteria in a decision support system for the machine re-layout planning. The existing performance measures were evaluated and new indices were proposed to measure the system throughput and then the layout was improved by genetic algorithm. After that, a simulation model was developed which supported the if-then analysis and provided a structured method for making decisions in facility planning. As a result, it enhanced the method of information exchange between sub-systems of a manufacturing system.

Another dissertation that addresses the issue of integration of manufacturing shop layout design concurrently with its material handling system is *Integrated Manufacturing Facility Design (Routing, Shop Layout)*, (Ioannou, 1995). This study proposes a method to develop shop floor designs that are both operationally efficient and can be economically set-up. While developing a comprehensive mathematical model, the

author addresses the three primary interconnected issues, namely, the topology of the material flow network, the transporter fleet size and routing, and the layout of the resource groups on the shop floor. This model will be able to capture the critical and practical factors such as investment and operational costs, shop floor capacities and traffic congestions.

S.Rajagopalan also considers product and process design as the two key element factors to be addressed while designing a manufacturing system in his *Flowpath Design and Analysis of AGV-Based Material Handling Systems* (Rajagopalan, 1999). According to the author, the process design covers equipment selection and designing of the machine layout and the material handling system. The efficiency of the manufacturing system is influenced by two key factors, namely, facility layout design and material handling system operation. The thesis primarily focuses on the flow path design and analysis of AGV based material handling systems. A framework is proposed that focuses on solving the facility layout problem, location and flowpath design problem in an integrated manner. The model attempts to solve the combined location and flowpath design through an intelligent agent-based simulation. The results of the simulation are then validated with the results obtained by using traditional methods.

F.Rembold in *An Integrated Framework for the Design of Material Flow Systems* (Rembold 1993), also restates the fact that facility layout design in manufacturing systems is a multifaceted problem where the designer is required to process a large amount of information and make complex decisions concerning design objectives. The thesis proposes an integrated design framework that had been developed to address the key issues in managing the design complexities. The framework is

primarily an object oriented model that is applied as a tool to breakdown the material flow system model, and the design environment into modules. The designer was provided with a generic material flow system model that would start the design process. Once the model was built, evaluated and improved, it provided assistance in building and evaluating facility layout systems for given plans and diagnosed their performance.

J.Huang considers material handling to be an important component of flexible manufacturing systems (FMS) in his thesis *Load Volume Considerations in the Collision Free Route Planning of Material Handling Devices in FMS (Flexible Manufacturing Systems)* (Huang, 1992). The research addresses the problem of optimal and efficient routing of AGV through a guide path network. The sequential approach to planned routes for one vehicle at a time is presented with the assumption that the size and load are negligible. Traffic constraints are also incorporated and the routing of AGV are formulated as a shortest time path problem in a network with time window constraints. The simulation of the sequential model is performed to study the performance and the routing. Finally, the extensions of the algorithms to the case of cooperative material handling systems are discussed.

Similarly, R. Pandit in *Job Shop Scheduling to Minimize Make span with Explicit Material Handling Considerations (Flexible Manufacturing)* (Pandit, 1990) pointed out that the flexible manufacturing system can be efficiently operated by exploiting routing flexibility and scheduling flexibility. The author used a binary linear programming formulation for the problem and discussed its mathematical structure. Routing of material handling vehicles and a classical job shop problem were identified as the two major sub-problems. The branch and bound procedure was adopted to solve the

overall problem. However, when the problem became more complicated, four heuristics were developed based on a sequential approach to scheduling of machines and material handling systems, shifting bottleneck approach, and differing the treatment of the material handling vehicle.

The study of a multistage, multi-product, decentralized, market driven manufacturing systems is carried out in the *Performance Analysis and Capacity Planning of Multi-Stage, Multi-Product, Decentralized and Market Driven Manufacturing Systems* (Cigdem 2002). The study consisted of unit production at each stage and transportation of material from one stage to another in batches. The system is responsive to a complete process that integrates production, procurement, inventory handling and material movement activities. The research developed algorithms for the purpose of performance analysis and system design. The main contribution of this research was to increase the handling effectiveness of material transfer between the stages that were controlled by inventory control policies. The solution provided, through an analytical approach, resolved a major difficulty that arose due to the material transfer of material in batches. Issues like optimal configuration of the manufacturing systems and the facility layout were also addressed.

The paper on *Facility Layout and Material Handling System Design Integration in Manufacturing Systems* (Taho 1996) deals with the generally known interaction between the facility layout and material handling system in manufacturing plants. The author analyzes the impact of the facility layout and material handling system on the performance of manufacturing production. However, developing approaches that will simultaneously determine the optimum layout taking into account both of the above

factors are difficult. As a result, the paper investigates the design problems in manufacturing systems and then proposes design methodologies to solve the combined design problems. The integrated design approach developed redefines the method of distance measurements based on the material handling equipments used. The proposed methodologies for integrated design covers three specific areas, namely, flexible manufacturing system with an undirected flow path, flexible manufacturing system with a directed flow path, and production facilities.

Another research study that generalizes the relationship between material flow patterns and the distribution of materials handling volume distance associated with layouts in a manufacturing system is *Material Flow and Volume Distance Relationships in Line Layout Manufacturing Systems* (Abdulghani, 1996). In this thesis, the “*total expected unit load travel distance over the average system operating period*” is represented as the material handling volume distance. Moreover, the material flow patterns are depicted as the average rate of unit load flow between the workcenters of a station and is defined by the part-routings and production schedules. The material flow patterns are represented by the categorization of the distribution of net incoming and outgoing flow volumes for individual workcenters, and the distribution of average flow volumes between individual pairs of workcenters. The research was technically approached by performing a series of empirical studies that focused on measuring general relationships between the material flow patterns and the distribution of materials handling volume-distance in a line layout. The researcher developed the results by using a classification system based on five alternative probability distributions and the results predicted the form of the material handling volume-distance distribution based on the

material flow patterns. The results suggest that volume-distance sampling and material flow analysis procedures may have practical value in the development of cost effective criteria for heuristic line layout methods in manufacturing systems. The volume-distance parameter estimates thus generated, can be used to define satisfying criteria for layout algorithms and can be modeled through a series of quadratic assignment problems (QAP) with known optimal solutions. Moreover, the research also provides the methodology of the investigation and develops the sampling method for characterizing the probability distributions of material handling volume-distances. In addition, the research further identifies the general relationship between the distribution of volume distance values associated with the solution space of a layout problem and the patterns of material flow within a manufacturing system.

It is a widely accepted fact that the manner in which empty devices in a trip-based material system are dispatched affects the overall productivity of the material handling system. The researcher in *New Strategies For Device Dispatching in Trip Based Material Handling Systems* (Yaen 1996), mentions some of the existing dispatching rules, namely,

- Do not assign a move request until a device that deposits a load becomes empty
- Do not allow an empty device to be reassigned to another move request
- Do not consider the status and current assignment(s) of other devices before assigning a move request
- Do not take advantage of available information such as processing times
- May lead to considerable empty travel that reduces the efficiency of the system

The author proposes new dispatching rules in the dissertation to address the shortcomings of the existing rules and utilize the information readily available from the centrally controlled systems. The proposed new rules are,

- Modified shortest time first (MOD STTF)
- Bidding based dynamic dispatching(B2D2)

Both of the above mentioned rules aim to minimize expected load waiting times and empty device travel.

Ramu in *Design Methodology for Modeling Warehouse Internal Layout Integrated with Operating Policies* (Ramu 1996), states that a warehouse performs on the basis of the appropriateness in its design, layout configuration and operation, and material handling systems. According to the author, the conversion of an existing building to a warehouse is more challenging for a facility planner rather than building a new facility. The designer had to take into account all the factors like flexibility, layout configurations, storage density and throughput. The warehouse planning problem can be analyzed in two ways: static and dynamic. The problem is made simpler by analyzing the static elements initially which later help to achieve the effective design in minimum amount of time and reduce the number of alternatives to be considered in the future dynamic analysis. The research develops a design methodology that integrates internal layouts and warehouse operating policies to match flexibility requirements. The concepts of the methodology primarily deal with the mathematical model and the simulation modeling within the structure of a decision support system. The methodology can be adopted by the designer to use integration of the layout, equipment and operating procedures to calculate the space needed, to determine the optimal internal layout, the type and amount of material

handling equipment required and functioning methods for storage and retrieval functions.

The paper on *The Simulation of Material Flow and Productivity in a Manufacturing Facility*, (Li 1994), focuses on the prediction of the output rate and material flow in a manufacturing process. The author proposes to perform the job of prediction through the construction of a simulation model. The author has studied a real-life manufacturing process and defined the simulation model of the process by deriving the step-by-step simulation formulas. The author runs the model and validates the model with the real life production and material flow results. Once the model is validated, various “what-if” scenarios are performed for prediction.

2.3.1.2 *Modeling Techniques for Facility Layout Design*

The author in *A System for Facility Layout Design* (Rongliang, 2001) develops a facility layout tool that is easy to manipulate, incorporates a variety of optimum algorithms and processes large amount of data. A Graphical Use Interface (GUI) system is introduced and is defined as the communication interface between the user and the computing software. The author presents two separate kinds of algorithms that are implemented for the GUI evaluation, developed for the purpose of facility layout design. The author emphasizes the tactical and strategic importance of Facility Layout Problem (FLP) and states that the layout of the machines (facilities) in a factory (system) plays a significant role in determining the flexibility and efficiency of a system. According to him the cost of moving materials from one location to another is directly dependent on the location of the facilities and, as a result, the efficiency of a layout design lies in the reduction of the material handling costs. The classical Quadratic Assignment Problem (QAP) model is

used to solve the FLP. However, the second degree quadratic expressions presented in the QAP models often yield sub-optimized results, as there is no dominant algorithm that can solve effectively the combinatorial optimization problems. As a result, Genetic Algorithms (GA) are developed to provide new ways to solve QAP. The paper presents genetic algorithm as a search algorithm based on the mechanics of natural selection and genetics.

Another way of evaluating the facility design alternative for ever-changing manufacturing systems is presented in *Design and Implementation of A Decision Support Framework for Evaluating Manufacturing Alternatives* (Budiman 1999). The author developed a decision support framework for modeling the evaluation and selection of facility layout designs. The framework was based on data collected from a selected sample from industry, and its effectiveness was evaluated using a case study. A computer implementation of the decision support framework provided a simulation model that was integrated with the evaluation model for the comparison of alternatives. The research finally had a practical implication as well as an academic one. Practically, this framework would assist decision makers to better understand and apply the justification process and the system behavior under different manufacturing scenarios. Academically, it could also be used as an educational tool for students to understand the justification process and its trade-offs and complications.

Throughout the dissertation *Interactive Optimization Based Facilities Layout* the author proposes a new approach to deal with facilities block layout (Montreuil 1982). The proposed new methodology integrates three major mechanisms, namely, optimization models, color graphic computer interface and human facilities designer. The

basic underlying structure of the layout is achieved by solving the models and is displayed in a graphical form on a colorgraphic terminal. After this the human designer utilizes his knowledge to develop the layout structure in details. This is a repetitive process between the designer and the models through the graphic interface and this iteration continues until a suitable layout is generated. The author demonstrates two interactive structural prescriptive methodologies for computer aided facilities block layout. *“The MATCH layout approach deals with layout design situations where department weighted adjacencies maximization is the main objective and rigorous department configurations are imposed.... The TREE layout approach is oriented toward the design of layouts where the material flow movement is imposed to be along a fixed tree flow structure as a compromise between traffic control, layout adaptability and flow efficiency”*. In the context of the current thesis, the concept of MATCH and TREE approach can be broadly described as qualitative approach and quantitative approach respectively. Both the MATCH and TREE approaches can be represented and generated in colorgraphic microcomputer and provide access to the designer with a series of specialized functions for the layout design process.

Open Queuing Network Performance Analyzer for Reconfigurable Manufacturing Systems (Meng 2003) focuses on the open queuing model for estimating the operational performance measures for a given layout. According to the author, the manufacturing industry is experiencing two major changes. The first step involves the change in material used to make the end products and the machining technology. The second change occurs because the traditional mass manufacturing environment is gradually being replaced by a manufactured-to-order environment characterized by

higher variety, smaller batches and less production times. These changes make it necessary to design layouts that are easily reconfigurable and responsive to fast changing demand patterns. The model that was developed in the thesis used the proposed manufacturing system information as the input and incorporated parameters such as setup time, batch size, machine failure etc. This procedure helped the user to analyze a real world manufacturing system more accurately. Existing technologies were used to generate alternative layout designs that take into consideration deterministic design factors, such as material handling and machine relocation costs. The alternative designs were analyzed using an open queuing network model and, based on the analysis, minor changes were made to the design; the one that performed well with respect to design and operational measures was selected.

Another research study that deals with the modeling, design and control of manufacturing facilities with multiple products is *Issues in Design, Planning and Control of Multi-Product Manufacturing Systems*, (Sheikhzadeh, 1997). The main focus of the research was to identify strategies at the design, planning and operational level that would make the manufacturing plants capable of producing multiple items with higher quality. The research proposes the guidelines for the manufacturers, which will enable the manufacturers to accommodate high product variety without sacrificing the quality and cost issues. In order to prepare the guidelines, the researcher deals with the problem at three levels: (1) Short term (operational), (2) Medium term (tactical), and (3) Long term (Strategic).

In *Autonomy and Viability in Agent-Based Manufacturing System* (Huang 1999), the author developed a new model of manufacturing systems which was called

Agent Based Manufacturing Systems (ABMS) on the basis of agent theory and organization. In the ABMS model, the agents were autonomous, were working collaboratively with each other, through the regulation of structured dialogues, and were connected by communication links. The ABMS was developed to identify and evaluate the performance characteristics and investigate the new paradigm of manufacturing systems.

S. Chittratanawat in his dissertation paper *Operations Based Facilities Design* (Chittratanawat 2001) addresses the integration of facility layout and inventory and called it an operation based facility layout problem. Even though the inventory problem has always been associated with production / operation planning problem, it has seldom been considered a part of facility layout. Traditionally, facility planning has addressed the structure of a manufacturing system, and it was generally believed that there was no explicit interaction with production / operation planning or the inventory system. However, facility layout and inventory are inherent elements of a manufacturing system and there is interaction between these elements. The author develops an integrated systems design approach to solve this problem that has been overlooked in the past, and uses fixed interval discrete distribution inventory theory approach.

The author in *A Design Algorithm For Continuous Melt-Phase Polyester Manufacturing Processes; Optimal Design, Product Sensitivity, And Process Flexibility* (Joseph 1998), presents an algorithm for modeling the continuous manufacturing production process in a polyester manufacturing plant. The goal of the paper is to determine optimal plant designs taking into account plant costs, product quality and

flexible operation. The designs are developed so that they can incorporate the desired amount of flexibility in the production process at the lowest cost.

The dissertation paper on *A Design Methodology for Scalable Machine Systems* deals with the design of machine systems that are adaptable to the shorter product life cycles and variation in the products (Patrick 2002). The need for systematic manufacturing system design methodologies has given rise to the design issues that are scalable in relation to the volatile product structure. In order to solve the scalable system design problem, an integer linear programming based partial enumerative procedure was developed. The solution procedures tried to optimize the total life cycle cost of the system that comprised the investment costs, operating costs, and reconfiguration costs. The model was implemented in a case study, and it was observed that if implemented the investment cost and floor space requirements would reduce significantly.

Several articles published in the *Operations Research* journal also confirm the impact of the facility planning and management in the field of manufacturing processes. The authors in the *Finite Size Facility Placement in the Presence of Barriers to Rectilinear Travel* (Savas, Bhatta & Negi 2002) considers the placement (location & orientation) of a single finite-size (finite-area, arbitrary shape) facility in a plane, under the assumption that all travel occurs according to the rectilinear metric in the presence of an impenetrable barrier to travel.

In *A Spatial Modeling Perspective to Problems in Facilities Design* (Savas 2001), the author made an effort to relate facility location, facility layout and material handling systems design from a spatial planning point of view to the overall problem of facilities design. The facility location and facility layout both deal with the location of

new facilities and have new constraints, like determining area requirements and area restrictions. The author used finite-size facility placement problem in order to bridge the gap between the facility location and facility layout and identify the criteria for the optimal placement of the stations with a fixed orientation. Moreover, spatial issues (aisle widths, traveling paths of material handling equipment) and non-spatial issues (aisle capacities, turning radii) were integrated, and solutions for the problems were proposed.

A robust modeling framework that can provide a globally optimized plan and **control** for operations planning scheduling and control systems for the manufacturing and **distribution** companies was developed in *Intelligent Agent Based Planning, Scheduling, And Control: Warehouse Management Application* (Kim 2002). The framework **co**nsiders both the horizontal as well as vertical decisions that are made between various **lev**els of controllers. In order to validate the effectiveness of the proposed framework, it **is** applied to an actual industrial warehouse problem with three levels of agents, namely, **sys**tem global planner, control level guide and lower level execution agents. The chaos **con**cerns in manufacturing systems are also addressed in this thesis. The guidelines for **des**igning intelligent based operations planning scheduling and control systems are also **pre**sented.

The concept of activity based analysis (ABC) was used as a tool to find out the **pro**duct cost distortion due to the use of traditional costing system. In the paper, *Analysis Of Operations Research Models Using Activity Based Costing* (Churirat, 2002) the author implements the cost accounting system as an important tool for formulating the parameters for the modeling of the facility layout and the manufacturing process. The effect of ABC on the inventory system, investment analysis and material handling

systems are analyzed, and a revised model based on the mentioned cost-drivers as the parameters is proposed.

The primary method of modeling the complex and dynamic manufacturing systems is the discrete event simulation described by Tompkins in *Optimization Of Qualitative Variables in Discrete Event Simulation Models (Manufacturing, Genetic Algorithm)*, (Tompkins, 1995). According to Tompkins, although a simulation model **helps** the user to understand and estimate the system behavior, it is unable to suggest **changes** for improving the system performance. However, the simulation models can be **integrated** with the optimization procedures to overcome its optimization incapability. In **order** to do this, the response values generated by the simulation models are treated as the **objective** function value and the optimization procedure suggests the recommendations to **the** system parameters that direct the response in the desired direction. However, the **simulation-optimization** procedures deals mostly with the quantitative parameters, while **there** are many qualitative factors that affect manufacturing systems. The paper **developed** a simulation-optimization procedure that can incorporate qualitative system **parameters** in the simulation model. The objective is attained by coupling an *Automatic Simulation Model Generator* with a Genetic Algorithm (GA) that searches for the **alternative** combination of qualitative variables. The combinations suggested by the GA **helps** the model generator to create the simulation models and execute them. Implementation of this combined simulation value finally resulted in a 37% improvement in the initial objective function value.

The author in *Function Approximation Concepts For Multidisciplinary Design Optimization*, (Houten 1998) also highlights the fact that the interfacing of analysis tools

and optimization algorithms is a major difficulty in multidisciplinary design optimization. In addition to the programming difficulties, optimization of the industrial designs frequently involves extensive computational efforts since optimization algorithms need several evaluations of the objective and constraint functions. Attempts are made to overcome these difficulties by introducing an interface between the analysis software and optimization algorithm. The dissertation develops and implements function approximation techniques so that the part or entirety of the design space is modeled using data from a set of analyses. In order to validate the approximation methodology, various optimization problems were solved. It was concluded that, if applied in a proper way, the approximation methodology can help the designer to solve his layout design problems in a fast and systematic way.

In the paper *Performance Analysis and Design Issues in Transfer Lines (Manufacturing)*, (Dogan 1995), the author has studied the effects of station breakdowns and buffer capacities on measuring the performance of transfer lines through scrapping of workpiece or failing machines. The author makes certain assumptions: e.g., the failure and repair times of the machine are geometrically distributed, and the blocking and starvation of the machines exist due to finite capacities of the buffers. A methodology is proposed to obtain the distribution of the number of units produced over a period of time. Moreover, this methodology also helps to estimate the gradient of the output rate with respect to the vector of repair rates in a transfer line, that can be used in the optimal repair rate allocation problem.

Facility Layout with an Iterative Algorithm, (Gau, 1998), also deals with the modeling concept and presents a weighted objective function for the facility layout

problem that attempts to effectively combine the adjacency based objective and distance based objective. A genetic algorithm heuristic for facility layout problem is developed. In addition to this, an iterative approach that iterates between the genetic algorithm and mixed integer program is developed to solve the facility layout problem.

2.3.1.3 *Advanced Facility Layout Design Concepts*

Traditionally the facility layout problems were discussed on the basis of three implicit **a**ssumptions: (1) the facilities are arranged in a two dimensional plane, (2) the facility **d**esign of a manufacturing facility is made with prior information of future product and **m**anufacturing activities, and (3) The product mix and volume remain fairly constant **(H**eragu 1997). These assumptions do not hold true for the modern manufacturing **s**ystems. Modern manufacturing systems have become highly complex and volatile and **t**he facility layout design problems now require the implementation of more innovative **t**echnologies and concepts. This section discusses some of the novel techniques and **s**ubjects in the field of facility design.

The authors in *Improving Job Shop Performance Through Utilization of System **I**nformation in Process Queue Management Under Transfer Batching* (Litchfield & Joel **A**rdon 1996) states that this approach, along with the Shortest Processing Time (SPT) **q**ueue management rule, dramatically reduces mean flow time of the process. This **a**pproach takes into account the sequential processing of all transfer batches, of the released batch at each processing stations. The factors affecting the job shop performance were found out and analyzed in order to maintain the smooth continuity of the process flow. The analysis of a simulation model based on a job shop case study showed that the SPT modifications improved the process flow.

Another relatively new concept in facilities planning and designing was added when J. Chen in the *Cellular Manufacturing System Design: Optimal Solution of Large Scale Real World Problems* (Chen 1995) presented the idea of “Cellular Manufacturing”. The inherent idea of cellular manufacturing, which has been widely applied in the manufacturing industry, is to divide a manufacturing system into several subdivisions based on design requirements and manufacturing similarities of products in the processing system. The various advantages of this idea are the reduction in material handling cost and setup time, decreased amount of work-in-process, improved product quality, and increased job satisfaction. The author in this thesis primarily proposed an integrated design approach that considers both design and planning issues and the emphasis is primarily on the optimal solution of the cell formation problem in Cellular Manufacturing System design. The problem is solved by developing mathematical models of two types, one for finding the optimum number of individual machine types required to satisfy the capacity constraint; and the other for looking into three critical aspects, namely, resource utilization, alternate routings and practical constraints while solving the cell formation problem. The second model is a linear mixed integer model that has fewer integer variables, as compared to the conventional models, and permits the optimal and efficient solution. This model is heuristic in nature and can be implemented to solve additional larger and complicated problems in order to provide real solutions for cell manufacturing systems design process in the facility.

The author (Lars Peter 2002) in *A Framework for Analyzing the Performance of Sequential Module Flows* presents the sequential module flows (SMFs) along with their operative performances. According to the author, the SMF represents the

preassembly of components into product modules that are delivered in the same manner as the product variants are assembled in the final assembly line. Moreover, SMFs help to increase the efficiency and reduce the lead time for variant products. Any company that has variable products can greatly benefit from the SMF concept. The paper develops a framework for analyzing the operative performance of sequential module flows and their influence on the design and operation of the final assembly line. The proposed framework also recommends the use of processible and structural criteria, and these criteria are used to analyze various factors that influence the SMFs output.

Koo in *Flow Planning and Control of a Single-Stage Multimachine Systems* (Koo 1997), introduces the concept of single-stage multimachine systems (SSMS) that has been presented for a newly emerging manufacturing environment. In SSMS, the complete operations of a workpiece are performed on a machine tool in a single machine setup and are characterized by custom made manufacturing, unstable demands, large numbers of parts, tool movement policy, and no part routing between the stations. While developing the framework for the SSMS model, the author considered coordination of the operation of several machines in terms of tool requirements as a critical factor. The framework presents a real time operations selection algorithm and has the concept of product flexibility embedded within it. The simulation experiments are performed to verify the effectiveness and feasibility of the proposed control scheme and to compare the presented operational decision methods with existing approaches. This research also addresses the tool requirement planning problems.

The dissertation *A Method For Simulation Optimization With Applications In Robust Process Design and Locating Supply Chain Operations* (Waraporn 2002)

discusses the genetic algorithms in the context of stochastic optimization in locating and designing facilities and manufacturing processes. The paper describes the proposed stochastic optimization method as a process that integrates sequential ranking and selection procedure for facility design with an elitist generic algorithm. This methodology is based on the direct minimization of expected cost methods and is implemented in a practical manufacturing facility.

Sam in *Strategic Planning of Flexible Assembly Systems for Electronic Industry*, (Sam 1996) introduces three specific models for planning the flexible assembly systems design so that the production systems in electronics manufacturing plants are more efficient. According to the author, the electronic industry faces the challenge of producing widely varied products with short product life cycles and undergoes fast and continuous product development. The initial step to develop strategic planning of multiple stage assembly includes determining the initial system, design like number and type of facilities, the capacity of each resource in each facility, and the number of products assigned to each facility over time. The next step involves the understanding of any system changes, like opening of new facilities, closing down of existing facilities, adding capacity to facilities, removing capacity from facilities, and reassigning capacity between facilities. The integer programming model is adopted to formulate the problem, and is based on simulated annealing and genetic algorithms, two approaches adopted to solve the problem. The author has further subdivided the strategic planning problem into two sub-problems, namely, a capacity planning problem and a product assignment problem. The capacity planning problem deals with the challenge in determining the initial system design that is required to meet production without allowing the change in

system design; while the product assignment problem involves the determination of the product to facility assignments for a given system design, or to justify the alternative tasks given to a system. The first problem is formulated as a multicommodity network flow problem, while heuristics are developed for the second problem on product assignment.

The focus of the paper on *Analysis of Cellular and Functional Manufacturing Systems (Conversion)*, focuses on studying performance and cost characteristics during the conversion of a functional manufacturing system to a cellular manufacturing system (Agarwal, 1995). In other words, this research deals with the changes reflected during the transformation of an existing manufacturing system to a more novel and flexible facility. In order to investigate, a stochastic analytical model is introduced that studies the relative performance of cellular and existing manufacturing systems as a function of set-up time, processing time, and their ratio over a wide parametric range. Moreover, a total cost model is also developed to analyze the value ranges and economics of implementing cellular systems. The proposed model also analyzes the interaction between the set-up time reduction and design and operational factors involved in the transformation of a functional system to a cellular system. The total cost model comprises a total annual cost function and a set of constraints applicable to a typical manufacturing facility. The objective function, which is the total cost function, is then minimized, subject to the constraints for operational variable values and optimal design. Once the equations are solved, the sensitivity of the optimal solution is examined by varying the parametric values of the variables to the acceptable limits. After noting the differences between threshold and economic level of set up reduction, a decision framework is developed to

assist the decision-maker in selecting the suitable range of set-up reduction among the threshold, economic, and maximum technically allowable set-up reduction levels. Moreover, the effect of set-up time reduction trade-offs on the performance and cost of a cellular manufacturing system is also analyzed. The case study in the research examines the performance and cost implications of the firm during the conversion. The total cost model is applied and validated by using the actual operational data of the case study firm.

Fractal Layout for Job Shops (Workstations) (Venkatadri, 1995), discusses the fractal layout that assigns the workstations for processes, which are roughly equal across the fractal cells. The author defines fractal cells as “*regions within job shop layout, similar in machine composition as a whole.*” The advantage of this kind of allocation lies in the fact that it provides flexibility in production, since each cell can produce nearly every product. Moreover, since individual stations are not dedicated to a single product or group, it reduces the minimum number of workstations required for given functional organizations. However, the spatial distributions of workstations for various processes that occurs by positioning some of these workstations in each cell keeps travel and material handling burdens in fractal design quite low. The three major components studied during the duration of the research are as listed below.

- Introduction to fractal organization: This includes the isolation of the building blocks of the fractal layout and identification of the design assignments necessary for the implementation.
- Development of an integrated design methodology: The factors responsible are capacity planning, cell creation, flow assignment, cell layout, and global layout.

- Quantitative evaluation of the fractal layout in contrast to process, group, and holographic layouts

2.3.1.4 *Computer Applications In Facility Design*

Modeling of facility layout problems, discussed in earlier part of this chapter, helped to clarify the problem by taking into account those factors that are critical to develop the layout. Algorithms are the sequential procedures that can be coded in a computer programming languages. Based on the algorithms, several type of software have been developed for layout problem analysis and modeling (Heragu 1997). The details of the software available and their advantages and disadvantages are discussed in Chapter III. For this research purpose, the author uses FactoryFLOW layout software as the facility layout modeling and analyzing tool. FactoryFLOW is basically a post-processing evaluator of facility layouts capable of performing “what-if” analysis. The details of this software and its working methods are illustrated in Chapters III and IV. Below is the summary of some of the advanced research studies on layout algorithms and computerized techniques.

R. Bhat introduced FADAMATES, a knowledge based system for facilities design and material handling system (Bhat 1989) that is a complete environment used for designing a comprehensive manufacturing design facility. This system involves the development of an expert system employing artificial intelligence that guides the user to interactively design a facility, taking into account all possible constraints that affect the facility layout design. The expert system implemented helps to identify the best suited algorithm for the given constraints and transfers control to the FEDAMATES – layout

module. This layout module, with the help of the knowledge base, develops the input data file for the conventional layout algorithm that then generates a pictorial facility layout with extensive details. The expert system helps to identify the material handling equipment for the designed layout and accesses the knowledge database.

In *A Facility Description Language for Distributed Design Integration* (Witzerman 1996) the author states that the primary goal of concurrent engineering is to reduce the development cycle and time for new products. However, this effort brings about a simultaneous need for rapid design, evaluation, and reconfiguration of the facilities required to manufacture these products. Currently, not much advancement has been made towards developing an integrated environment that supports the interaction of multidisciplinary facility design teams, that are otherwise found in the enhanced product design process. The traditional facility layout design methods follow a sequence of actions, although the author acknowledges that recent techniques have automated and improved this sequential process. The author introduces a generic Facility Description Language (FDL), which provides a common formal platform for collaborative work and detailed analysis of process layout, flow geometry, visual aspects of control, and safety. FDL, as a language, utilizes the capabilities of simulator / emulator design workstations to integrate the physical and logical aspects of manufacturing facility design, defines the prototype implementation architecture, and in the process forms a powerful tool for modeling that allows the planners to achieve a higher level of design interaction.

A genetic algorithm based approach is introduced in designing a dynamic facility in *Design of A Dynamic Facility* (Kochhar 1998). The dissertation addresses the issue of responsiveness of a manufacturing facility to frequent changes in product mix

and demand. The traditional goal of the facility layout design problems was to minimize production and material handling. In this thesis the author discusses the issues related to the design of dynamic facilities, keeping in mind the rapidly changing nature of technological innovations and product designs. The author defines a dynamic facility as a facility that can respond efficiently and effectively to the changes in the product design, mix and volume in a continuously changing work environment. The thesis presents a nonlinear model for a dynamic, multiple-floor facility layout, which does not require the departments to be of fixed sizes or orientation; the departments also have variable length, width and area. The model defines the framework for genetic algorithm based heuristics that take into account many of the constraints. The solution for this framework are evaluated to find the best set of parameters for genetic algorithms.

In order to increase design quality and to reduce design process development time, a computer supported collaborative approach to facility design is mandatory. This was the main focus of the authors in *Conflict Resolution in Collaborative Facility Design* (Gracia Antonio 2001). The conflict situations that arise due to the interactions between the co-operating designers need to be resolved in a computer-supported collaborative facility design. The research introduced a method to resolve conflict situations, such as layout design, equipment selection, automation plan and material flow, which normally occur in collaborative facility design. The method also considered the rational execution of pre-ordered conflict resolution approaches like direct negotiation, third party mediation etc. The authors used a graph model for conflict resolution and introduced a neural fuzzy inference system to support the confrontation phase between the conflicting parties and the result of this model presented a procedure for the integration of conflict

detection and the resolution that can lead to an increased effectiveness of the facility design process.

Layout Design and Analysis Software (Sly et al. 1996) is the third part of a three part series published in *IIE Solutions*. This paper discusses the issues related to facilities layout and design that software needs to consider in order to produce layouts of high efficiency and exceptional quality. Issues that need to be addressed by factory layout software include physical, organizational, and capacity transformations. Basic design skeletons like that of Reed (1967), Muther (1973) and Apple (1963) are also described. The paper goes on to suggest the interactive computer-aided relationships and flow-based layout design techniques like relationship charts, diagramming, flow diagramming, and flow paths (1996). Finally, Sly et al. explains the classification of layout algorithms in terms of mathematical procedures, heuristics, probabilistic approaches and graph theory (1996). The authors argues that *“a good layout well suited to the manufacturing philosophy is the fundamental starting point for total production system design, and provides a solid foundation on which to build dynamic simulation studies should they be appropriate.”* (Sly et al. 1996). Also, with the availability layouts produced by the software solutions material flow, WIP, and throughput times can be reduced.

In the paper on Measurement of Cellular Manufacturing: Evaluation of The Efficiency of Clustering Algorithms and The Performance of Alternative Layouts (Hsieh, 1994), the author introduces the concept of cellular manufacturing which implements the group technology concepts. He feels that, although there are possibilities of gaining economic advantage by using the “small batch” concept from cellular manufacturing, there is a lack of systematic approach. To meet this need, the author develops a

systematic methodology to analyze the efficiency of clustering algorithms that designate the cells and groups in the initial stage for planning cellular manufacturing. Several clustering methods were evaluated and, finally, cellular layout versus process layout was tested by using simulation models.

2.4 Layout Design Process in Manufactured Housing Production Plant

The goal of the research “*Manufactured Housing Production Plant: Layout Design Process*” (Mehrotra 2002) was to come up with systematic guidelines for the design of a layout for a manufactured housing production plant, strictly from the qualitative aspect and based on the objective of maximizing the adjacency criteria. For this purpose, the tools and techniques available in the field of industrial engineering are adopted. Space and proximity requirements in a production plant are understood, and a layout design software program, namely, FactoryPLAN, was used to prepare production line layouts. Based on the complete process, layout design guidelines were produced in the form of a process flowchart. The following section describes the objectives used to reach this goal

Objective I: To Compile the Process Details of Manufactured Housing Production

Objective II: To Understand Techniques Related to Manufacturing Facility Layout

Design Available in the Field of Industrial Engineering

Objective III: To Collect Space- and Proximity-Related Data, Based on the Layout

Design Techniques and Manufactured Housing Production Process Details

Objective IV: To Develop Layout Design for the Manufactured Housing Production Plant

Objective V: To Formulate Layout Design Process Guidelines Based On Objectives I to IV.

Though manufactured homes have come a long way from recreational trailers, there has been very little effort to improve the production plants in which they are constructed. There is no standard method or procedure adopted to prepare a layout for these production plants. This industry lacks any knowledge associated with the process of layout design of a manufactured housing production plant. There is a need to learn and adopt techniques and procedures from other industries that are more knowledgeable in this area. This research is the first stepping-stone to bridge the gap between the manufactured housing industry and more developed industries in the area of production plant layout design. The author develops qualitative charts for the analyses that will be described in details in Chapter III The following section presents the major conclusions from this research work:

- ♦ The author observed that a U-shaped layout is the most common layout in manufactured housing production plants. Based on the scores obtained for the different layouts, several layout options are feasible, and manufacturers should not limit themselves to one particular layout. As this industry is a labor-intensive industry, it has an opportunity to experiment with different options and is not tied down to the limitations of fixed machine/equipment-based layouts.

- ♦ The author strongly believes that manufacturers who are developing layouts should either follow a methodical guideline or a checklist in order to develop a design layout.
- ♦ All the participant parties in this industry should be educated in the area of production process and design. Training should be provided to all members of the industry, especially the workers.
- ♦ In the long run, the author believes that the present production process should be studied in greater detail and certain radical changes could be made, alleviating changing/improving the present layout design limitations.
- ♦ Manufactured housing industry is a labor-intensive industry. Although this allows for a lot of flexibility in design, manufacturers should consider implementing certain forms of automation. Specific areas, like interior wall fabrication and cabinets production, should be mechanized to improve and speed up the production process.

This research provides insight into and an understanding of various qualitative parameters related to the manufactured housing layout design process. Manufacturers can use the different layout options and the process guideline models and tailor them to their requirements. However, this developmental research does not take into account the quantitative aspects of the facility layout design parameters.

2.5 Summary

This chapter presents a review of existing and ongoing research and literature in the field of facility design and planning and in the manufactured housing industry. It briefly gives an overview of the state-of-the art works in the facility planning fields. However, the

techniques and mathematical models, which are an inherent part of the quantitative analysis of facility design systems, are explained in greater detail in Chapter III. The background work presented in this chapter truly emphasizes the fact that the facility layout designing process in manufactured housing plants requires the implementation of the latest trends and technology in order to meet the competition.

CHAPTER THREE

**EXISTING TECHNIQUES AND TOOLS FOR
COMPUTER-AIDED FACILITY LAYOUT EVALUATION**

3.1 Introduction

The production process of the manufactured housing production industry can benefit from new research and expertise. The significant advances that have occurred in the past decades in the manufacturing industries, especially in facility planning and layout design, can be incorporated in the manufactured housing factory to make its production process more efficient and technically up to date. Chapter II provided an overview of the contemporary approaches and theories for a facilities design and planning system in other manufacturing facilities. In this chapter, the author has made an effort to capture the contemporary tools and techniques in facility planning by summarizing the different state-of-the-art procedures used for developing and presenting layout designs for manufacturing processes, layout problems and the methods for evaluating facility design alternatives.

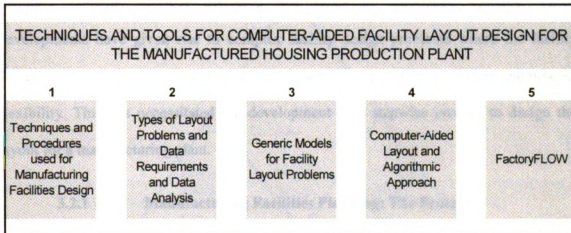


Figure 3.1: Framework for Facilities Design Techniques Adopted in Chapter III

The later part of this chapter provides examples of certain types of quantitative models that can be used to develop an alternative facilities plan. It also explains the role of the computer in the generation of facility layouts, and gives a detailed description of the FactoryFLOW software, that has been used for data analysis and development of factory layout design alternatives in this thesis. The chapter also presents various facility layout concepts, algorithms and models that are used for developing computer software for designing facility layouts. Figure 3.1 illustrates the structural framework behind Chapter-III.

3.2 Facilities Planning Techniques and Procedures used for Manufacturing

Facilities Layout And Design

The manufacturing facilities in recent years have witnessed much transformation, due to the increase in the number and types of product variety, manufacturing systems, material handling systems, services delivered and types of automated systems. These developments have given rise to complex facility design problems where the facility designers have to keep in mind long term and short term impacts, cost factors and process flexibility. This has necessitated the development of a stepwise process to design the layout for a manufacturing plant.

3.2.1 Manufacturing Facilities Planning: The Process

The product, process and schedule (PP&S) design are the major tasks that should be performed by the facility designers before starting the process of designing the layout of a manufacturing facility, since the plant design is a result of integration of these three components. The product, process and schedule design in facilities planning are

interrelated and the interrelationship is shown in the figure 3.2. According to Apple (1963), plant layout can be defined as:

“Planning and integrating the paths of the component parts of a product to obtain the most effective and economical interrelationship between men, equipment, and the movement of materials from receiving, through fabrication, to the shipment of the finished product.” (Apple, 1963)

Additionally, the facilities planning process can also be defined as a continuous improvement life cycle process, as illustrated in figure 3.3. In a broader sense, the terms like facilities planning, facilities location, and facilities design, facilities system design and layout design can be collectively called the facilities planning process. The procedures of planning and designing facilities are project-specific and they can be categorized as manufacturing plant, office, hospital, emergency room etc (Tompkins et al. 1996).

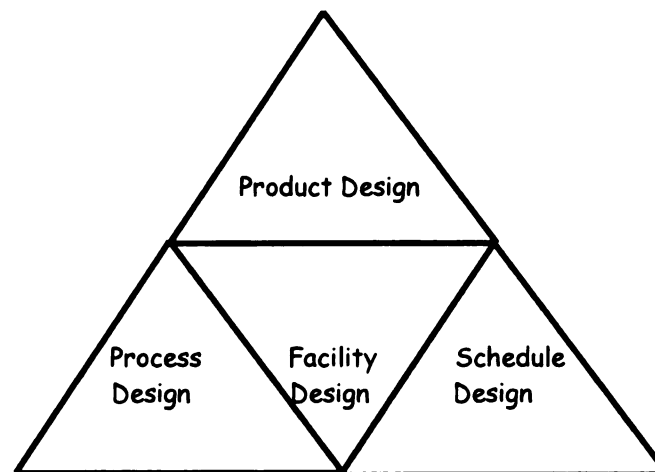


Figure 3.2: Relationship between product, process, and schedule (PP&S) design and facility planning
(Tompkins et al. 1996)

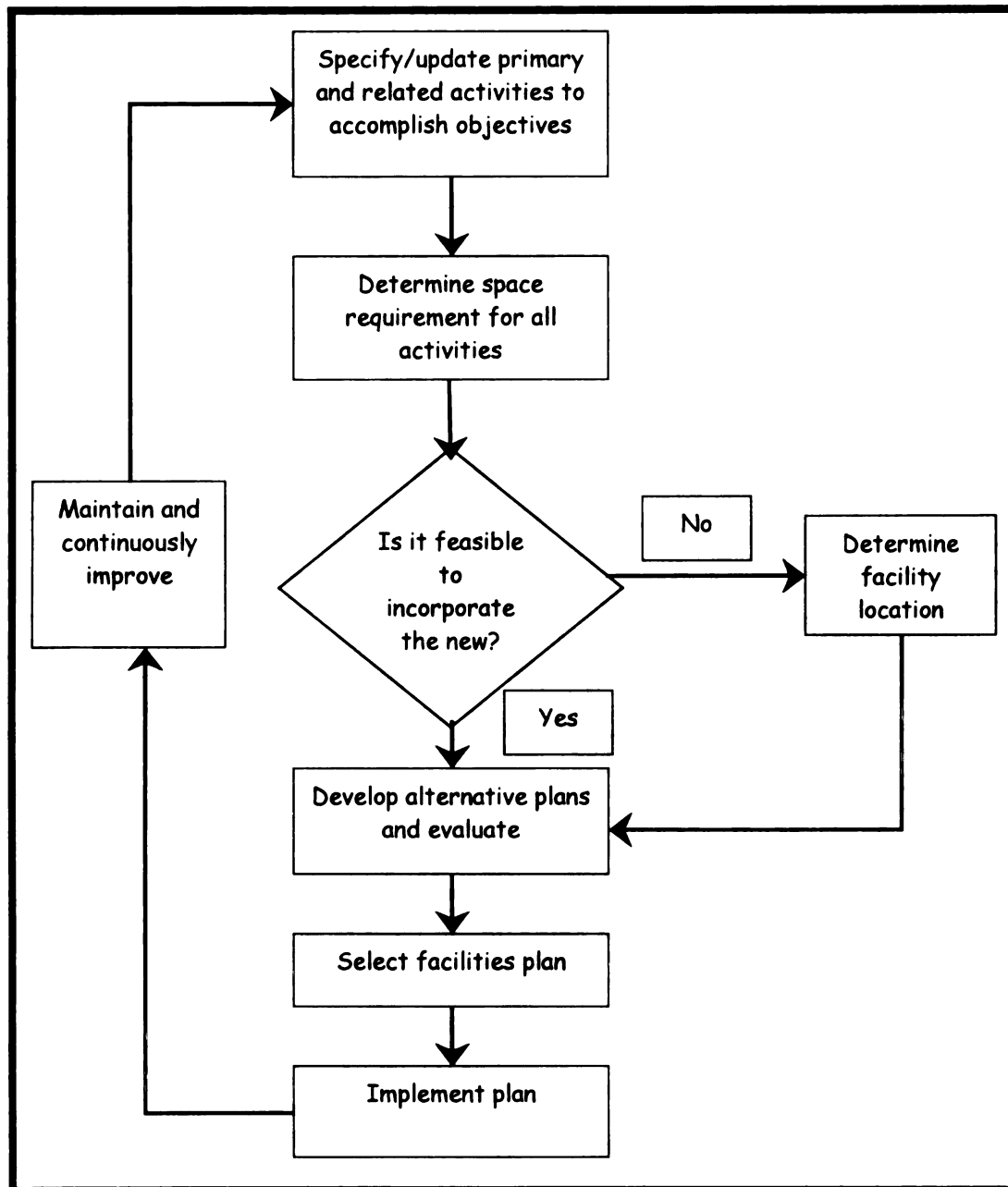


Figure 3.3: Continuous Improvement facilities planning cycle
(Modified from Tompkins et al. 1996)

The field of manufacturing facilities planning is broadly classified into plant location, and plant design. Plant location refers to the placement with respect to the customers, suppliers, and other facilities in the supply chain. As shown in Figure 3.4, plant design is further divided into plant facility system, plant layout, and material handling. Plant facility system consists of the structure, atmosphere, enclosure, lighting, electric, communication, life safety, and sanitation related systems. Plant location addresses the macro issues while plant facility design deals with micro elements (Tompkins et al. 1996).

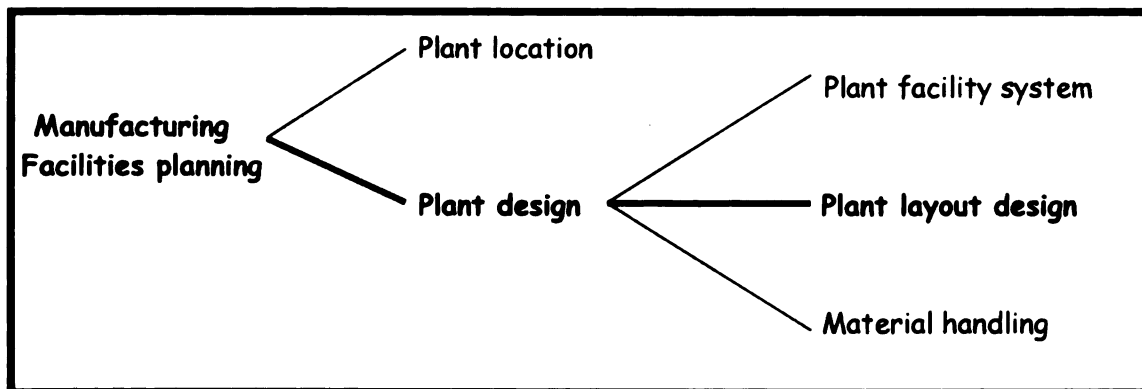


Figure 3.4: Subdivisions of Facilities planning for a manufacturing plant facility
(Tompkins et al et al., 1996)

3.2.2 Layout Procedures: Traditional Method of Approach

Over the years, several new layout procedures have evolved to assist the planner in designing layouts. Described below are some original approaches to layout problems. The concepts used in these approaches are still the backbone for many approaches presented today (Tompkins et al et al. 1996). The layout procedures can be broadly categorized in the following two divisions:

- ♦ *Construction-type layout* methods which basically involve the development of new layout from scratch.

- ♦ *Improvement procedures* generate layout alternatives based on an existing layout.

1. Apple's plant layout procedure

Apple (1977) proposed the following steps in producing a plant layout:

1. Procure the basic data
2. Analyze the basic data
3. Design the productive process
4. Plan the material flow patterns
5. Consider the general material handling plan
6. Calculate equipment requirements
7. Plan individual workstations
8. Select specific material handling equipment
9. Coordinate groups of related operations
10. Design activity interrelationships
11. Determine storage requirements
12. Plan service and auxiliary activities
13. Determine space requirements
14. Allocate activities to total space
15. Consider building types
16. Construct master layout
17. Evaluate, adjust, and check the layout with appropriate persons
18. Obtain approvals
19. Install the layout
20. Follow up on implementation of the layout

Apple (1977) also specified that no two projects are the same, and hence the procedures for designing them would also be different. Therefore, the steps described above need not take place in the specified order everytime. They might change, based on the layout design problem for the given manufacturing plant type that is being addressed.

2. Leed's layout procedure

Leed (1967) recommended the following systematic steps in planning and preparing layouts.

1. Analyze the product or products to be produced
2. Determine the process required to manufacture the product
3. Prepare layout planning charts
4. Determine workstations
5. Analyze storage area requirements
6. Establish minimum aisle widths
7. Establish office requirements
8. Consider personnel facilities and services
9. Survey the plant
10. Provide for future expansion

3. Systematic Layout Planning (Muther 1973)

Richard Muther (1973) formulated a high-level approach to the entire process of plant layout design. The method developed, is called Systematic Layout Planning (SLP) and outlines the sequence of steps that should be followed while designing a plant layout. Figure 3.5 depicts Systematic Layout Planning (SLP) procedure in a flowchart format.

Most of the present day layout design tools use the Systematic Layout Planning techniques that was developed by Muther.

- ♦ Quantify the flow of material between departments
- ♦ Create an activity relationship chart
- ♦ Create a relationship diagram
- ♦ Determine the space requirements
- ♦ Create a space relationship chart
- ♦ Create alternate layouts

In the manufactured housing plants, the layout specifically consists of production areas, production-related areas and personnel areas. This include the production line, the major assembly stations, subassembly stations, feeder stations, storage areas, and personnel areas, like rest rooms, first-aid rooms, tool rooms and lunchrooms. In addition to the flow of material, there is also the flow of material, personnel, equipment and information between the different stations (Mehrotra 2002). The facilities planning process for manufactured housing plant can be listed as follows (Tompkins et al. 1996):

1. Define the homes to be manufactured
2. Specify the production process line and related feeder stations, substations and activities
3. Determine the interrelationships among all the activities
4. Determine the space requirements for all activities
5. Generate alternative facilities plan
6. Evaluate alternative facilities plan

7. Select the preferred facilities plan
8. Implement the facilities plan
9. Maintain and adapt the facilities plan

While designing layout for a manufactured housing plant a strategic facilities planning approach should be adopted in order to create a layout design which supports the production process (generic process model) in the best possible way. The layout design should be complementary to the existing production conditions and management strategies. The emphasis on the later issue will make the process design adaptable to future changes and expansion. Ideally, the facilities plan must address various issues like: receiving, inbound inspection, storage, retrieval, dispatching to production and assembly, production and assembly, movement within production and assembly, work-in-progress storage, material control, packaging, dispatching to and from storage, order picking, dispatching to shipping, order accumulation, shipping maintenance and personal service. There is also a need for feedback from inventory control, production control, quality control, purchasing, marketing, product design, packaging product development, manufacturing, information systems and management (Tompkins et al. 1996).

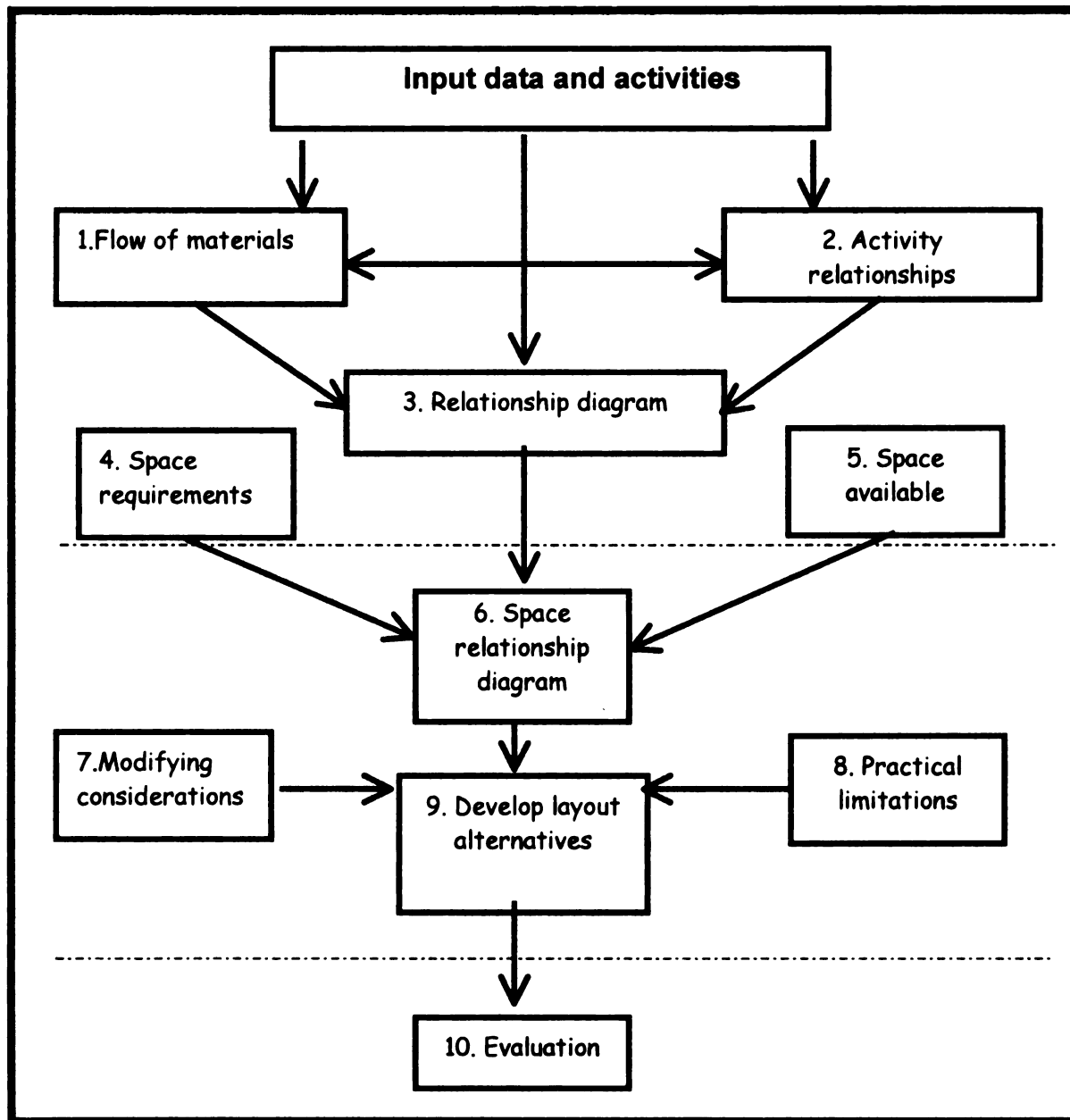


Figure 3.5: Systematic Layout Planning (SLP) procedure
(Modified from Muther, 1973)

In this thesis, issues like space requirements, smooth and minimum movement of material, and personnel in the production line of a manufactured housing production plant will be addressed. In addition, an attempt will be made to design alternative layouts based on the interrelationships (qualitative and quantitative) between departments in order to develop a generic process model for a manufactured housing plant. The placements of departments in a manufacturing facility on the basis of their “closeness

ratings” or “material flow intensities” is an issue that has been developed into algorithmic process approaches. The following methods are available (Tompkins et al., 1996):

1. Relationship diagramming
2. Pairwise exchange methods
3. Graph-based construction methods

The relationship diagramming algorithmic approach is a well known model that has been used to design a number of plants. It is a variation of Systematic Layout Planning (SLP; Muther, 1973) and the method developed by Reed (1967). Relationship diagramming will be further studied and utilized in the thesis. The pairwise exchange method is based on the travel chart method developed by Reed (1967) and the CRAFT procedure (which is discussed in detail in this chapter). The graph-based construction method is purely based on graph theory. Graph theory methods are mathematical tools with conceptual similarities to the SLP method. The graph based construction method uses both planner and dual plane graphs to compare the layout alternatives.

3.3 Types of Layout Problems and Data Requirements and Analysis for Evaluating Layout Alternatives

This part of the chapter gives a brief overview of the types of layout problems, data requirement and analysis for layout decisions and alternatives.

3.3.1. Types of Layout Problems

Layout problems are found in both manufacturing facilities and service-based facilities. These layout problems may occur while designing new facilities or expanding or

modifying existing facilities. In general, the layout problems are divided into four major categories that are described below (Heragu, 1997).

1. Service system layout problem

Service system layout problem refers to layout problems in facilities like restaurants, offices, hospitals, airports, etc. For example, while designing an office space, the planner needs to consider issues like the available space, the location, the company's image, flexibility, etc. The general layout structures in service facility can be (a) closed structure, (b) semi-closed structure, (c) open structure and (d) semi-open structure.

2. Manufacturing layout problem

Manufacturing layout problem” refers to the design, expansion, and modification of manufacturing systems. The major concerns while designing manufacturing layouts are (a) minimizing the material handling costs, and (b) providing a safe environment for employees. A manufacturing facility, not only includes workstations and machines but also rest rooms, inspection stations, tool rooms, etc.

3. Warehouse layout problem

Warehouse layout problem refers to the requirement to use the available storage space effectively so as to minimize the cost involved in storage and material handling. The planner needs to consider factors like shape and size of warehouse, height, location, and orientation of the warehouse.

The facility planning of a manufactured housing plant may be described as the hybrid of manufacturing layout problem and warehouse layout problem as it deals with production of a house as well as storage for the home components and finished products.

4. Nontraditional layout problem

Nontraditional layout problem refers to those types of layout problems that have not been discussed above. For example the design of the layout of keys on a keyboard or the arrangement layout of the Central Processing Unit, keyboard, monitor, and mouse (and their wiring) in such a way that they utilize minimum space. These types of problems are termed as nontraditional layout problems.

3.3.2 Layout Types

The general material flow determined by the process, supply and material flow within a manufacturing facility decides the layout type require for the facility planning and the process is called “manufacturing flow system” The type of material flow system of a department in a manufacturing facility is determined by the planning of the activities within the department. As a result, the four types of departments based on material flow process is listed below in Figure 3.6 (Tompkins et al. 1996):

- Production line department
- Fixed material location department
- Product family department
- Process department

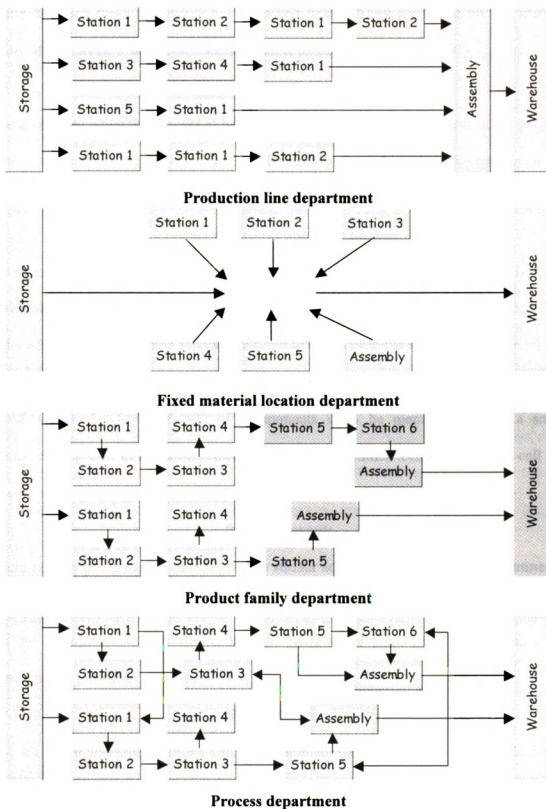


Figure 3.6: Material flow systems for various types of departments
(Modified from Tompkins et al. 1996)

Some common types of layouts are described below. They are based on the specific material flow system within each department (Palekar 1998, Heragu 1997).

Static/fixed layout:

These are used when the product to be made is large and bulky. In such cases, the product is manufactured or assembled at a fixed location and machinery is moved around the product as needed. Examples: aircraft manufacture, ship building yards, etc.

Product or Production Line Layout:

These are used when a single or a closely-related set of products are manufactured in high volume. Machines/workstations are arranged in a manufacturing/assembly line. The order of machines in the line follows the order in which processing is to be performed.

Group or Cellular Layout:

These are used when a family of components is to be manufactured by a small manufacturing cell. In this arrangement, a cluster of machines forms a cell. Each cell has its own material handling system, typically a robot or a conveyor system.

Process Layout:

These layouts group machines that perform similar activities into processing departments. Thus, in a plant with a process layout, there may be a turning department (all lathes), a milling department, a grinding department, etc. Process layouts are common in older plants and in job-shops.

Hybrid Layout:

Not all manufacturing facilities can adopt one of the layout types described above. Hence, they use a combination of the above layouts; such types of layouts are called hybrid layouts.

3.3.3 Data Requirement For Layout Decisions: Flow

In order to provide a good layout alternative for facility design the following data provide the required information to the designers (Heragu 1997):

- Frequency of trips or flow of material or some other measure of interaction between stations
- Shape and sizes of the facilities
- Floor space available
- Location restrictions for facilities
- Adjacency requirements between pairs of facilities

The data collected above are collectively known as the *flow data*. The *flow process chart* and *flow diagram* depicts various steps of the process and sequence of the process respectively (Heragu 1997). The formulation of alternative layouts is the most critical step in the formulation of facilities planning as the layout generated will cater to establish the physical relationship between the activities. The relationship between the departments or activities is determined with the help of following factors:

- **Flow** is determined by lot sizes, unit load sizes, material handling equipment & strategies, layout arrangement and building configurations.
- **Space** is a function of lot sizes, storage systems, production equipment. type and size, layout arrangement, material handling equipment
- **Activity Relationships** is defined by material or personal flow, environmental considerations, organizational structure, process requirements.

3.3.3.1 Flow and Flow Patterns

Flow process can be defined in terms of the subject of flow, the resources that bring about the flow, and the communications that coordinate the resources. A variety of flow patterns can be utilized in layout design determined by the product being manufactured and the production process being used. Product flow can be considered within workstations and departments and between departments, where individual/single stations are called workstations and group of workstations are called a department. Described below are some of these product-flow options (Tompkins et al. 1996).

Flow within workstations:

This flow can be established based on motion studies and ergonomic considerations. The flow within workstations should be simultaneous, symmetrical, natural, rhythmical, and habitual.

Flow within departments:

This flow depends on the type of departments involved. For example, in a product family department, the flow follows the product. Some of the major flow patterns followed are depicted in Figure 3.7. End-to-end, back-to-back, and odd angle flow patterns are used in product departments where one operator works at each workstation, whereas a front-to-front flow pattern is used when one operator works on two workstations, and a circular flow pattern is used when one operator works on two or more workstations. In a process department, little flow occurs between departments, it mainly occurs between aisles and workstations. Figure 3.8 illustrates the different flow patterns within process departments.

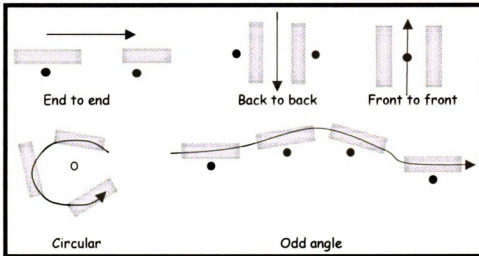


Figure 3.7 Flow within product departments
(Tompkins et al. 1996).

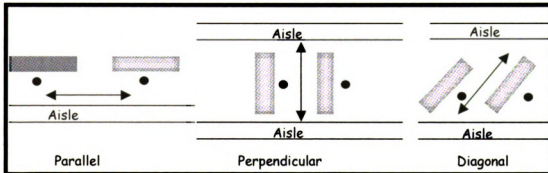


Figure 3.8: Flow within process departments
(Tompkins et al. 1996).

Flow between departments:

Flow between departments is a factor that is used to assess the overall flow within the facility. Typically, the flow patterns consist of a combination of the few general flow patterns shown in Figure 3.9. Depending on the physical arrangements of the machines within the facility there are several flow patterns. Some of these flow patterns are illustrated below.

The straight line and L flow patterns are used when the production process is short and simple in nature and contains none or few common components or production equipment.

Straight-line flow and L-flow are the other most commonly used flow patterns.

The U flow pattern is used when it is necessary to keep both receiving and shipping ends of the line at the same end of the plant. The pattern is also useful when there is a material-handling consideration or external-access consideration.

The O flow pattern is used in machine cells that are serviced by a common material-handling robot.

Serpentine patterns are used for long assembly processes that have to fit in a square area. Such layouts are also called S type layout pattern.

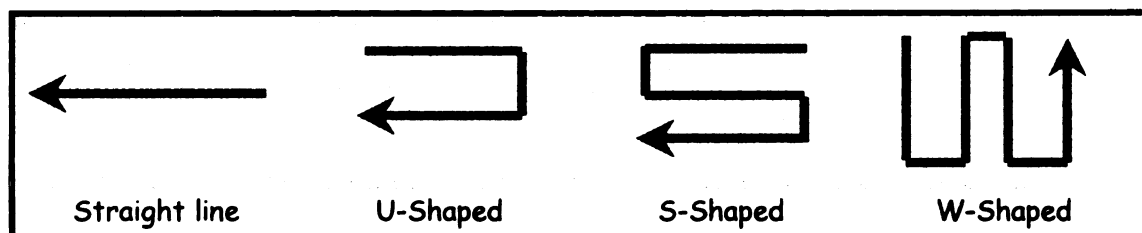


Figure 3.9: General flow patterns
(Tompkins et al. 1996)

Figure 3.10 shows the examples of flow within a facility based on entry and exit restrictions. Some literatures also discuss a combination-type flow pattern or the dendrite pattern (Heragu 1997). This pattern is suitable for assembly operations. In this pattern, the subassembly lines are arranged in such a way that they feed the main assembly line directly. In Figure 3.11, the vertical lines represent the subassembly lines and the horizontal lines represent the main assembly line. When the subassembly lines feed the main assembly line from both sides, the pattern is called spine arrangement.

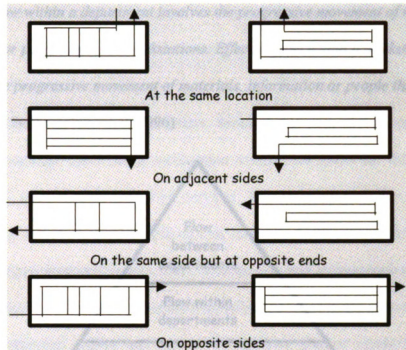


Figure 3.10: Flow within a facility considering the locations of the entrance and exit
(Tompkins et al. 1996)

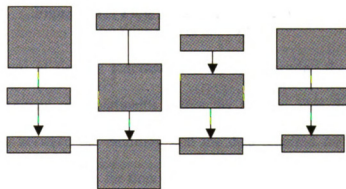


Figure 3.11: Dendrite flow pattern
(Tompkins et al. 1996)

Flow Planning

Flow planning revolves around the effective combination of the layout patterns described above (Refer to figure 3.12). Effective flow within a facility includes the progressive movement of materials, information or people within the department.

“Effective flow within a department involves the progressive movement of materials, information or people between workstations. Effective flow within a workstation addresses the progressive movement of materials, information or people through the workstations.” - (Tompkins et al. 1996)

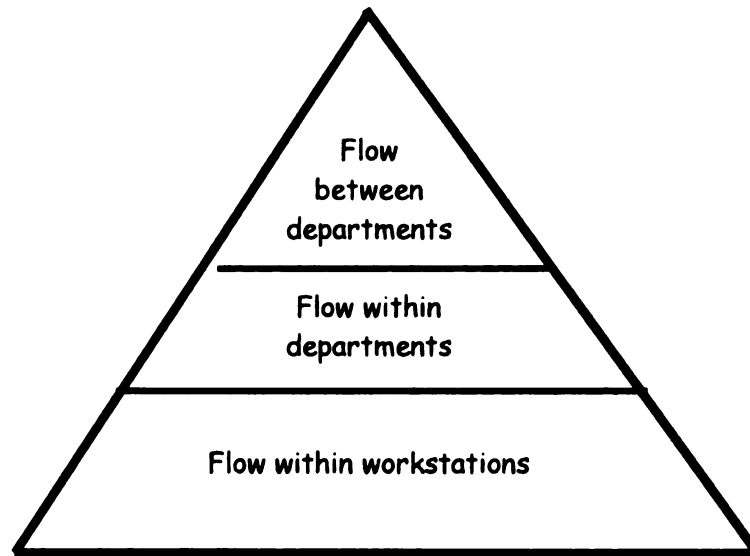


Figure 3.12: Flow Planning Hierarchy
(Tompkins et al et al., 1996)

The measure of flow is required in order to determine the most important factors in the arrangement of departments within the facility. This flow measurement gives the interaction between the facilities, and the data required for this process are called as flow data. The technique for flow measurement is discussed in the later part of this section.

3.3.3.2 Space Requirements

Decisions about space requirements are among the most complex tasks to be undertaken in facilities planning. Tremendous uncertainty exists concerning the impact of technology, demand levels, product mix, future expansion prospects etc. In manufacturing environments, space requirements should be determined first for

individual workstations and then the department requirements should be determined (*as each department is a collection of workstations*) (Tompkins et al., 1996).

3.3.3.2.1 Workstation Specification

A workstation includes space for equipment, material and personnel (Tompkins et al. 1996). The equipment space for a workstation consists of space for the equipment, machine travel, maintenance, and plant services. The material area in a workstation covers receiving and storing material, in-process material, storing and shipping material, storing and shipping scrap and finally, tools, fixtures, jigs, and maintenance material.

The personnel area for a workstation includes space for the operators, material handling and operator ingress and egress. A facilities planner needs to take into consideration the above space requirements when designing a production plant.

3.3.3.2.2 Department Specifications

Once space requirements for the individual workstations have been identified, it is easy to determine the space requirements for each department. It is the sum of the individual workstations involved in that department and the common department service requirements. The department service requirements include common tools, spare parts, housekeeping items, information-communication boards etc.

3.3.3.2.3 Aisle Arrangement

Aisles are provided within the facility to facilitate effective flow. Designing too-narrow aisles may result in congested facilities, whereas too wide aisles result in wasted space. Therefore aisle width should be designed considering the type and volume of flow to be handled. Table 3.1 shows the different aisle allowance estimates.

Table 3.1: Aisle allowance estimates
(Tompkins et al., 1996)

If the largest load is	Aisle allowance % is
<i>Less than 6 ft²</i>	5-10
<i>Between 6 and 12 ft²</i>	10-20
<i>Between 12 and 18 ft²</i>	20-30
<i>Greater than 18ft²</i>	30-40

3.3.3.3 Activity Relationship

The primary relationships that form the basis of many decisions in facility planning process are the activity and the material relationships. The relationships that are mainly considered are listed below (Tompkins et al et al., 1996):

- Organizational Relationships are sorted by span of control and reporting structure
- Flow Relationships are the quantitative relationship viewed as the movement of goods, materials, information and people within a house manufacturing facility system.
- Control Relationships include centralized versus decentralized control, decentralized versus batch inventory control, shop floor control, and levels of automation and integration
- Environmental Relationships include safety considerations, as well as temperature, noise, fumes, humidity and dust.
- Process Relationships are other relationships like floor loadings, chemical processing etc.

3.3.4 Flow Data And Relationship Charts

As discussed earlier, flow is the major factor that affects the layout of departments within the facility and must be measured with the flow data. Measure of flow is required to:

- 1) View alternate flow arrangements and
- 2) Evaluate alternate flow arrangements.

Flow data may be specified in quantitative measure or qualitative measure (Tompkins et al. 1996). A home manufacturing industry has both a large volume of materials, information, and people moving between departments and significant communications and organizational interrelations; hence, it will require both measures of flow to evaluate the layout alternatives.

3.3.4.1 Qualitative measure

Space relationship between two departments range widely. In some cases it may be absolutely necessary for two stations be close to each other; in other case, there may be a strong preference that the two departments not be close to each other. In facilities having very little movement of material, information, or people, qualitative measure is the basis for arrangement of departments. A relationship chart is one of the common ways of presenting the qualitative measure of flow. It describes qualitatively the degree of closeness that should exist between various workstations (Sule 1988). Following are the steps used in creating a relationship chart (Tompkins et al. 1996):

- ◆ List all the stations on the relationship chart.
- ◆ Conduct interviews and surveys with persons from each station listed and with the management responsible for all departments.

- ◆ Define the criteria for assigning closeness relationships and itemize and record criteria used as reasons for relationship values on the relationship chart.
- ◆ Establish relationship values and the reason for the values for all pairs of department.
- ◆ Allow everyone having input to the development of the relationship chart to have an opportunity to evaluate and discuss changes in the chart. Figure 3.13 shows a basic relationship chart presenting the different clusters in a manufactured housing production plant.

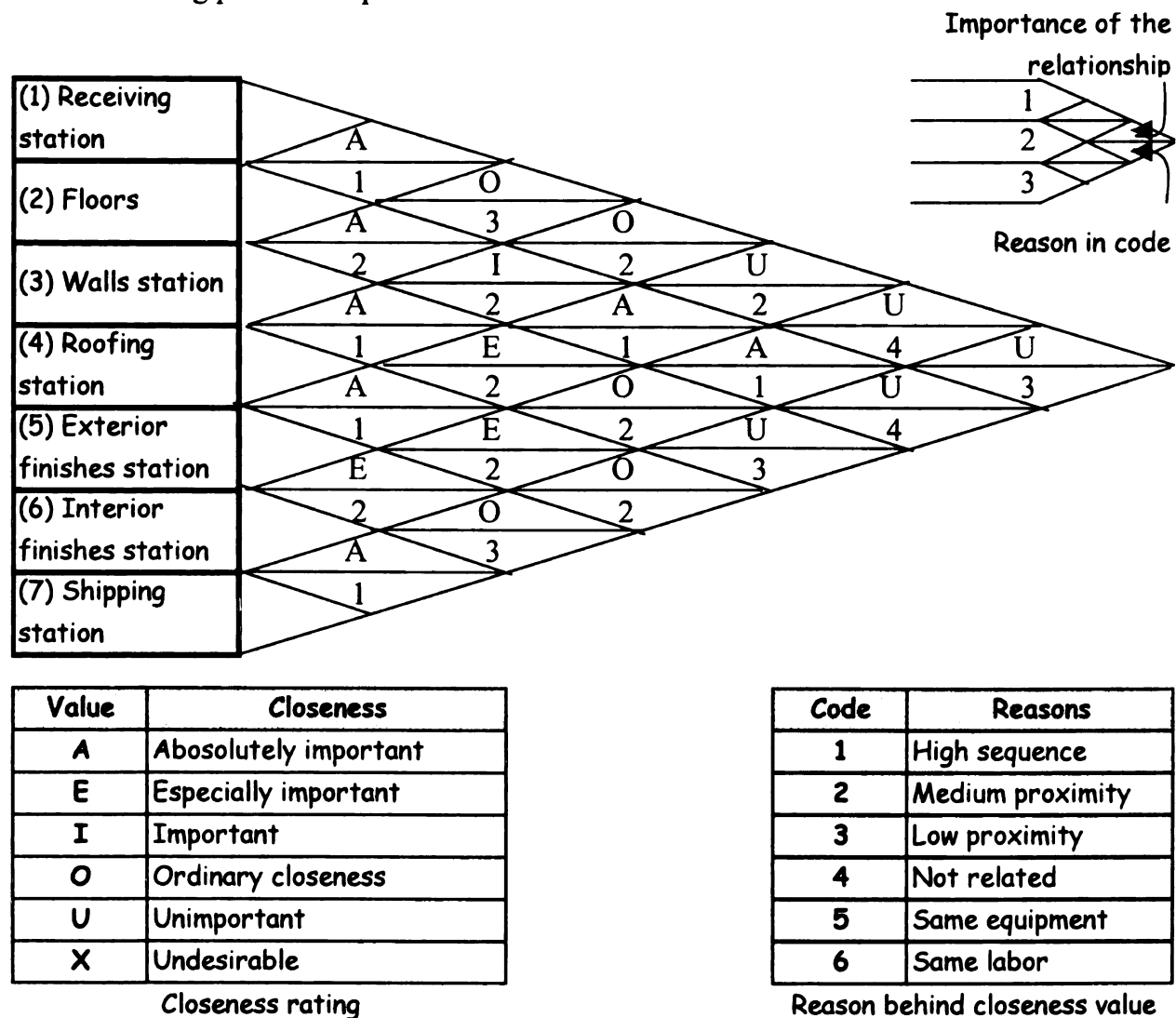


Figure 3.13: Relationship Chart
(Adapted from Mehrotra 2002)

3.3.4.2 Quantitative measure

This measure of flow indicates the level or extent of interaction between two facility pairs. The pairs with greater interaction between them should be placed closer to each other than those with limited interactions (Heragu 1997). This measure of flow involves the measurement of large volumes of materials, information or people moving between the stations (e.g. pieces per hour, moves per day, or pounds per week). For facilities having a large volume of materials, information, and people moving between departments, a quantitative measure of flow will be the typical basis for the arrangements of the departments. Flow may be measured quantitatively in terms of the amount moved between the departments and expressed in From-To charts, in the form of a matrix that displays the distances that the material moves between stations. Steps used to construct a *From-To chart* are illustrated below (Tompkins et al., 1996):

- ◆ Following the overall flow pattern, list all departments down the first row and across the top column.
- ◆ Establish a measure of flow for the facility that indicates equivalent flow volumes. If items vary in size, weight, value, etc., then items may be established so that the quantities recorded represent the appropriate relationships among the volume of movement.
- ◆ Based on the flow path for the items to be moved, establish the measure of flow volumes in the From-To charts.

Analysts often use frequency of trips between facilities as a measure of quantitative flow. The cost of investment, operating and maintenance of material handling systems, which are used for transporting the material are considered. The

distance traveled and the number of trips made by the material handling systems can also be developed into the frequency charts. If people move material or travel between facilities, then the trips made by these people are also considered. Generally two types of matrices are used to capture the frequency of trips between facilities.

- ◆ From-to frequency of trips matrix (Refer to Table 3.3)
- ◆ Frequency of trips between facilities matrix (Refer to Table 3.3)

Table 3.2 shows a basic From-To chart depicting the major clusters in a manufactured housing production plant. The values represent the distance between the clusters. There are various methods to measure the distances between the respective stations, namely Euclidean, Squared Euclidean, Rectilinear, Tchebychev, Aisle Distance, Adjacency and the Shortest Path. For the purpose of this thesis we will use the actual aisle distances between the stations, *i.e.*, the length of the routes traveled by the material handling systems like fork lifts, electric hoists etc (Heragu, 1997).

Table 3.2: Example of Distance Based From-To Chart
(Modified from: Tompkins et al., 1996, Mehrotra 2002)

Stations	Receiving station	Floor stations	Walls stations	Roofing station	Exterior finishes stations	Interior finishes stations	Shipping station
Receiving station		5	8	12	15	17	20
Floor stations	5		3	10	12	20	15
Walls stations	8	3		19	25	30	35
Roofing station	12	10	19		18	15	16
Exterior finishes stations	15	12	25	18		20	27
Interior finishes stations	17	20	30	15	20		17
Shipping station	20	25	35	16	27	17	

Table 3.3: Example of Material Movement Based From-To Chart
(Based on the data collected from case study)

Part Name	Parts/ Product	From	To	To
House	7	Station 35	Station 36	
Part A (Toilet & Kitchen)	1	Station 34	Station 35	
Final Finish Assembly - A	1	Station 32	Station 34	
Fasteners	1	Receiving Dock-9	Storage 26	Station 34
Trim - A	1	Station 30	Station 32	
Electrical Assembly - A3	1	Station 32	Station 32	
Gypsum Vinyl Moroccan Sand	231	Receiving Dock-9	Storage 28	Station 30
Support Shelf	8	Receiving Dock-9	Storage 28	Station 30
Shelving-Wire Closet	26.3	Receiving Dock-9	Storage 28	Station 30
Flat A	153	Receiving Dock-9	Storage 28	Station 30
Flat B	36	Receiving Dock-9	Storage 28	Station 30
Lockset	6	Receiving Dock-9	Storage 28	Station 30
Door Stop	51	Receiving Dock-9	Storage 28	Station 30
Door Jamb	102	Receiving Dock-9	Storage 28	Station 30
Door Hinge	9	Receiving Dock-9	Storage 28	Station 30
Door	6	Receiving Dock-9	Storage 28	Station 30
Corner Brace Shelving	2	Receiving Dock-9	Storage 28	Station 30
Cab Crown	40	Receiving Dock-9	Storage 28	Station 30
Brackets-U Clamp	20	Receiving Dock-9	Storage 28	Station 30
Brackets-End Shelving	10	Receiving Dock-9	Storage 28	Station 30
Skylite lip moulding	68	Receiving Dock-9	Storage 28	Station 30
Smoke Detector	1	Receiving Dock-9	Storage 23	Station 32
Sleeve Wire	40	Receiving Dock-9	Storage 22	Station 32
Ceiling Light	8	Receiving Dock-9	Storage 22	Station 32
Cover Waterproof Receptacle	2	Receiving Dock-9	Storage 22	Station 32
Exterior Jelly Jar Light	1	Receiving Dock-9	Storage 22	Station 32
Exterior Light Fixture	1	Receiving Dock-9	Storage 22	Station 32
Fan	2	Receiving Dock-9	Storage 22	Station 32
Flexi Duct	20	Receiving Dock-9	Storage 22	Station 32
Plate-Nail	33	Receiving Dock-9	Storage 22	Station 32
Globe Fluted Ball	8	Receiving Dock-9	Storage 22	Station 32
Refer, 16f	1	Receiving Dock-9	Storage 26	Station 32
Range Gas	1	Receiving Dock-9	Storage 26	Station 32
Range Hood	1	Receiving Dock-9	Storage 26	Station 32
Pipe-Range Hood	1	Receiving Dock-9	Storage 26	Station 32
Drapes	1	Receiving Dock-9	Storage 25	Station 32

The basic data required to solve the manufacturing layout problems are usually available from the personnel on factory floors. The key pieces of data required to measure the quantitative flow within a manufacturing facility are listed below.

Name and Code for Each Part

Each of the parts required to build a unit of a manufactured home has a unique alphanumeric code assigned to it. This information helps to determine the total number of parts required to manufacture the product.

Name and Code for Each Station

Similarly, to the parts each of the workstation has a unique name. For example, Station 1A in the manufactured housing plant in the case study is referred to as the station where the chassis is assembled.

Routing Information for Each Part

Each of the part has a routing information that specifies the sequence in which the operations will be performed on the part. This information can be used to determine the sequences of the stations visited by the part.

Production Volume for Each Part

The number of units of each part type required to manufacture the product (e.g. home) will provide the volume of the material flow.

Machine Dimensions and Space Requirements

This information is available through equipment catalogs, drawings or the actual measurement of the machines.

Cost of Handling Unit Load of Material Between Each Workstations

This cost typically depends on the material handling carrier used. This information helps to determine the material handling cost of a unit load. For example, in the plant used for the case study, a fork-lift as well as hand trolleys are used for transferring the materials between stations. The cost of the fork lift is higher than that of the trolley.

Special Location Restrictions or Adjacency Information

Companies generally have some workstations that cannot be moved from certain locations due to some constraints. Information about such constraints also helps the facility planner to design the layout alternatives.

3.4 Generic Models for Facility Layout Problems

Models are the imitation of real world. They may be classified as physical, analog or mathematical. The physical models are the models that have same shape and the appearance as the real system but of smaller size, e.g., models of buildings, airplanes etc. Analog models provide necessary information of the real system; however they are not required to resemble the real system, e.g., a graph showing the increase in population over time. There are two types of mathematical models: descriptive (predicting performance of a system) and prescriptive or normative (providing values for a set of decision variables) (Heragu 1997).

After the models are generated, the techniques developed to solve the models are known as the *Algorithms*. Most of the facility layout design and planning problems are computationally difficult. As a result several generic tools are implemented for modeling design and planning problems. These generic tools implement the three modeling tools - mathematical programming, queuing and *simulation modeling* in right

sequence in order to get feasible and optimum solutions for design and planning problems.

3.4.1 Mathematical Models

The mathematical programming approach attempts “*to optimize a quantifiable objective function so that some specified set of constraints is not violated*” while the “*objective function minimizes costs or maximizes profit, and the constraints specify a bounded region of feasible solutions to the problem.*”

Layout Evaluation Criteria

Based on quantitative flow of the production process, a basic measurement criterion model is developed that explains layout problem and identifies critical factors. The equation below explains the following objective function.

$$\sum_a \sum_i \sum_j c_{ij} f_{ij} d_{ij}$$

Where

c_{ij} = cost of moving a unit load of material distance between stations i & j per unit distance.

f_{ij} = number of trips between stations i and j

d_{ij} = distances between stations i and j

a = number of material types

3.4.1.1 Traditional Quantitative Models for Facility Layout Problems

We need to model a layout problem in order to develop an efficient solution for the layout design of a given facility. Mathematical models have found wide application for

representing the layout problems and are solved by suitable algorithms. By using commercially available software, the mathematical models that are developed can be solved. There are several varieties of quantitative models that have been applied to understand the parameters and that help in making design decisions while planning the facilities layout. This section presents the overview of a number of analytical models of facility planning problems. However, for the purpose of modeling, it is convenient to classify layout problems into two types, namely, single-row layout problems and multi-row layout problems (Heragu 1997). The single row and multi-row layout problems are also known as one-dimensional and two-dimensional space allocation problems, respectively (Simmons 1969).

- Single row layout problem/ One dimensional (Refer Figure 3.14)
- Multi row layout problem/Two dimensional (Refer Figure 3.14)

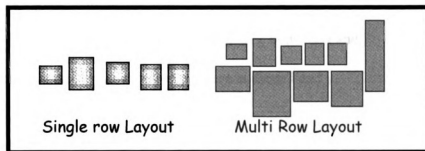


Figure 3.14: Types of Layouts
(Heragu 1997)

As the name indicates, in the single row layout problems the facilities are arranged linearly in one row, and in multi-row problems the facilities are arranged in two or more rows. The layout of machines on one side of an automated guided vehicle (AGV) on a factory floor is an example of single row facility layout problem. The single-row and multi-row layout problems are modeled and they have absolute terms in the objective functions, the constraints, or both.

ABSMODELS for the single-row and multi-row layout problems

The models are known as ABSMODELS, as they have absolute terms (i.e. a quadratic or modulus expression) in the objective function, the constraints, or both. These models are nonlinear models and are formulated on the basis of the following assumptions:

1. The facilities are square or rectangular and their sizes are known a priori
2. The facilities are arranged in a straight line
3. The orientation of facilities is known a priori
4. There is no restriction on the shape of building where facilities are to be placed

The examples of some of the ABSMODELS are given below:

ABSMODEL 1

ABSMODEL 1 is used to formulate single-row layout problems.

Parameters

n = number of stations in the problem

c_{ij} = cost of moving a unit load of material distance between i and j

f_{ij} = number of loads or trips required between stations i and j

L_i = length of horizontal side of station i

d_{ij} = minimum distance by which stations i and j are separated horizontally

Decision Variables

x_{ij} = distance between the center of station i and the Vertical Reference Line (VRL)

Objective Function

The parameters and decision variables pertaining to the single-row layout problem are illustrated in figure 3.15. Since we are considering only the single-row layout problem,

the vertical dimensions of floor plan and vertical side of the facilities are not considered.

The following equation represents the ABSMODEL 1.

Minimize $\sum_i \sum_j c_{ij} f_{ij} |x_i - x_j|$

Subjected to: $|x_i - x_j| \geq 1/2 (l_i + l_j) + d_{ij}$

$i = 1, 2, \dots, n-1$
 $j = i + 1, \dots, n$

The objective function of the model minimizes the total cost involved in making the required trips between stations and the constraint ensures that no two facilities in the layout overlap.

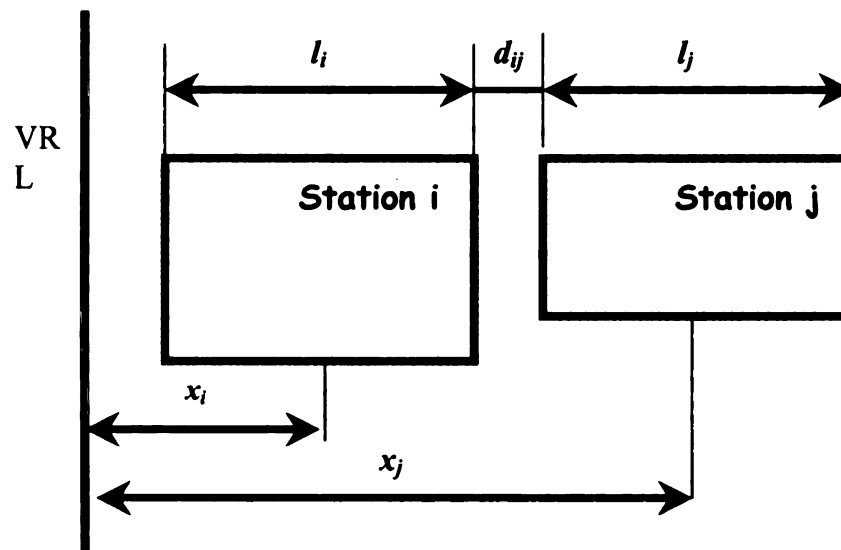


Figure 3.15: Illustration of parameters & decision variables for the single-row layout problem- ABSMODEL 1
 (Heragu 1997)

ABSMODEL 2

This model can be used to formulate multi-row facility layout with facilities having equal square area. This model is similar to ABSMODEL 1 and has the following notations used in addition.

Decision Variables

x_{ij} = distance between the center of station i and the Vertical Reference Line (VRL)

y_{ij} = distance between the center of station i and the Horizontal Reference Line (HRL)

Minimize Objective Function:

$$\sum_i \sum_j c_{ij} f_{ij} (I x_i - x_j I + I y_i - y_j I)$$

Subjected to:

$$I x_i - x_j I + I y_i - y_j I \geq 1 \text{ where } i = 1, 2, \dots, n-1 \text{ } j = i+1, \dots, n$$

$$x_i, y_i = \text{integer}$$

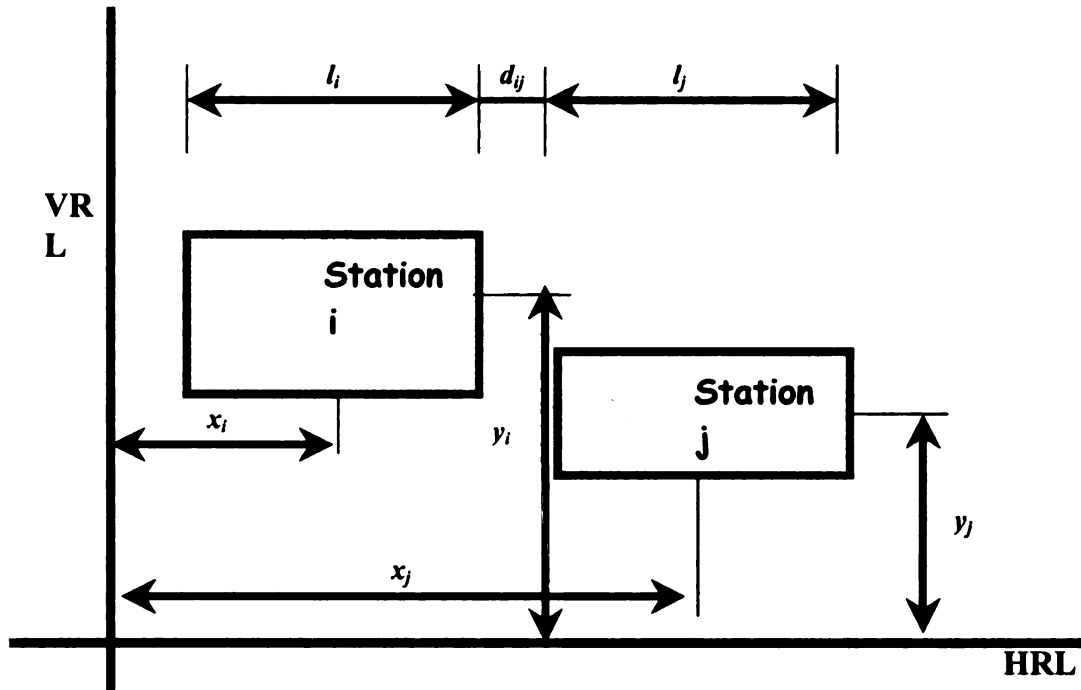


Figure 3.16: Illustration of parameters & decision variables for the multi-row layout problem: ABSMODEL 2
(Heragu 1997)

The constraints ensure that no facilities in the layout overlap and impose integrality. In both the above models, the facilities were assumed to have equal areas and this assumption is not very realistic.

ABSMODEL 3

ABSMODEL 3 model assumes that facilities are square and rectangular and their physical orientation are known a priori. This model takes care of the equality assumptions

and is formulated in a similar manner as the ABSMODELS described earlier (Heragu 1997).

Limitations of ABSMODELS:

ABSMODELS are not specific but general models. They can be solved using simple heuristic techniques. They assume that facilities have equal area and when facilities have unequal areas, the models have to be modified suitably and as a result the models become more complicated in both formulation and computation. Moreover, the models are non-linear and the solution produced by the software may be sub-optimal. To remove the non-linearity in ABSMODELS the mixed integer formulations of the ABSMODELS are introduced. Such models may be solved optimally by using branch and bound methods and other general techniques available for solving mixed-integer problems.

3.4.1.2 Quadratic Assignment Problems

The Quadratic Assignment Problems (QAP) are also non-linear models with absolute terms, formulated to solve multi-row layout problems with facilities having equal areas (Heragu 1997). In a facility layout problem, in which there are n facilities to be assigned to n given locations, the term *assignment* refers to the matching of each facility with a specific location. As a result, we need equal number of facilities and location to formulate a QAP models. If we have a greater number of locations, we assign dummy facilities with zero flows to make the number equal. The problem becomes infeasible when there are fewer locations. The following notation is used:

Parameters

n = number of facilities and locations

a_{ij} = net revenue from operating facility i at location j

f_{ik} = flow of material from facility i to facility k c_{jl} = cost of transporting unit material

from location j to l **Decision Variables**

$x_{ij} = 1$ if facility I is at location j

$x_{ij} = 0$, otherwise

The assumptions that are made for QAP formulation are listed below:

- a_{ij} includes gross revenues minus the cost of primary input but does not include the transportation cost of materials between the facilities.
- f_{ik} is independent of the location of the facilities.
- c_{jl} is independent of the facilities
- It is cheaper to transport material directly from facility i to facility k than a third location.

Minimize Objective Function: $\sum_i \sum_j a_{ij} x_{ij} - \sum_i \sum_j \sum_k \sum_l f_{ik} c_{jl} x_{ij} x_{kl}$

Subjected to: $\sum_j x_{ij} = 1$ where $i = 1, 2, \dots, n-1, j = i+1, \dots, n$

$x_{ij} = 0, 1$

3.4.1.3 Linear Mixed-Integer Models

Linear Mixed-Integer Models for the Single-Row Layout Problem (LMIP)

To develop an equivalent linear mixed-integer programming model for the single-row layout problem, the following additional variables are introduced.

Decision Variables

$x_{ij}^+ = \{(x_i - x_j) \text{ if } (x_i - x_j) > 0, \text{ otherwise } 0\}$

$x_{ij}^- = \{(x_j - x_i) \text{ if } (x_i - x_j) \leq 0, \text{ otherwise } 0\}$

$z_{ij} = \{1 \text{ if } x_i > x_j, \text{ otherwise } 0\}$

Minimize Objective Function: $\sum_i \sum_j c_{ij} f_{ij} (x_{ij}^+ + x_{ij}^-)$

Subjected to:

$$x_{ij}^+ + x_{ij}^- \geq 1/2 (l_i + l_j) + d_{ij}$$

where $i = 1, 2, \dots, n-1$ $j = i+1, \dots, n$

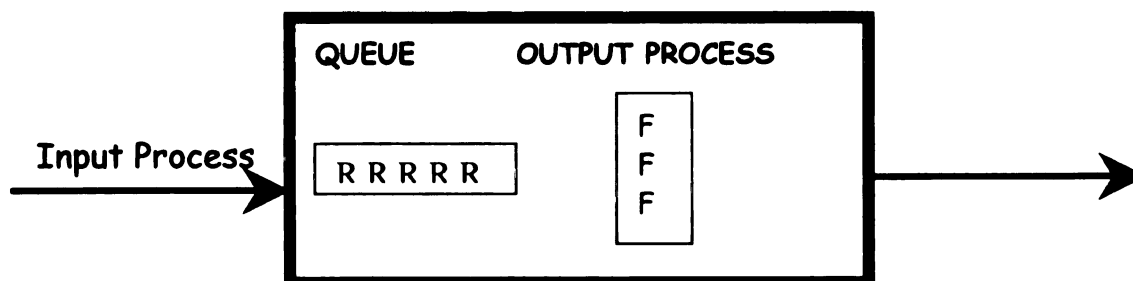
$$x_i - x_j = x_{ij}^+ - x_{ij}^-$$

The constraints here take care of the overlapping issues within the facilities and the left or right positioning of them. For multi-row layout problems, the same formulation procedure is adopted by introducing the vertical “y” co-ordinates as the variables.

3.4.2 Queuing Theory

Queuing theory can be described as the mathematical tool that can give estimates of the variables in the following (Refer to Figure 3.17):

- ◆ Number of parts waiting in queue in production line
- ◆ Time a part spends waiting in a queue
- ◆ Probability that a machine/worker is idle
- ◆ Probability of a queue being filled to capacity (Heragu 1997)



R: Raw material; F: Finished Goods

Figure 3.17: A queuing system

(Adapted from Heragu 1997)

3.4.3 Simulation Models

Simulation is a performance evaluation and modeling tool widely used in manufacturing systems. Simulation approach can analyze complex stochastic systems and is able to capture unlimited number of complexities in one system. In fact, a simulation model can closely reflect reality, and the accuracy of the result depends on the mode of programming. A simulation model consists of three entity classes: resources, transactions, and queues (Heragu 1997).

3.5 Computer-Aided Layout and Algorithmic Approach

An algorithm can be defined as a technique or procedure used to solve a problem, in this case a layout design problem. Even though the existing computer-based layout algorithms cannot capture the qualitative characteristics of a layout, which are best adjudged by human knowledge and reasoning, computer-generated algorithms can enhance the efficiency of a facility layout planner and the quality of final solution by numerically generating a large number of layout alternatives in a shorter time. The computers are also very efficient in rapidly performing “what-if” analyses based on varying input data and layout algorithms.

3.5.1 Algorithm Classification

The layout algorithms can be classified in a number of ways. Based on Tompkins et al. (1996), a few of the major classifications are presented in this section. Also, the algorithms may be classified as the following:

- ♦ *Optimal Algorithms*
- ♦ *Heuristic Algorithms*

- *Construction Algorithms*
- *Improvement Algorithms*
- *Hybrid Algorithms*

3.5.1.1 *Based on type of input data required:*

Most layouts can be classified based on the type of data required. Some algorithms require qualitative flow data like relationship charts, while others work with quantitative flow matrices expressed as a From-To chart. Some algorithms, such as BLOCPLAN, accept both forms of data.

3.5.1.2 *Based on the objective function:*

Two major objectives by which algorithms can be classified are

- (a) *Minimizing the sum of flows times distances* (also called a distance-based objective): this objective is applicable to data in the form of From-To charts (Quantitative Algorithm).

The objective is to minimize the cost per unit time for movement among the department.

This objective can be mathematically expressed in the form of the following equation

(Tompkins et al., 1996):

$$\text{Minimize } Z = \sum_{i=1,2,\dots,n} \sum_{j=1,2,\dots,n} f_{ij} c_{ij} d_{ij}$$

Where:

m = number of departments

f_{ij} = flow from dept i to dept j .

c_{ij} = cost of moving a unit load one distance unit from dept i to dept j .

d_{ij} = distance from dept i to dept j .

- (b) *Maximizing the adjacency score*: this objective is applicable to data in the form of relationship charts (Qualitative Algorithm).

The objective of this adjacency score-based example is to maximize the adjacency score.

This objective can be mathematically expressed in the form of the following equation (Tompkins et al. 1996):

$$\text{Maximize } Z = \sum_{i=1,2,\dots,n} \sum_{j=1,2,\dots,n} f_{ij} x_{ij}$$

The adjacency score can be computed as the sum of all the flow values (or relationship values) between the departments that are adjacent in the layout.

$x_{ij} = 1$ if departments i and j are adjacent (share a border) in the layout.

$x_{ij} = 0$ if the departments i and j are non-adjacent.

3.5.1.3 Based on format used for layout representation:

Most layout algorithms use *discrete* representations. In this form of representation, the computer stores and manipulates the layout as a matrix (Figure 3.18). The area of each department is rounded off to the nearest integer in the grids. The other form of representation is a continuous representation, where there is no underlying grid (Figure 3.19). Although this representation is theoretically more flexible, it is difficult to implement on the computer.

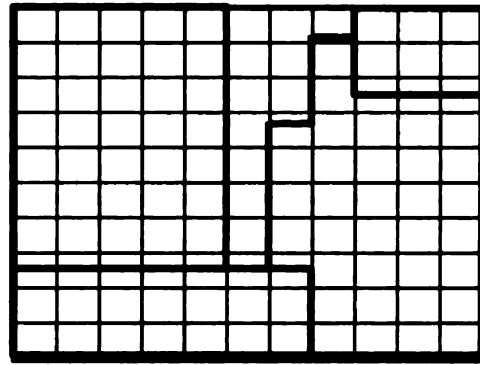


Figure 3.18: Discrete layout representation
(Tompkins et al. 1996)

Department shapes play an important role in layout algorithms. A department represents the smallest indivisible entity in layout planning, and a layout algorithm must not split a department. If any department is too big in size, the planner should look at the how the department was defined and, if required, change one big department into two smaller ones. Consider the following examples (Figure 3.20) of discrete representation.

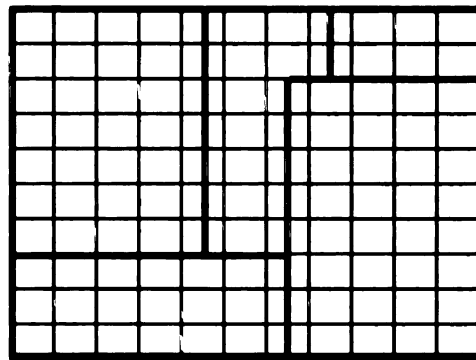


Figure 3.19: Continuous layout representation
(Tompkins et al. 1996)

Departments are considered adjacent if they share a border of positive length. Figures 3.20a and 3.20b are representations of split departments, whereas Figures 3.20c and 3.20d are examples of unsplit departments. For the purpose of facilities layout the layout in Figure 3.20e is considered not practical, as it has an enclosed void in the center of the layout. In cases where the planner wishes to create an irregularly shaped layout or has to

incorporate non-assembly-line related objects like stairs, offices, or plant services, the planner can create a dummy department.

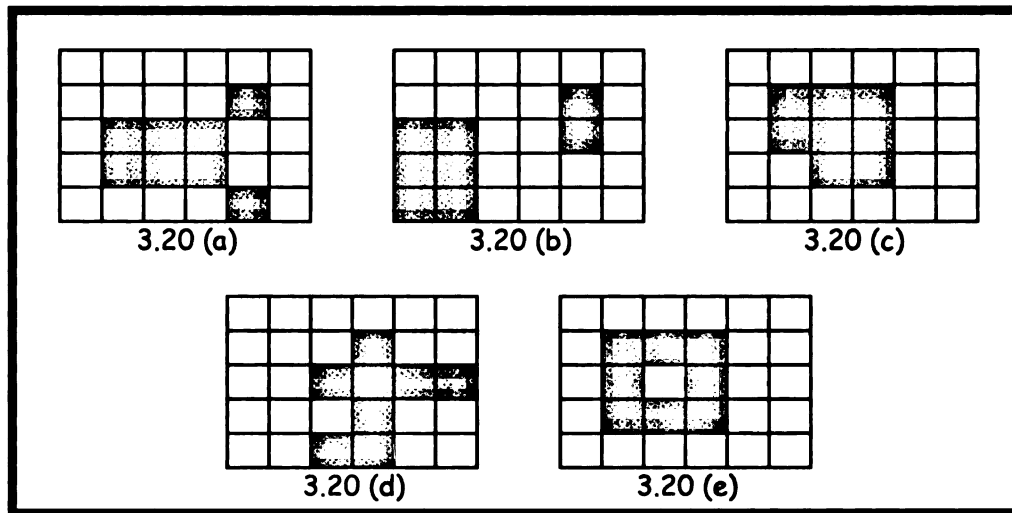


Figure 3.20: Split and unsplit departments
(Tompkins et al., 1996)

3.5.1.4 Based on the primary function of the layout

Finally, algorithms can be classified on the basis of the primary function of the algorithm, e.g. (a) layout-improvement type algorithm, and (b) layout-construction type algorithms.

An improvement-type algorithm starts with an initial layout, and improvement on the objective function through incremental changes. A construction type algorithm is developed from scratch. The construction-type algorithm can be further subdivided into algorithms that assume that building dimensions are provided and algorithms that do not. In the following section, a few of the major layout-improvement algorithms and computer-based algorithms are described.

3.5.2 Computerized Relative Allocation of Facilities Technique (CRAFT)

CRAFT was first introduced by Armour and Buffa in 1963 and by Buffa, Armour and Vollmann in 1964. CRAFT, which is an improvement-type algorithm, uses From-To charts as the input data for measuring the flow. CRAFT first calculates the rectilinear distance between pairs of department centroids on the initial layout and stores the value as a distance matrix. The initial layout cost is determined by multiplying each entry in the From-To chart with the corresponding entries in the unit cost matrix (e.g. c_{ij} values) and the distance matrix.

Then CRAFT considers all the possible two-way or three-way department exchanges and identifies the best exchange (the one with the least cost). After identifying the best exchange, CRAFT updates the layout and computes new department centroids and the new layout cost, completing the first iteration. The next iteration starts with the identification of best exchanges in the updated layout. This process continues until no reduction in layout cost can be obtained. The final layout thus obtained is also called two-opt (three-opt) layout as no exchanges can further reduce the layout cost. Departments are not restricted to rectangular shapes. Sometimes this feature causes a layout that is not very practical in nature. Also it hampers the ability to have long and continuous aisles (Tompkins et al. 1996).

3.5.3 ALDEP and CORELAP

ALDEP and CORELAP are both construction-type algorithms. The form of data input is qualitative in nature and is given in the form of a relationship charts. Although these two

algorithms are no longer supported commercially, they are important in understanding the evolution of computer-aided layout algorithms.

ALDEP, or Automated Layout Design Program, begins by selecting a department at random. It then continues by choosing a second department with an 'A' relationship with the department previously selected. It continues through all departments with ties being broken randomly. The idea is to progressively build around strong relationships.

The placement of departments begins by placing the first department in the upper left corner of a predefined border of the complete facility. The width of the downward extension is inputted by the designer and is called the sweep width. Each of the following departments begins where the previous department ends, and the departments are arranged in a serpentine pattern. After the layouts are prepared, each of the layouts is evaluated. ALDEP rates by assigning values to the relationships among the adjacent departments. Each of the relationship codes (A, E, I, O, U, X) has a preassigned value. ALDEP produces many layouts, rates each one, and leaves the final selection of the layout to the designer (Tompkins et al. 1996).

CORELAP, which is also a construction-type algorithm, stands for Computerized Relationship Layout Planning. Like ALDEP, it uses qualitative data for construction of layouts. It constructs a layout by evaluating the total closeness rating (TCR) for each department. TCR is the sum of the values allocated, using the relationship codes (A=6, E=5, I=4, O=3, U=2, X=1) between the departments. The department with the highest TCR rating is placed in the center of the layout. The department with the next highest TCR rating, that has an A relationship with the first department, is placed on the

layout next. Once the final layout has been prepared CORELAP evaluates the layout by calculating the layout score which is the sum of the numerical closeness ratings over all departments multiplied by the length of the shortest path (Tompkins et al. 1996).

The basic procedural difference between ALDEP and CORELAP is that ALDEP breaks ties between departments randomly while CORELAP uses TCR, or Total Closeness Rating. After the final CORELAP layout has been prepared, a score is found for that particular layout using the shortest rectilinear path between departments. One of the problems with CORELAP is that the shortest rectilinear path between departments may not always be a realistic measure (Tompkins et al. 1996).

3.5.4 BLOCPLAN

BLOCPLAN, which was developed by Donaghey and Pire, at the Industrial Engineering Department, University of Houston, accepts data input from both From-To charts and Relationship charts, i.e. both quantitative and qualitative data are accepted. It is a part of the MHAND package (Material Handling and Facility Location models).

This algorithm can be used both as an improvement and construction type algorithm. The major purpose of BLOCPLAN is to generate and evaluate block type layouts in response to the user supplied data. BLOCPLAN also uses the relationship codes specified by Muther in Systematic Layout Planning (1973). BLOCPLAN provides an empty relationship chart and the user is prompted to furnish the codes for each of the department relationships. To prepare a layout, BLOCPLAN needs the number value of each of the relationship codes. Both user and program-specified values can be used. BLOCPLAN provides nine zones for locating departments. This feature can be used

when the user has to fix certain departments, either due to entry/exit restrictions or due to preplanned positioning of departments.

To evaluate the relative-distance score, BLOCPLAN calculates the sums of the products of the distances between each pair of departments and the corresponding relationship score. The lower the relative-distance score, the better the layout.

In the case of a distance-based objective, data from the From-To charts are used. The aim is to minimize the sum of the products of flow, cost and distance. Though it is difficult to capture, the initial layout, BLOCPLAN helps in improving the initial layout (Donaghey 2000).

3.5.5 AutoCAD Based Tools

AutoCAD is a standard design and drafting package for the creation and manipulation of 2-D and 3-D line drawings and images. The factory products group at Engineering Animation, Inc. (EAI) developed software that simplifies designing a new factory or improving an existing one. The three programs FactoryCAD, FactoryPLAN, and FactoryFLOW run inside AutoCAD and allow for both qualitative and graphical analysis as well as providing valuable tools for creating a layout (Owen 2002).

3.5.5.1 FACTORYCAD

FactoryCAD is an AutoCAD-based tool used to develop new factory layouts and modify existing ones. It provides all the equipment objects such as racks, cranes, and conveyors, and design/construction-based elements such as walls, doors, windows, columns, work centers, utility lines, etc. It is a drafting tool that can be used to develop a virtual model of the factory. FactoryCAD allows for automatic layering, automatic area and tool clearance hatching, and detailed reporting. FactoryCAD customizes AutoCAD to automate drawing

plant layouts and reporting assets. FactoryCAD menus take the user, step-by-step, through the drawing process, from drawing double-line walls of any thickness and creating building grids, to locating individual electrical outlets and gas line valves (Owen 2002).

3.5.5.2 FactoryPLAN

FactoryPLAN is a software that can be used to develop the layout of the factory. It is a qualitative layout tool and uses the SLP-approach developed by Muther (1973). FactoryPLAN requires data input in the form of space requirements and activity relationships. The user can specify the individual department dimensions and the overall facility shape too. With these data FactoryPLAN creates, manipulates, and scores qualitative relationship diagrams. These diagrams can be used to prepare various layout alternatives, and, based on the user's requirements, the best layout can be chosen. FactoryPLAN can be used as either an improvement-type layout algorithm or a construction-type layout algorithm (Owen 2002).

Each of these programs addresses individual issues related to layout design. With the help of these AutoCAD-based tools (FactoryCAD, FactoryPLAN, and FactoryFLOW), the user can completely develop and present a production plant layout. FactoryFLOW is the software, which is used in the proposed research and it provides an integrated material handling system in visual environment. It can be defined as a post-processor to evaluate layouts, as it requires an existing layout that is to be generated by an AutoCAD software. The details of this software is given in the next section.

3.6 FactoryFLOW Software

FactoryFLOW is neither a planning tool nor a drafting tool. It is a tool that can be used to analyze and evaluate a layout that has already been created. “FactoryFLOW integrates AutoCAD facility drawings with production routing and material handling data to compute material travel costs and distances and create product-flow diagrams for graphical flow analysis” (Owen 2002). It is a software application that generates material flow and aisle congestion diagrams and reports. With the help of the graphical flow information in a factory layout drawing, FactoryFLOW helps to identify the critical paths, potential flow bottlenecks, production flow efficiency, storage space requirements and material handling requirements (EDS 2002).

FactoryFLOW enables the user to examine the effects of changes in routing and handling methods, ranging from simple changes in lot size to large-scale changes in layout. It helps improve throughput times and work-in-progress (WIP) levels by decreasing part-travel distance and the number of pick-ups and set-downs of the materials (Owen 2002).

However, the user can make minor changes based on the “what-if” analysis performed by this software and can try to improve the previously developed layout (E-Bundle, 2003). It also enables the designers to analyze factory layouts by using part routing information, material storage needs, and material handling equipment specifications. FactoryFLOW is used for optimizing layouts based on material flow distances, frequency, and costs.

FactoryFLOW requires information on each move for each part in the form of the quantity moved, material-handling device used, and unit load. The information for

these factors can be loaded into the software by using spreadsheets or word processing software. Based on the data entered and the AutoCAD layout file, the software calculates total move distance and cost (Heragu 1997). These representations of flow and material handling events over the analysis time period significantly boost understanding of the production system. FactoryFLOW enables rapid, easy modeling of changes to the layout, routings, production volume, material handling systems, and material handling activities (EDS 2002).

The major advantages of using FactoryFLOW are (EDS 2002):

1. Planning or improving the layout of a single work cell, a production line, a department, or a plant
2. Working to improve the material flow efficiency of a product, a part, or groups of parts or products
3. Calculating storage requirements
4. Calculating material handling system requirements
5. Changing product mix, adding new production, or working to improve plant efficiency
6. Implementing new production philosophies, such as Just-In-Time or Group Technology
7. Presenting layout alternatives
8. The comparisons of alternative design layouts made in FactoryFLOW can illustrate and evaluate (1) Different levels of production,(2) Various storage,

machine, line, and dock locations, (3) Alternate product routings, (4) Different material handling methods, and (5) Effect of activity time on operator walk paths.

The major objectives for FactoryFLOW analysis are illustrated below (EDS 2002):

1. Evaluating material handling requirements
2. Eliminating non-value-adding material handling
3. Reducing total product travel
4. Improving product throughput
5. Reducing work-in-process inventories
6. Redesigning material flow for Just-In-Time or Group Technology
7. Identifying storage space requirements
8. Analyzing layout feasibility for operator walk paths

3.6.1 Data Requirements for FactoryFLOW Analysis

The amount of data and detail required depends on the level of analysis. The basic data that are usually required are (1) An AutoCAD layout drawing, (2) Production quantity information, (3) Parts routing information, (4) Material handling equipment information, and (5) Material handling activity information.

3.6.2 Stages in FactoryFLOW Analysis

The *FactoryFLOW Class Guide Manual* (EDS 2002) describes six common stages of the FactoryFLOW analysis that are illustrated below.

1. Identify the goal(s) of the study and determine areas or products affected

A FactoryFLOW study can help to determine several factors like adding new products or changing existing products, expanding or contracting a facility, constructing a new

facility, creating manufacturing cells, planning storage or work-in-process locations, moving manufacturing lines, adding new equipment or relocating existing equipment, improving material handling system efficiency and estimating material handling labor requirements. Once the objective is determined, the analysis can be limited to an appropriate level and data can be collected and structured accordingly.

2. Determine the level of detail

The analysis should be done taking one level at a time. For Example, in order to revise the layout of an area containing several work cells, the cell locations within the area should be considered first. All moves within the cells could be ignored, but all moves to/from a cell should be considered to have a single destination or origin within the cell, regardless of the actual individual machine locations within the cell. One may also choose to analyze only high-volume products, specific areas, expensive handling devices, and so on.

3. Adopt Data Naming Conditions

For the ease of analysis the names assigned to products, parts, material handling devices and activity points should be easily recognizable.

4. Gather And Organize Input Data

The type of data to be collected is determined by the type of analysis one intends to perform. The table of analysis tasks accomplished with factory tools reviews typical analysis tasks, their associated data inputs, and the outputs created by FactoryFLOW. FactoryFLOW stores all data in a single database file, which is named with a .FLO filename extension.

5. Produce an AutoCAD plant layout drawing

FactoryFLOW uses an AutoCAD drawing of the facility or analysis area to compute travel distances. Depending on the type of analyses required, the drawing also provides information, which the FactoryFLOW software uses to size aisles, pack containers in storage areas, document manufacturing cells, and generate operator walk paths.

6. Produce Reports and Diagrams For Analysis

Given input data and a layout drawing, FactoryFLOW calculates distances, costs, intensity (frequency of path use), and material handling activities, and then diagrams the material flow. Factory FLOW generates three types of material flow paths, namely, (1) Euclidian, (2) Rectilinear, and (3) Actual (Refer to Figure 3.21).

All flows that have the same routing (from activity point, to activity point and material handling device) use the same flow path. As flows are identified, FactoryFLOW performs the distance, cost, and path use calculations. The results for each flow path are summed, and each flow line's width is adjusted to reflect the intensity (frequency of path use) of material handling along the path. When actual paths have been calculated and drawn, FactoryFLOW can then calculate and diagram aisle congestion.

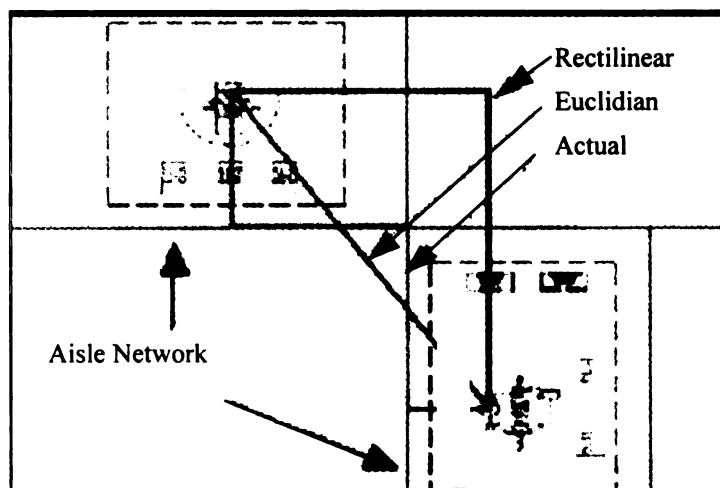


Figure 3.21: Material Flow Path
(EDS 2002)

The FactoryFLOW diagrams, charts, and reports are used to find out areas of possible improvements. It can also perform “what-if” analysis by changing activity locations, editing paths, or input data and immediately calculate the impact of the change. Alternate layouts and material handling systems can be compared, and the output reports can be used for justifying the recommendations for change in layout or material handling systems.

3.6.3 FactoryFLOW Equations

FactoryFLOW utilizes the following equations to calculate distance, cost, time and material handling utilization (EDS 2002):

The number of trips for a move:

$$\#trips = \frac{\{(Product\ Volume)(Part\ Quantity)(Part\ Usage)(Flow\ \%)\}}{(Parts/Container)(Container/Trip)}$$

The total distance for a move:

$$Total\ distance = (\#\ of\ Trips)(Trips\ Distance)$$

The total time for a move:

$$Total\ Time = \frac{Total\ Dist}{Speed\ of\ Device} + (Time\ Det\ by\ Load\ Temp) + (Time\ Det\ by\ UnLoad\ Temp) + (Time\ Det\ by\ MHTemp)$$

The total cost for a move:

$$Total\ Cost = (Fixed\ Cost) + (F/P/M\ Cost/hr)(Total\ Time)/60\ min + (labor/hr)(Total\ Time)/60\ min$$

The material handling device utilization:

$$Utilization = \frac{Total\ Busy\ Minutes}{Total\ Available\ Minutes}$$

This section outlines the various aspects of FactoryFLOW as a quantitative analyzing and evaluating tool for facility layout alternatives based on the material movement within a given manufacturing plant. The reports and charts generated through the FactoryFLOW evaluation are based on the equations presented above.

3.7 Summary

This chapter presents an outline of the major contemporary tools and techniques used for planning, developing, evaluating and presenting facility layout design in manufacturing facilities. The author attempts to emphasize the significance of material flow and material handling systems as some of the major quantitative elements that enable the facility planner to design a cost-efficient plant. Various activity relationships and flow relationships are described in this chapter. Among the flow relationships, the quantitative flow relationship and the From-To charts are especially significant to the author, as the research intends to focus on the quantitative relationships within the stations and substations of a manufactured housing plant.

CHAPTER FOUR
QUANTITATIVE MODEL FOR THE FACILITY LAYOUT

4.1 Introduction

In this chapter, the implementation of some of the tools and techniques presented in Chapter III dealing with the facility layout in a manufactured housing facility are described. As already discussed in Chapter III, there are number of quantitative models that can be used to facilitate the process for developing the alternative facilities plan. In this chapter, the author explains the methodology for modeling the facility layout of a manufactured housing factory using a quantitative approach. This research introduces the FactoryFLOW software and its implementation. The manufactured housing plant used as a case-study plant is described. In addition, this chapter draws on the case-study to document the details of the manufactured house- its production process, the materials used and their flow, and the material handling system and devices used for the manufactured housing facilities. The analysis of the data collection; development of the product-tree structure, and identification of the activity points and their interrelationship with the material handling system necessary for the formulation of the quantitative model in the software are also explained. The latter part of this chapter gives a brief outline of the qualitative analysis of the facility layout problem of the manufactured housing plant (Mehrotra 2002). Finally, the reports and analysis of the quantitative model based on the existing layout of the manufactured housing factory are generated using the FactoryFLOW software. Figure 4.1 represents the framework used for this chapter.

STRUCTURAL FRAMEWORK FOR QUANTITATIVE MODELLING PROCESS FOR FACILITY LAYOUT				
Quantitative Approach in Modeling	Manufactured House	Data Collection for The Quantitative Analysis Of Facility Layout	Case-Study: Application of the Data Collection Methodology	Quantitative Modeling In Layout Evaluation Software (FactoryFLOW)
Selection of Material Flow as a Quantitative Flow Measure	Description of the Case Study	Obtaining basic data	Space Requirements and Layout Drawing	Understanding The FactoryFLOW Data Structure
Quantitative Modeling Approaches	Materials, Components of Manufactured Home	Extracting relevant data	Production Quantity Information	AutoCAD Plant Layout Drawing
Material Handling System and Facility Layout Design	Manufactured House Production Process & Facility Layout	Generating data in the required format	Material Handling System and Facility Layout Design	Starting FactoryFLOW
Material Handling Equipment	Stations Process Details	Documenting data	Material Handling Equipment	Tree Diagram or Product Structure
Top-To or bottom-up approach to quantitative modeling can be developed for organizational, cost, and process factors. A bottom-up approach is a more individual material handling flows measures activity, which involves a huge movement of material. A very demanding process and is beyond the scope of the From a facilities planning perspective, all	Qualitative Approach Based on Space Requirements and Proximity		Material Handling Equipment Information-Cost Factor)	Activity Points
			Material Handling Activity Information-Time Factor)	Material Handling Devices
			Quantitative Modeling Approaches	Production of Analysis Reports & Diagrams and Verification of The Existing Layout (Case Study)
			Material Handling System and Facility Layout Design	
			Material Handling Equipment	

Figure 4.1: Framework for Chapter IV

4.2 Quantitative Approach in Modeling

Quantitative modeling of the facility layout of manufacturing facilities is one of the common approaches to addressing the selection of the best alternative layout. As mentioned earlier in Chapter III, activity relationships and space requirements are essential elements in facilities planning. Measures of flow indicate the level of interaction between two pairs of stations and these are determined by activity relationships. However, while using the interaction between two stations as the guide in determining

the relative facility layout, consideration for the area, shape and space requirements of the facilities should be kept in mind. In addition, among the activity relationships considered, the quantitative flow relationships are of considerable importance to the facility planner. Quantitative flow relationships include the movement of goods, material, information, and people.

4.2.1 Selection of Material Flow as a Quantitative Flow Measure

Due to the multiplicity of relationships involved, it is necessary to construct separate From-To quantitative matrices for every major flow involved. For example, different From-To or quantitative matrices can be developed for material, personnel, information, organizational, control, environmental, and process flows. However, the development of the individual matrices for each of the flows mentioned above for a home-manufacturing facility, which involves a huge movement of material, people, information etc, can be a very demanding process and is beyond the scope of this Master's thesis.

From a facilities planning perspective, all the above-mentioned flows (except material flow) are often translated into *proximity requirements* (Tompkins et al. 1996) and can be developed into qualitative relationship charts. These flow relationships can be easily translated into qualitative measures that may specify the level of closeness between two departments. The different flow-relationships and their nature of measure are expressed in Figure 4.2. (*The relationship chart constructed for the manufactured home industry and used for qualitative analysis of the facility layout is described in the later part of this chapter*). Since this research primarily concentrates on the quantitative modeling approach, it takes into account only the material flow aspect of the activity relationships.

Qualitative Flow	Quantitative Flow
Space Requirements	Flow Volume Distances
Proximity Requirements	Material Flow
Adjacency	Distance
Information	Information
Process	Process
Control	Control
Organizational	Organizational

Figure 4.2: Flow-Relationships & Their Nature of Measure

The material flow measure is a quantitative measure and is very important for house manufacturing facilities where the volume and variety of materials flowing between and across the departments is large. “ *The combination of material characteristics and move or flow requirements is referred to as material flow*” (Tompkins et al, 1996). As the quantitative measures generally include pieces of material per hour, number of material moves per day or the pounds of materials moved, they cannot be easily translated into qualitative charts, and require From-To matrices and quantitative models. The Figures 4.3 and 4.4 represent the From-To quantitative matrix and triangular quantitative charts based on distances between stations for a typical manufactured housing factory.

to from	Station 1A	Station 1B	Station 2A	Station 2B	Station 2C	Station 2D	Station 2E
Station 1A		25	150	125	150	100	175
Station 1B	25		125	75	100	125	150
Station 2A	150	125		150	100	100	50
Station 2B	125	75	150		50	75	125
Station 2C	150	100	100	50		50	100
Station 2D	100	125	125	75	50		75
Station 2E	175	150	75	125	100	75	

Figure 4.3: Quantitative Distance Matrix Between Stations
(Modified from Tompkins et al, 1996)

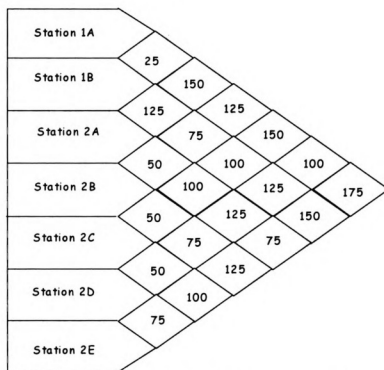


Figure 4.4: Triangular Distance Matrix Chart Between the Stations
(Modified from Tompkins et al, 1996)

4.2.2 Quantitative Modeling Approaches

The assessment of the quantitative flow relationships is a primary criterion for efficient facilities planning and serves as the basis for developing quantitative models to evaluate the facility layout alternatives. In order to assess the facility layout problem in terms of minimizing the sum of quantitative flow times the distance of the material handling cost, quantitative modeling approaches are adopted. Some of the commonly used forms of quantitative modeling have already been explained in Chapter-III (Section 3.3.1).

The major focus of a facility layout problem is to develop the appropriate model for solving the problem. The author adopts the ABSMODEL for the purpose of modeling the facility layout of the manufactured housing plant for two reasons. First, a layout is both an optimization and design problem; and secondly, the FactoryFLOW software operates on an algorithmic structure, which is based on the ABSMODEL. A detailed description of the ABSMODEL is provided in Chapter III (please refer to Section 3.3.1).

4.2.3 Material Handling System and Facility Layout

As stated in Chapter III, material handling system design is an important factor of the facility layout design problem of the manufactured housing factory. The facility layout design and material handling systems are strongly interrelated and as a result material-handling procedures must be considered while planning the facility layout. In this section, the author defines material handling in the context of house manufacturing facility.

Material handling is composed of three basic elements, namely, material, move, and method. By redesigning the facility layout system we are dealing with two of these elements: move and method. While designing new or improved material handling

systems the six-phased engineering layout design process is generally used. These phases can be translated in terms of manufactured house industry as below (modified from Tompkins et al, 1996).

- Defining the objectives and the scope of material handling system generally used to carry the parts/components products or assembly from one station to other.
- Understanding the house construction process and analyzing the requirements for moving, storing , protecting and controlling the materials/parts/components.
- Generating alternative layout designs for meeting material handling system requirements (for example placing the storage for the roofing components near the roof assembly station so as to reduce the travel distance between the storage and the station for the material transporting equipment).
- Evaluating alternative layout based on the material handling cost (i.e. determining the most effective design based on the cost efficiency of the material handling).
- Selecting the preferred facility layout. While evaluating the best facility design layout, the layout that suits all the requirements, both qualitative and quantitative, should be selected for the manufactured housing industry.
- Implementing the preferred layout-design system.

In order to develop the material flow requirements, one should focus on the material to be handled, stored and controlled and the flow or throughput rates required for the system. Material flow is converted to material handling by the method of handling, storing and controlling material. The changes made in the facility layout in order to consider the changes in material handling system in an organization may result in reduction of cost and damage, increase in space and equipment utilization, increasing

throughput and productivity, and improving working conditions. However, these changes, if not made judiciously, may decrease the flexibility and reliability of a facility layout system and increase capital investment (Heragu 1997).

4.2.4 Material Handling Equipment

This section presents a number of material handling equipment alternatives and also discusses briefly the material handling devices generally used in manufactured housing facilities. However, the detailed description of the devices used in the home producing factory is given in section 4.4.4 of this chapter. As already mentioned in Chapter III, there are basically four major kinds of devices used and four categories are mentioned in Table 4.1.

Table 4.1: Classification of Commonly Used Material Handling Equipment
(Modified from Tompkins et al. 1996)

Containers & Unitizing Equipments	Material Transport Equipments	Storage & Retrieval Equipments	Storage & Retrieval/Automatic Identification & Communication Equipment
A. Containers 1. Pallets 2. Skids and Skid Boxes 3. Tote Pans B. Unitizers 1. Stretchwrap 2. Palletizers	A. Conveyors 1. Chute Conveyor 2. Belt Conveyor 3. Roller Conveyor 4. Wheel Conveyor 5. Slat Conveyor 6. Chain Conveyor 7. Tow Line Conveyor 8. Trolley Conveyor 9. Power & Free Conveyor 10. Cart-on-Track Conveyor 11. Sorting Conveyor B. Industrial Vehicles 1. Walking a. Hand Truck b. Pallet Jack c. Walkie Stalker 2. Riding a. Pallet Truck b. Platform Truck c. Tractor Trailer 3. Automated a. Automated Guided Vehicles b. Automated Electrified Monorail c. Sorting Transfer Vehicle C. Monorail, Hoists, and Cranes	A. Unit Load Storage & Retrieval 1. Unit Storage Equipment 2. Unit Retrieval Equipment a. walkie Stacker b. Counterbalance Lift Truck c. Narrow Aisle Vehicles d. Automated Storage/Retrieval Machines B. Small Load Storage Retrieval Machines 1. Storage Equipment 2. Retrieval Equipment 3. Operator Equipment	A. Automatic Identification & Recognition 1. Bar Coding 2. Optical Character Recognition 3. Radio Frequency Tag 4. Magnetic Stripe 5. Machine Vision B. Automatic Paperless Communication 1. Radio Frequency Data terminal 2. Voice Headset 3. Light and Computer Aids 4. Smart Cards

4.3 Manufactured House

A manufactured house, as defined earlier, is a house on a permanent chassis built in a controlled factory environment and is designed for use with or without foundation. In

order to understand the facility layout problem, one has to understand the product that is to be manufactured and the production process. Although Chapter II presents an overview of the manufactured house and its production process, the latter part of this section will provide the reader with a detailed understanding of the product and process. In order to maintain the continuity of the text, some of the definitions may have been repeated.

4.3.1 Description of the Case Study

With an objective to model an almost typical facility layout design of a manufactured housing facility, the author performed a comprehensive and detailed study of a manufactured housing plant. The readings were taken under different conditions and scenarios, and several visits to the factory were made in order to better understand the generic production process, and to take into account all the possible variables and constraints that may occur while modeling the facility layout problem for a home manufacturing facility.

The following part of this section discusses in detail the factory that was used as a case study. However, in order to protect the confidentiality of the establishment, the name and information specific to the factory of the factory are not mentioned in this thesis.

The manufactured housing plant, which has been used as the case study in this thesis, is typical of manufactured housing plants. The factory has the capacity to produce 6 units/day. The factory primarily produces three kinds of products, namely, the entry-level homes (Product-1), middle-level homes (Product-2) and luxury-level homes (Product-3). Although the production process is almost the same, the products generally

have vary in size, materials, components, and appliances, according to customer need. For the purpose of this thesis, we assume a single kind of product since the material flow movement and material-handling system employed for each different product is almost the same. Please refer to Figure 4.5, for the layout of a typical kind of double-bay house produced in the factory.

The production unit is generally a housing floor. The case-study factory primarily produces double bay housing units, which is composed of two 14-20-feet wide and 48-80-feet long housing floor modules. As the plant does not produce any single bay unit, only a single type of product is considered. Since, the production process takes place considering a single floor module or half a house at a time, the products are further subdivided into two parts: Part A and Part B. Part A is the module that has a kitchen and bathrooms, while Part-B is without kitchen and toilet (refer to Figure 4.5), which represents the layout of a typical house.

Based on the production process and the method of assembling the components the house can be broken down into a number of assemblies, sub-assemblies and parts. Table-4.2 gives the generic breakdown of a typical double unit manufactured house. The Appendix-B represents the detailed breakdown of the sub-assemblies into parts/components. The later part of this chapter provides a brief description of individual parts/materials/components that are used for manufacturing a house.

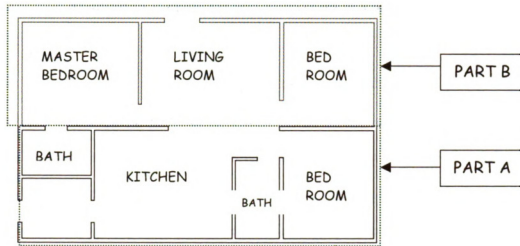


Figure 4.5: Floor Plan of a Typical Double Bay Manufactured Home
(Based on the case study)

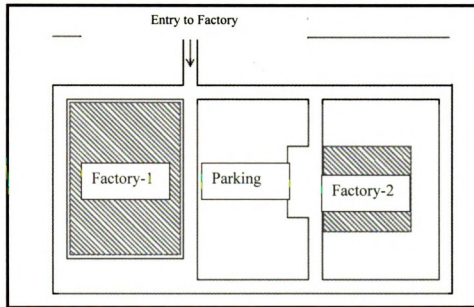


Figure 4.6: Site Plan for the Case Study Factory
(Based on the case study)

The factory layout is composed of two rectangular warehouses. The first part will be referred to as Factory-1 and the second part will be referred to as Factory-2 in this thesis. Most of the assemblies are done in Factory-1, and only a part of the trim assembly and final finishes are done in Factory-2. Both the factories are connected by a $\frac{1}{4}$ mile long road. Please refer to the Figure 4.6 for the site plan.

4.3.2 Materials, Components and Appliances of a Manufactured Home

This section presents a brief description of the individual parts that are generally used to build a typical manufactured house. The materials, components and appliances used by both site-built and manufactured houses are almost similar. Figure 4.7 shows most of the major assemblies of the manufactured house. However, there are several sub assemblies or parts, which are not shown in the figure, but are described in details in the latter part of this chapter. Information about the materials, components and appliances described below are based on both the literature review and the case study (Barshan et al. 2003).

Table 4.2: Product Structure of a Typical Manufactured House
(Based on the case study)

House:Product Structure	
Part A (with toilet & Kitchen)	Part B
1 <i>Frame Assembly</i>	1 <i>Frame Assembly</i>
2 <i>Floor Assembly</i>	2 <i>Floor Assembly</i>
3 <i>Gas Assembly</i>	7 <i>Electrical Assembly-B</i>
4 <i>Water Supply</i>	7.1 <i>Electrical Assembly Stage-B1</i>
5 <i>DWV Assembly</i>	7.2 <i>Electrical Assembly Stage-B2</i>
6 <i>Plumbing Fixtures</i>	7.3 <i>Electrical Assembly Stage-B3</i>
7 <i>Electrical Assembly-A</i>	8 <i>Interior Partition B</i>
7.1 <i>Electrical Assembly Stage-1</i>	8.1 <i>Interior Partition Type1</i>
7.2 <i>Electrical Assembly Stage-2</i>	8.2 <i>Interior Partition Type2</i>
7.3 <i>Electrical Assembly Stage-3</i>	8.3 <i>Interior Partition Type3</i>
8 <i>Interior Partition A</i>	8.4 <i>Interior Partition Type4</i>
8.1 <i>Interior Partition Type1</i>	8.5 <i>Interior Partition Type5</i>
8.2 <i>Interior Partition Type2</i>	8.6 <i>Interior Partition Type6</i>
8.3 <i>Interior Partition Type3</i>	8.7 <i>Interior Partition Type7</i>
8.4 <i>Interior Partition Type4</i>	8.8 <i>Interior Partition Type8</i>
8.5 <i>Interior Partition Type5</i>	
8.6 <i>Interior Partition Type6</i>	5 <i>Side Walls</i>
8.7 <i>Interior Partition Type7</i>	6 <i>End Wall Type-B</i>
9 <i>Side Walls-A</i>	6.1 <i>End Wall Type-A1</i>
10 <i>End Wall Type-A</i>	6.2 <i>End Wall Type-A2</i>
10.1 <i>End Wall Type-A1</i>	7 <i>Mating Walls-Type B</i>
10.2 <i>End Wall Type-A2</i>	8 <i>Ceiling Type B</i>
11 <i>Mating Walls-Type A</i>	9 <i>Exterior Roof Finish Assembly-B</i>
12 <i>Ceiling Type A</i>	10 <i>Trim -B</i>
13 <i>Exterior Roof Finish Assembly-A</i>	10.1 <i>Trim -B1</i>
14 <i>Trim -A</i>	10.2 <i>Trim -B2</i>
14.1 <i>Trim -A1</i>	10.3 <i>Trim -B3</i>
14.2 <i>Trim -A2</i>	11 <i>Final Finish-B</i>
14.3 <i>Trim -A3</i>	12 <i>Fasteners</i>
15 <i>Final Finish-A</i>	
16 <i>Cabinet Assembly-A</i>	
16.1 <i>Base Assembly-6"</i>	
16.2 <i>Base Assembly-19"</i>	
16.3 <i>Base Cabinet Assembly</i>	
16.4 <i>Corner Base Cabinet Assembly</i>	
16.5 <i>Sink Base Cabinet Assembly</i>	
16.6 <i>Bar Base Cabinet Assembly</i>	
16.7 <i>Bar Overhead Cabinet</i>	
16.8 <i>27" Overhead Cabinet</i>	
16.9 <i>Overhead Range Cabinet</i>	
16.10 <i>Corner Overhead Cabinet</i>	
16.11 <i>Reference Shelf</i>	
16.12 <i>21" Pantry Shelf</i>	
16.13 <i>Vanity Cabinet Module-A</i>	
16.14 <i>Vanity Cabinet Module-B</i>	
16.15 <i>Kitchen Counter Tops</i>	
17 <i>Fuse Panel Doors</i>	
18 <i>Fasteners</i>	

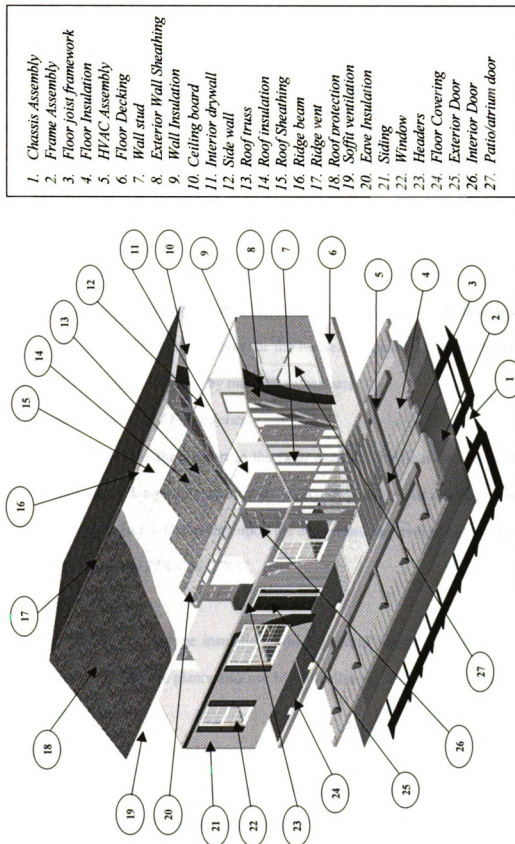


Figure 4.7: Components of a Manufactured House
 (Modified from Fall Creek Homes poster & Barshan et al, 2003)

1 Chassis

Chassis is the framework of steel beams on which the manufactured house is built. The chassis is attached to the wheels and becomes a permanent part of the house after the house is installed. Depending on the design and size of the house that is being manufactured, the size of the beams varies from 8"-12". The wheels and the axles used in the chassis assembly are generally recycled, since they are removed from the house during installation.

2 Bottom Board

Bottom board is the second layer of the manufactured house. It supports floor insulation and acts as the moisture resistance layer for the house. It is generally tarpaulin type jute knitted fabric and is typically used by most manufacturers.

3 Frame Assembly and Floor Joists

The joist system provides the support to the floor decking, the floor and the walls. The joists are either placed longitudinally or horizontally. Typically, joist spacing varies from 16" to 24" on centers (o.c.). Depending upon the design and the level of house, the size of the floor joists vary from 2"X6" to 2"X8".

4 Floor Insulation

Traditionally fiberglass batt-type insulation, which generally come in rolls, is used for floor insulation. Some of the plants also use blown cellulose, used for roof insulation as insulation, for the floor.

5 HVAC duct or Gas Assembly

Heating, Ventilating and Air Conditioning (HVAC) ducts either run through the floor or through the attic. The registers are either located in the center of rooms (typically for

entry/middle level homes) or along the inside perimeter. Materials for the ducts vary from sheet metal to fiberglass, depending on each manufacturer's choice of material. Typically, flex pipes are used as branch ducts.

6 Floor Assembly

Floor decking is a layer of wooden board attached to the joist framework to create the floor of the house. Usually, OSB (oriented strand board) is used for the floor decking. The most commonly used thickness for the floor decking is either 5/8" or 3/4".

7 Wall Assembly

The side, mating, end, exterior and interior wall assemblies in manufactured homes are primarily composed of wall studs and dry walls. Wall studs are vertical wooden members that are attached to the floor system. Wall panels consist of studs and dry wall on one face and are typically assembled off the main production line and then moved to the floor deck location. This panelized framework is attached to the floor system.

The size and spacing of the studs vary for internal walls, external walls and mating walls. Usually, the size and spacing of internal wall studs is 1"X 3" at 24" o.c., the size of internal shear walls is 2"X3" at 16" o.c. External walls were typically 2"X4" spaced at 16" o.c. In order to insulate the house properly sometimes it becomes necessary to use 2"X6" studs for external walls.

8 Exterior Wall Sheathing

After the rough Electrical Assembly Stage -1 and Plumbing Assembly is completed and the wall insulation is installed, the external wall exposed to the outside weather is typically covered with either plywood/OSB or with insulation board panels.

9 *Wall Insulation*

Similar to floors, the walls are typically insulated with fiberglass batts of varying thickness for different R-values. The R-values usually range from R-11 to R-32 (commonly R-19 is used).

10 *Ceiling board*

Ceiling board is a part of the roof assembly and is the ceiling surface below the roof trusses that divides the attic area from the living space below. Typically sheetrock (drywall) of varying thickness is used. The finish provided to the ceiling is either a vinyl coating pre-installed on the sheetrock or a sprayed on popcorn paint. Sometimes, the manufacturers provide a tape and textured finish with mud. The thickness of the ceiling board is usually 5/16" - 1/2".

11 *Interior Drywall*

Similar to the ceiling board, sheetrock (drywall) also provides a covering to the wall stud framework and forms a part of the interior partition assembly. As mentioned above, the finish of the material varies from vinyl coated sheetrock to tape and textured finishes. The thickness of the drywall typically observed during the plant visits was 5/16" - 1/2".

12 *Exterior Sidewalls*

The materials used in exterior sidewalls vary considerably in all houses. As the name implies, these walls are located on the sides of the house. The height ranges from 84" for entry-level homes to 96" for luxury homes. The materials used for these walls are the same as those used for exterior walls.

13 Roof Trusses

Roof trusses are the structural members of the roof assembly. Most of the manufacturers use prefabricated trusses that are engineered to the slope of the roof that typically varies from a 3/12 to a 7/12 pitch. The trusses are made of lumber, and steel gusset plates connect each truss member.

14 Attic Insulation

A layer of insulation is provided between the ceiling board and the roof sheathing. Generally the manufactured plants use blown-in cellulose as the insulation material. The insulation is blown-in over the ceiling board in layers, in order to get at the R-value that is required. The standard roof insulation is R-21.

15 Roof Sheathing

After the insulation is placed, the roof truss is covered with either plywood or OSB panels to complete the exterior skin of the house. Plywood or OSB boards of typically 1/2" to 3/4" thickness are used as roof sheathing and forms a part of roof assembly.

16 Ridge Beam

In case of double section homes where there are large openings at the connection of two sections, a ridge beam is provided where the two sections meet to ensure the structural stability of the roof framing system. This beam is either fabricated using plywood or OSB by workers in the plant, or prefabricated laminated wooden beams (also called 'microlam' beams) are used.

17 Ridge vent

This feature is provided in most manufactured homes in order to improve the ventilation to the attic.

18 Roof Protection

Frequently used roof protection materials include a sheet metal covering or asphalt fiberglass shingles.

19 Soffit Ventilation

Some of the manufacturers provide bathroom and toilet ventilation through the soffit of the roofs in the eaves portion.

20 Eave Insulation

Sometimes a dam of fiberglass batt insulation is provided at the roof edge near the eave for better insulation.

21 Siding

Siding provides the final layer of exterior skin and forms a part of the exterior finish assembly. Sheet metal, wooden or vinyl sidings are used as siding materials. Moreover, a material called "house wrap" is required under the siding for thermal protection.

22 Windows

Windows also form the part of exterior finish assembly. The windows used are generally prefabricated and are primarily composed of the frame, the window glass and the final trim. Window frames are typically plain aluminum or vinyl. Some dual pane windows contain argon (or similar) gas, which provides a higher R-value than single pane windows. The trim around the windows is usually wood, vinyl, or aluminum.

23 Headers

These are lintels (small beams) above windows and doors, which carry the load above the door and window openings to the wall forming the system. Typically, the headers are of

the same material and size as the frame studs. The number of headers varies from single to triple, depending upon the load.

24 Floor Covering

The floor covering forms a part of floor assembly. The wet areas, such as the kitchen, and bathrooms, have vinyl floor covering in various designs (Part-A). Other rooms (e.g. living or bedrooms) typically have carpets (Part-B). Most of the manufacturers also provide vinyl in the entryway.

25 Exterior Door

Most of the manufacturers provide a 3' wide exterior door made of steel with an insulated core. The height of the door varies from 6.5 to 7 ft, depending upon the height of the exterior sidewall.

26 Interior Doors

Interior doors are available in various widths, heights, and styles. The widths of the interior doors typically vary from 28" to 32". The height varies from 6.5' to 7.0'. They are available as either plain (LUAN) or paneled doors. The material used is either wood, Medium Density Fiber (MDF) board or Masonite (which is becoming popular because of its durability). In most homes, the doors are hung using 2 or 3 surface mounted hinges. In some luxury homes doors are hung using fully mortised hinges. The trim around the interior doors is either wood or vinyl.

27 Rear Door

This is a feature provided by the manufacturers wherein they supply 3 feet wide doors as the service door, is made up of steel, and has a insulated core.

28 *Plumbing Assembly*

A number of plumbing assembly components that are not detailed in Figure 4.6 are presented below:

Water pipes and fittings: The materials for these vary with the level of homes. PVC is used for most entry-level homes. A new material called PEX is used in the middle of the line houses. Luxury homes are typically provided with copper piping and copper fittings. Some manufacturers also use brass or copper fittings in middle of the line homes.

Sanitary, Drainage and Vent pipes: Most of the manufacturers use ABS pipe, which is a thick plastic pipe.

Shut-off valves: In the plumbing system, shut-off valves are either provided at a single junction or under every sink.

Vanity Sinks: Entry/Middle-of-the-line-level homes use plastic sinks, while luxury homes use porcelain sinks.

Faucets: Plastic faucets are typically used for Entry/Middle of the line level homes while metal faucets are used in luxury homes.

Bathtub and Shower: Most manufacturers use a two-piece PVC bathtub and shower, while a few manufacturers provide one-piece fiberglass bathtub and shower units.

Water Heater: Capacity varies from 30 gallons to 50 gallons.

29 *Electrical Assembly*

A number of electrical assembly components that are not added in Figure 4.6 are presented below:

Wiring: Copper wires are used as the wiring material.

GFI's: The manufacturers provide one or two GFI's per house.

Boxes: There are typically two types of electrical boxes used namely, drywall mounted or stud mounted. Stud-mounted boxes are preferred to wall-mounted boxes.

30 *Mechanical (HVAC)*

Registers: These are openings provided for heating/cooling and ventilation and form a part of Floor Assembly Stage-1.

31 *Cabinets*

There is a considerable variation in the design and materials for kitchen cabinets generally used. Generally hardwood, particleboard or medium density fiber (MDF) are used as the base material. A combination of hardwood and particleboard/MDF, with hardwood are used for the exposed parts and the remaining is made up of particleboard/MDF. The design of the cabinets varies too from ordinary to modular. The shelves are either fixed or adjustable. The rollers used for the drawers are either plastic or metal. The other components like hinges; back sockets, drawer guides and hardware components also form a part of the cabinet assembly.

32 *Appliances*

Appliances are amenities provided with the manufactured house. The following is the list of appliances that are typically provided (optional ones are indicated) in the houses that were observed in the Case-Study-1 factory.

- Refrigerator
- Microwave
- Dishwasher
- Electrical Fixtures

- Cooking Range
- Fireplace (optional)
- Garbage Disposal (optional)
- Air Conditioner (optional)
- Clothes Washer and Dryer (optional)

The preceding part of this section presents only some of the major components that are used in the building of manufactured homes. There are several smaller parts like nails, wires etc that are used but are not mentioned in the above description; but they have been considered while developing the model for the quantitative analysis of the facility layout problem for the case study.

4.3.3. Manufactured House Production Process and Facility Layout

Based primarily on the production process in the case-study factory and taking references from the literature review and existing research on manufactured housing, a detailed typical production process of manufactured house in a factory is developed. According to the nature of the factory, the construction process describes the production of double-section or multi-section homes. The following part of this section provides the details of the process.

4.3.2.1 Station Classification

Depending upon the nature of the activities performed during the production process of a manufactured home, the plant can be broadly divided into major activity areas which are usually termed as the *stations*. These areas in the plant are further divided into multifarious stations along the production assembly line. The stations can be classified

into main assembly stations, sub-assembly stations, feeder stations, and internal and external storage areas, based on the type of activity taking place at that station/area.

Main assembly stations are the major stations (sometimes referred to as primary stations) on the assembly line, and the location where sub-assemblies (components) are installed. The roofing stations (Stations 10 and 11 in the model), for example, are the main assembly stations where the roof trusses from the roofing sub-assembly stations (Stations 8B and 9B) are installed over the home units (Part A and Part B). Figure 4.8 indicates the main assembly station for the roof.

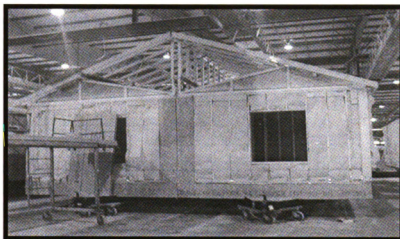


Figure 4.8 Main Assembly Station for the Roof
(Barshan et al. 2003)

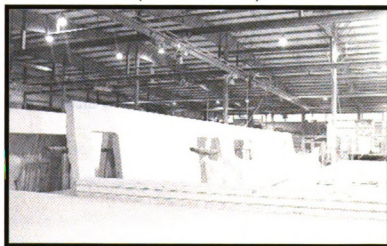


Figure 4.9: Sub-Assembly Station for Walls
(Barshan et al. 2003)

Sub-assembly stations are secondary stations that fabricate sub-assembly components for installation at main assembly stations. For example, interior and exterior walls are first assembled at a sub-assembly station or a feeder station; then they are installed at the walls main stations. The stations 5A and 6A in the layout diagram in the figure 4.17 are the sub-assembly stations for the external and internal walls respectively. Figure 4.9 indicates the wall sub-assembly station.

Feeder stations are the stations that provide individual components to the main assembly stations, i.e., the raw material stored at the feeder station itself is installed directly. For example, the kitchen appliances are typically stored next to the assembly line near the interior finishes and cleanup main assembly station (For example, storage 23 in Factory-2), and are supplied directly to the interior finish activity stations, as and when needed.

Internal or external storage areas house inventory for different kinds of material. The choice of internal or external storages is based on weather conditions, and the size and cost of the material. Some of the materials that are stored externally are chassis, roof shingles, and trusses; whereas material such as drywall, foam, and carpets are stored under roof. For example, the storage 1 in Figure 4.4 is an external storage which stores materials like tires, axles etc., while storage-2A being an internal storage area stores lumbers, drywalls etc (See Figure 4.10).



Figure 4.10: Internal Storage Areas
(Barshan et al 2003)

A greater number of sub-assemblies/feeder stations are desirable to reduce the overall processing time of the product, and the number of operations taking place at the main assembly station. The manufacturers usually purchase sub-assemblies from suppliers and feed them directly to either the sub-assembly station or the main assembly line. An efficient assembly line usually has tasks broken down and divided in such a way that they are carried out with the minimum possible idle time on the main stations (Bernhardt 1980).

4.3.3.2 Construction Process Details

The production process of a manufactured home consists of sequential and systematic practices of interrelated tasks that are carefully coordinated to produce a home. The different activities on the assembly line are grouped into areas/departments based upon the assembly that is being built. The major areas in a manufactured housing production plant are listed below (Senghore 2002):

- The floor area
- The walls area

- The roof area
- The exterior finishing area
- The interior finishing area
- The final inspection area

1. The Floor Area

The production process typically begins with the fabrication of the chassis, or the structural frame on which the house is built, at a subassembly area. The chassis is then moved to the main assembly line when needed (Station 1A). The floor joists are fabricated, based on the structural requirements, at a sub-assembly station where fiberglass/cellulose insulation is laid on a bottom board. The ductwork for HVAC and plumbing trees and pipe are also provided at this sub-assembly area.

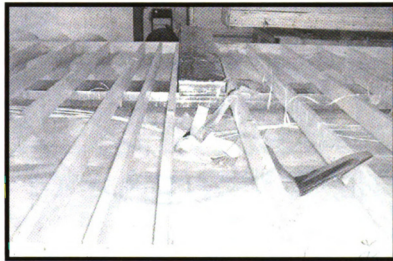


Figure 4.11: Floor Area
(Barshan et al. 2003)

The floor sub-assembly is then put over the chassis sub-assembly and is attached by using lugs. The movement of the chassis is generally accomplished using

either (a) inflated base plates or (b) on tires longitudinally and laterally, on movable metal tracks with track wheels perpendicular to the direction of the chassis wheels.

At the next station, which is still a floor system station, the floor joists are covered with decking. Decking is usually in the form of 5/8"-3/4" plywood or OSB panels which are nailed/stapled and glued in place. The wet areas are usually sanded at this station to allow for better adhesion of vinyl floor covering.

2. The Wall Area

The chassis is then moved to a station where vinyl sheet rolls are suspended from a metal roll and vinyl pieces of the correct size are cut and installed in the wet areas. The interior walls/ partitions are then placed.

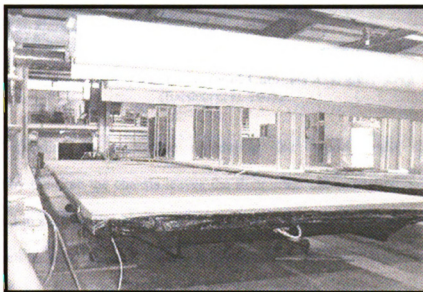


Figure 4.12: Floor Assembly-Stage-3
(Barshan et al. 2003)

The walls are usually fabricated as panels at a sub-assembly station and then installed in place, on the main assembly station, with the help of the electric hoist. The activities at the sub-assembly station consist of building of the wall panels to the desired sizes. The wooden studs (2"x4" or 2"x3") are fixed to top and bottom plates of the same

size. The drywall, usually sheetrock with a vinyl layer, is fixed to the wood frame using adhesive foam at intermediate studs and staples at seams of two sheetrock boards. Some manufacturers use plain drywall (See Figure 4.13).

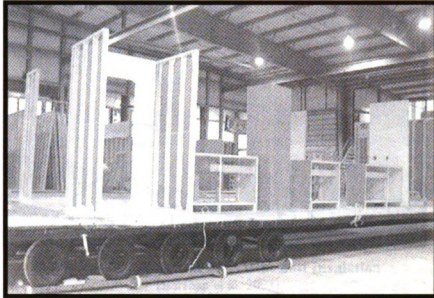


Figure 4.13: Internal Walls and Cabinets Assembly Area
(Barshan et al. 2003)

Depending on production scheduling, the interior walls are ready for installation by the time the chassis leaves the floor area. The heavy cabinetry, generally prefabricated in a subassembly area, is then moved to this station and other big bathroom fixtures, such as sink tops and shower compartments, are also installed at the interior walls main assembly station. The bathroom fixtures are brought from a feeder station near this main assembly station.

The partially completed house is then moved to the next station where the exterior walls are installed. Panelized, partly fabricated exterior walls are put in place on the main assembly station. Fiberglass batt insulation is then installed and the walls are

covered with exterior sheathing (if specified) at the main assembly station. Rough electrical and plumbing work is also performed at this station (See Figure 4.14).

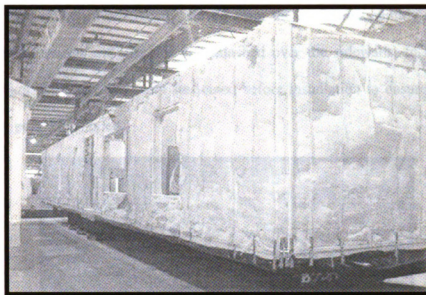


Figure 4.14: External walls with Batt Insulation
(Barshan et al. 2003)

3. *The Roof Area*

In most production plants, the prefabricated roof trusses are supplied by the plant frame truss manufacturer. Trusses arrive at the plant at a loading dock near the roof assembly station. The roof is then fabricated using these trusses and other raw material at the roof sub-assembly station. First, the individual trusses are positioned on the ceiling boards according to the spacing specified in the plans. The trusses and the ceiling board are then glued together. The glue is applied on one face of the truss, where it is located between the span of the ceiling board, and on both faces at the ceiling board joints. Figure 4.15 shows the assembly of the roof trusses with the ceiling.

At the next sub-assembly station, cavities between individual trusses are filled with loose blown cellulose insulation. The insulation activity in some plants is also carried out at the main assembly station. Underneath the attic area the ceiling boards

joints are taped and mud paint is applied. By the time the house arrives at the roof installation station, the ceiling board is dry and ready to be installed. The entire roof truss /ceiling system is then mechanically moved from the roof sub-assembly station to the main assembly station and installed and attached over the sidewalls. In the case of a double-section home the two units are joined before installation to ensure that the two sections are properly aligned.

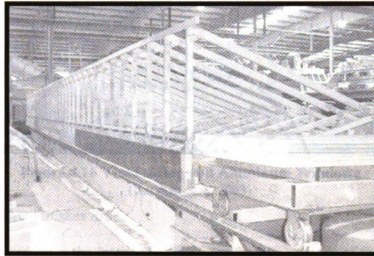


Figure 4.15: Roof trusses attached to the ceiling
(Barshan et al. 2003)

The next step involves the installation of roof sheathing (Oriented Strand Board). The panels are nailed in place. Installation of roofing paper, flashing and shingles is the next major activity at the main assembly station. Once the shingles are installed, the home is ready to move to the exterior finishes area.

4. The Exterior Finishes Area

Some of the exterior finishes activities are performed simultaneously with the roofing activities.

Doors and windows are supplied from a feeder station (Storage 11 in the layout drawing), and the installation of doors and windows involves marking the spacing,

installing the frame, and finally installing the door and window units as specified on the drawings. Finally, the exterior sidings (see Figure 4.16), exterior lamps, and doorbell are installed.

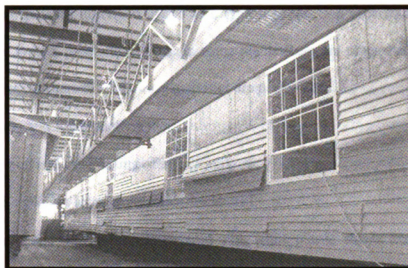


Figure 4.16 Vinyl siding and Aluminum Windows
(Barshan et al. 2003)

5. *The Interior Finishes Area*

When the home arrives at the interior finishes area the two sections of the double-section home will have been separated back into two single sections. In this particular case study, the separated units (Part-A and Part-B) are transported after this stage to the factory-2. The interior finishes and final cleanup activities are the last set of activities, which take place on the assembly line in the factory-2.

The final electrical, plumbing, HVAC, and mechanical work are also performed in this area. The installation of foam padding and carpet follows. The toilet is also installed in this area and the heavy kitchen appliances such as the refrigerator and cooking range are typically placed at the last station. The home is vacuumed and all cabinets are cleaned. Finally, the shop loose material, namely, dryers, washers, ovens

etc, which will be installed in the home after installation on the site, is placed inside the home.

6. The Final Inspection Area

The production process described above is a typical production process and the areas mentioned are typical production areas. In some plants there are other stations after the interior finish area where the following activities are performed:

- Cleaning and final touch up work
- Inspection and final testing of all systems.
- Post-installation loose accessories are loaded.
- The marriage wall section is covered with white plastic sheets and the housing unit is prepared for transportation.
- The HUD label is affixed to the housing unit.

After completing the activities at the final inspection area, the house is pulled out of the plant and is ready for delivery to the customer.

4.3.4 Qualitative Approach Based on Space Requirements and Proximity

As already mentioned in Chapter II and Chapter III, this section briefly discusses about the qualitative analysis of the layout problem of the manufactured housing factory, performed in the developmental research work by Namita Mehrotra (Mehrotra 2002). The data related to the qualitative analysis of the layout were divided into two categories and were collected on the basis of two case studies: namely, space requirements and proximity requirements

Space requirements:

From the different methods available for data organization, the table format was used to order the space requirement data of the case study plant. In order to have accurate data, the table included specific assembly stations, sub-assembly stations, feeder stations, and storage areas for each cluster and related space areas. Details associated with the type of material (stored, subassembled or installed) and area specifications were also collected. Table 4.3 shows a space requirement table for a roofing station in the case-study factory based on the chart developed by Mehrotra. The space requirements are shown for the roof installations cluster. In a similar manner, the space requirement format can be developed for any given manufactured housing facility.

Table 4.3: Table for Roofing Station Space Requirements
(Modified from Mehrotra, 2002)

Cluster Name	Description	Station Type	Area (lxb)	Major Activities
Roof	Preparation & Installation of roof	Main assembly Station	2500	Installing Roof to the Main House Assembly
		Sub Assembly Station	1800	Set the roof trusses based on spacing
		Sub Assembly Station	1800	Glue and nail the ceiling boards to the frame
		Sub Assembly Station	1800	Spray paint of the ceiling in the mud-pit
		Sub Assembly Station	1800	Drying and loose Insulation of the roof

Relationship chart development

The data collected for the relationship charts provide a qualitative measure, and therefore they are different from a quantitative space requirements measure. The relationship chart can be developed for the given case study factory as illustrated in the following sections.

The process began with the development of an empty relationship chart. Based on the production process information and the station description, all the stations were positioned in the top row and left column. Each of the stations was denoted either numerically or alphabetically. This empty relationship chart was then filled, based on the production process information. Each station in the relationship chart is either related or unrelated to every other station. Based on the relationship between each station pair, different closeness ratings were assigned. This rating could be due to one station being a direct source of raw material or sub-assembled component supply, or due to stations sharing common material, labor, tools, or equipment. The closeness ratings assigned are based on the SLP technique developed by Muther (1973) (Refer to Chapter III).

Next, the criteria were defined and the closeness ratings were assigned based on the criteria. Example: An “A” relationship (Absolutely necessary closeness rating) between stations was assigned when the stations had a direct high proximity (criterion). A closeness rating and a reason were established for each pair of stations in the relationship chart (Refer to Chapter III). Once this chart had been developed, the feedback from the industry is taken and they are incorporated in the relationship charts. Table 4.4 shows the relationship chart developed by Mehrotra for the qualitative analysis of the facility layout problem.

	1	2	3	4	5	6	7	8	9	10	11	12	13	A	B	C	D	E	F	a	b	c	d	e	f	g	h	i	j	k
1	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	A	1	U	4	U	4	U	4	U	4
2	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
3	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
4	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
5	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
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7	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
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B	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
C	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
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b	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
c	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
d	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
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i	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
j	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4
k	\	\	A	1	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4	U	4

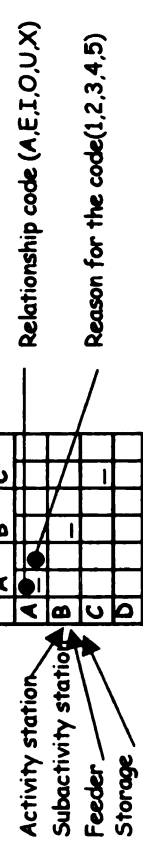


Table 4.4: Relationship Chart for Manufactured Housing Factory
(Mehrotra, 2002)

4.4 Data Collection For The Quantitative Analysis Of Facility Layout

The author presents a sequential step-by-step approach for gathering the relevant data from the case studies and developing them in required formats, namely: product tree structure and quantitative matrices, for the quantitative modeling of the facility layout problem. The modeling was done in two stages, namely, data collection and data entry. The major steps that were adopted during the data collection processes are listed below (Heragu 1997).

- Obtaining basic data
- Extracting relevant data
- Generating data in the required format
- Documenting data

4.4.1 Obtaining basic data

The basic data required to solve a facility layout problem are generally available from the factory floor personnel, like production managers, supervisors and workers. Sometimes, additional information is available from the purchasing department, maintenance department, and management information system (MIS) department of a manufacturing facility. Types and volume of products manufactured, components required for building the product, name and code of each component, space requirements, material handling devices and their cost are examples of some of the basic data.

Moreover, the basic data also comprise some of the qualitative information that should be considered while designing the facility layout. The position of power lines, coolant lines, their location and shape are examples of the qualitative information that should be collected while obtaining basic data to solve a facility layout problem. The

methods for collecting the basic data during the case study are described in detail in the following sections.

4.4.2 Extracting relevant data

Extracting relevant data from the basic quantitative data collected is undoubtedly one of the major steps for the data collection process, if not the most important step. Before the designers can generate the data in the required format, the initial information that is not relevant to the modeling purpose is removed from the set of data. Only the data required for modeling the problem should be carefully reviewed and extracted from the original data.

For the purpose of this thesis, the time related to the process of the material flow was required; e.g., time taken by the material handling equipment, like forklifts, to travel from one station to another, time taken to load and unload the materials, the effective time of the material handling devices utilized or the part-routing information of each material. However, information like set-up time for a process, movement within stations and the process time were not relevant for the quantitative modeling of the layout problem, and as a result they were not considered. Also, due to the limited scope of this thesis the micro-level material movement within a station was not considered, as it would have become analytically and computationally cumbersome. The quantitative model for the facility layout problem developed in this thesis only looks into the movement between the stations or the activity points.

4.4.3 Generating data in the required format

When the relevant data are extracted from the basic data, it is always useful to form the matrices and tables so that the data can be easily handled. Once the data are gathered, the next step is to organize the input data by adopting proper naming conventions. For example, while organizing data for the activity points, the stations, sub-stations and feeder stations for a major activity area were given similar annotations. The station for the Frame Assembly was named station 2A, while its related substation and feeder stations were assigned names such as storage 2A, storage 2B. This procedure is helpful for identifying the activity area to which an activity point belongs, when there are several activity points.

The case study factory had several stations for waiting-inspection-miscellaneous activities. Some of these stations in the FactoryFLOW model were considered as “delay” or “miscellaneous” stations.

4.4.4 Documenting data

This is the final step for the process of data collection. This step involves collating all the generated data and placing them in an electronic file. In this research, after the formulation of the charts, diagrams and all the required formats for the data collected from the case studies, the data was inputted in the FactoryFLOW software. The details of the documentation process of the data into Factory FLOW formats are described in the latter part of this chapter.

4.5 Case-Study: Application of the Data Collection methodology At The Manufactured Housing Facilities

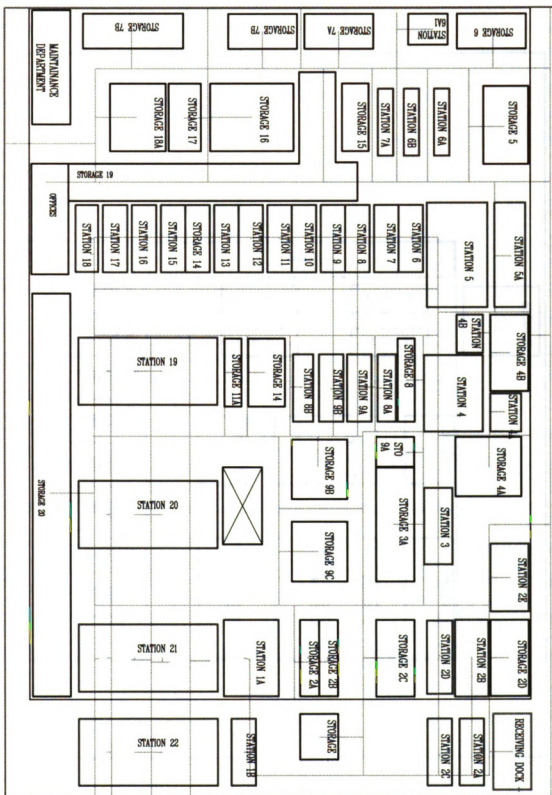
The data collection steps discussed in the preceding section were implemented with the facility layout system of the case-study.

One of the primary objectives of this research was to document the material flow related to each and every part in the plant, concentrating on the materials/components being transported from the receiving area to their point of use in the assembly area. As explained in Chapter III and preceding section, data related to space, material, material flow, material handling devices, labor costs, existing layout are needed for *From-To* charts. Data were collected according to the following categories listed below:

- Space Requirements And Layout Drawing
- Production Quantity Information
- Parts Routing Information
- Material Handling Equipment Information
- Material Handling Activity Information

4.5.1 Space Requirements and Layout Drawing

During the case-study factory visits, the author took measurements of the manufactured housing plant for both Factory-1 and Factory-2. The existing prints of the layout drawings available from the plant production managers were also collected. Based on the information collected, the layout drawings for both the factories were prepared in AutoCAD. The Figures 4.17 and 4.18 represent the layout drawings of the factories (for more detailed drawing please refer to Appendix-A).



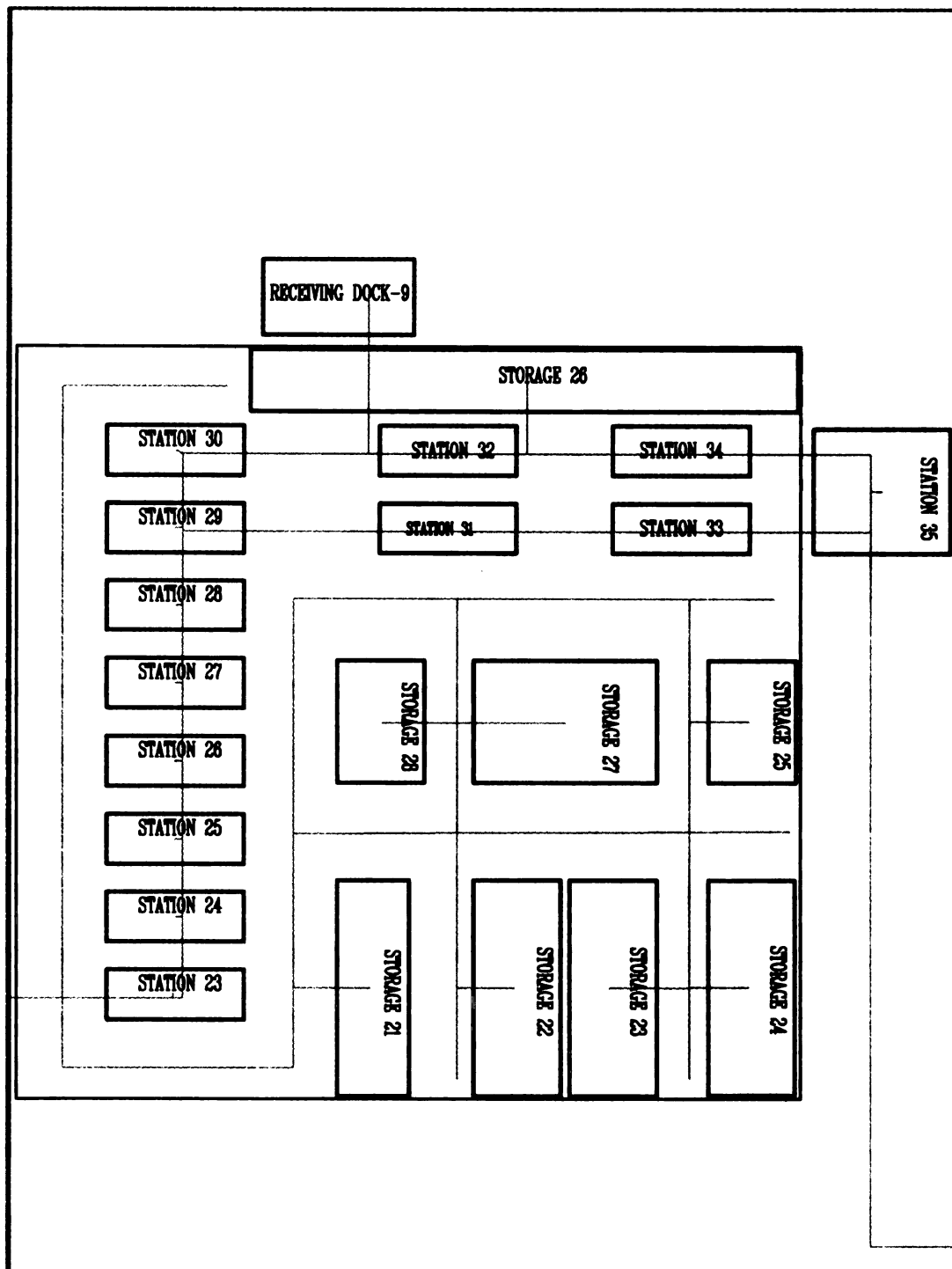


Figure 4.18: Layout Drawing For Case Study Factory 2

The layouts were drawn in AutoCAD, since the FactoryFLOW software can draw information like traveling distances, size of aisles, storage areas, station-areas from the AutoCAD drawings. Moreover, FactoryFLOW can also generate flowpaths, Congestion Aisle diagrams, and distance intensity charts within the AutoCAD drawing.

The AutoCAD drawing of the case-study factory layout was made in 1:1 scale so that the correct travel distances could be estimated. The imperial unit of measurement was used, inch being the base unit. The drawing also denoted the station names specified for each activity point, for example Station-1A is the assembly station for the Frame Assembly. Please refer to Table 4.5 for the list of the stations and their description.

The quantitative analysis of the facility layout problem in this thesis was done in a macro level i.e., the movement between the stations, substations and feeder station were considered. The micro level analysis that requires the material and personnel movement within the stations, is considered as a part of process analysis and is not included in this study, as it is beyond the scope of this masters' thesis. For similar reasons, the stations having storage racks very near them were grouped together to form a single activity station; e.g., the Station 1A is grouped along with the storage racks that hold the lumbers. During the assembly process, the workers just pick the lumber from the racks and place it on the chassis frame. The time taken for the worker to move the lumber from the rack to the frame that is only a couple of feet away is not considered and is assumed to be a part of process time. Similarly the routing information for the lumber does not include the movement of the lumber from the rack to the assembly frame.

Table 4.5 (i): List of all Receiving docks, Assembly Stations, & Storage Areas

Receiving Docks		
Station	Station type	Description
Receiving Dock-1	Dock	Receiving Dock For Tyres And Axles
Receiving Dock-2	Dock	Receiving Dock For Frames, Floor, Roof, Door Assembly
Receiving Dock-3	Dock	Receiving Dock For Tyres And Axles
Receiving Dock-4	Dock	Receiving Dock For Interior Cabinet, Partition walls Assembly
Receiving Dock-5	Dock	Receiving Dock for Exterior & Interior wall Finish Assembly
Receiving Dock-6	Dock	Receiving Dock For Windows, Roof & External Finish Assembly
Receiving Dock-7	Dock	Receiving Dock For External finish assembly, Electrical assembly
Receiving Dock-8	Dock	Receiving Dock For Final Finish Assembly
Receiving Dock-9	Dock	Receiving Dock For Refrigerators, ranges, microwaves
Assembly & Miscellaneous Stations		
Station	Station type	Description
Station 1A	Assembly	Chassis Assembly
Station 1B	Delay	Wait Area Chassis Assembly
Station 2A	Delay	Chassis Assembly
Station 2B	Assembly	Frame Assembly, DWV Assembly, Gas Assembly
Station 2C	Delay	Frame Assembly
Station 2D	Assembly	Floor Assembly
Station 2E	Assembly	DWV, Water, Gas Assembly
Station 3	Assembly	Floor-3 Assembly
Station 4	Assembly	Floor Assembly
Station 4A	Assembly	Plumbing Fixture Assembly
Station 4B	Assembly	Internal Cabinet Assembly
Station 5	Assembly	Chassis Assembly
Station 5A	Assembly	Internal Partitions Assembly
Station 6	Assembly	External Walls-Side Walls Assembly
Station 6A	Assembly	Side wall Assembly
Station 6A1	Assembly	lumber pieces Assembly
Station 6B	Assembly	Mating Assembly

Table 4.5 (i): List of all Receiving docks, Assembly Stations, & Storage Areas

Assembly & Miscellaneous Stations		
Station	Station type	Description
Station 7	Assembly	<i>Mating Wall Assembly</i>
Station 7A	Assembly	<i>Mating Wall Parts Assembly</i>
Station 8	Assembly	<i>End Wall Assembly</i>
Station 8A	Assembly	<i>End Wall Assembly</i>
Station 8B	Assembly	<i>End Wall Assembly</i>
Station 9	Assembly	<i>Roof Assembly</i>
Station 9A	Assembly	<i>Roof Assembly</i>
Station 9B	Assembly	<i>Roof Assembly</i>
Station 10	Assembly	<i>Roof Assembly</i>
Station 11	Assembly	<i>Roof Assembly</i>
Station 12	Assembly	<i>External Roof Finish Assembly</i>
Station 13	Assembly	<i>External Roof Finish Assembly</i>
Station 14	Assembly	<i>External Roof Finish Assembly</i>
Station 15	Assembly	<i>External Roof Finish Assembly</i>
Station 16	Inspection	<i>External Finish Assembly</i>
Station 17	Assembly	<i>Exterior Finish Assembly</i>
Station 18	Assembly	<i>Roof Assembly</i>
Station 19A	Delay	<i>Inspection & Repair</i>
Station 19B	Delay	<i>Inspection & Repair</i>
Station 19C	Delay	<i>Inspection & Repair</i>
Station 19D	Delay	<i>Inspection & Repair</i>
Station 20A	Delay	<i>Inspection & Repair</i>
Station 20B	Delay	<i>Inspection & Repair</i>
Station 20C	Delay	<i>Inspection & Repair</i>
Station 20D	Delay	<i>Inspection & Repair</i>
Station 21A	Delay	<i>Inspection & Repair</i>
Station 21B	Delay	<i>Inspection & Repair</i>
Station 21C	Delay	<i>Inspection & Repair</i>
Station 21D	Delay	<i>Inspection & Repair</i>
Station 22A	Delay	<i>Inspection & Repair</i>
Station 22B	Delay	<i>Inspection & Repair</i>
Station 22C	Delay	<i>Inspection & Repair</i>
Station 22D	Delay	<i>Inspection & Repair</i>
Station 23	Miscellaneous	<i>Inspection & Repair</i>
Station 24	Delay	<i>Inspection & Repair</i>
Station 25	Miscellaneous	<i>External Trim Assembly</i>
Station 26	Miscellaneous	<i>External Trim Assembly</i>

Table 4.5 (i): List of all Receiving docks, Assembly Stations, & Storage Areas

Assembly & Miscellaneous Stations		
Station	Station type	Description
Station 27	Delay	External Trim Assembly
Station 28	Assembly	External Trim Assembly
Station 29	Assembly	External Trim Assembly
Station 30	Assembly	Final Finish Assembly
Station 31	Assembly	Final Finish Assembly
Station 32	Assembly	Final Finish Assembly
Station 33	Assembly	Final Finish Assembly
Station 34	Assembly	Final Finish Assembly
Station 35	Assembly	Final Assembly
Station 36	Packaging	Shipping Area
Storage		
Station	Station type	Description
Storage 1	Storage	Storage Area for Frame & Chassis Assembly
Storage 2A	Storage	Storage Area for Frame 1 Assembly
Storage 2B	Storage	Storage Area for Frame 2 Assembly
Storage 2C	Storage	Storage Area for Frame 2 Assembly
Storage 2D	Storage	Storage Area for Frame 2, DWV, Water, GAS Assembly
Storage 3	Storage	Storage Area for Frame 3 Assembly
Storage 4A	Storage	Storage Area for Cabinet Assembly
Storage 4B	Storage	Storage Area for Plumbing Assembly
Storage 5	Storage	Storage Area for Interior Partition Assembly
Storage 6	Storage	Storage Area for Ext wall, Side wall Assembly
Storage 7A	Storage	Storage Area for Mating wall Assembly
Storage 7B	Storage	Storage Area for Wall & Ext finish Assembly
Storage 8	Storage	Storage Area for Roof Assembly
Storage 9A	Storage	Storage Area for Roof Assembly
Storage 9B	Storage	Storage Area for Roof Assembly
Storage 9C	Storage	Storage Area for Roof Assembly
Storage 11A	Storage	Storage Area for Door and ext finish Assembly

Table 4.5 (i): List of all Receiving docks, Assembly Stations, & Storage Areas

Storage		
Station	Station type	Description
Storage 14	Storage	Storage Area for Door and ext finish Assembly
Storage 15	Storage	Storage Area for Roof and roof finish Assembly
Storage 16	Storage	Storage Area for windows and electrical Assembly
Storage 17	Storage	Storage Area for ext fin assembly
Storage 18A	Storage	Storage Area for ext fin assembly
Storage 18B	Storage	Storage Area for ext fin assembly
Storage 19	Storage	Storage Area for ext fin assembly
Storage 20	Storage	Storage Area for ext fin assembly
Storage 21	Storage	Storage Area for Trim & Final Finish Assembly
Storage 22	Storage	Storage Area for Trim & Final Finish Assembly
Storage 23	Storage	Storage Area for Trim & Final Finish Assembly
Storage 24	Storage	Storage Area for Trim & Final Finish Assembly
Storage 25	Storage	Storage Area for Trim & Final Finish Assembly
Storage 26	Storage	Storage Area for Trim & Final Finish Assembly
Storage 27	Storage	Storage Area for Trim & Final Finish Assembly
Storage 28	Storage	Storage Area for Trim & Final Finish Assembly

4.5.2 Production Quantity Information

Production quantity information is the list of the type and quantity of all the materials/components or parts that are used for building a house. For example, the case-study plant produces six houses per day or 12 units of floors per day, and each unit requires six tires for chassis assembly. Similar kind of information was noted and charts

were developed for each of the components. Table 4.6 gives the production quantity information of the Frame Assembly of the houses produced in the case-study factory. (Please refer to the appendices for the production quantity information of all the parts required to build one complete house). This information was collected from the purchasing department, the *Bill of Materials*, interviewing production personnel; and continuous observation of the construction process during factory visits.

Table 4.6: Product Quantity Information for Frame Assembly-A
(Based on the case study)

Frame Assembly		
	Part Description	Parts/Assy Units
1	Frame	2 EA
2	Axle, idler,	4 EA
3	Axle, brake	2 EA
4	Tyre	12 EA
5	Bolt shackle	24 EA
6	Lock- nut	24 EA
7	Wire-primary red	116 LF
8	Wire-primary white	116 LF
9	Wire-primary black	116 LF
10	Wire brake	64 LF
11	Lug ground	2 EA
12	Wire-Bare Copper	6 LF

Obtaining production quantity information is one of the major steps of the data collection. These data are variable and fluctuate with several factors like demand, product design, and production capacity of the plant. However, it has been assumed that the data for the production are constant in the quantitative modeling carried out for the purpose of this thesis.

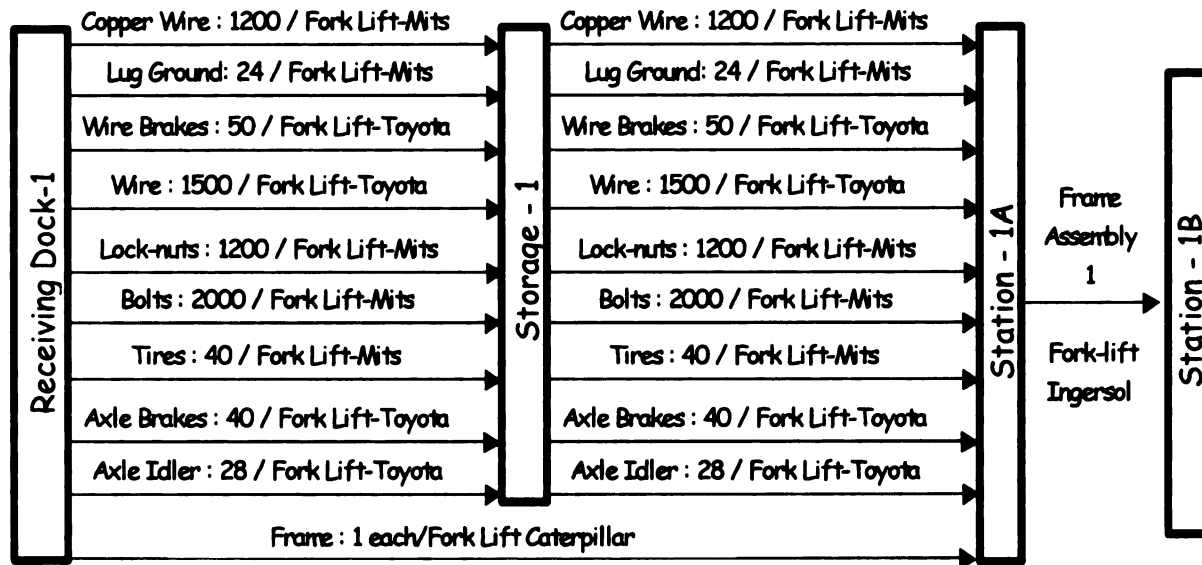
4.5.3 Parts Routing Information

Once the information on the product or parts per quantity was collected, then the sequence in which each of the parts visited the stations was noted. For example, the tires

required for the Frame Assembly initially arrived from the suppliers in the Receiving Dock-1; then they were carried to the Storage-1 by the forklift. Later they were carried to Station-1A and was assembled as a component of the Frame Assembly. Similarly, all the components moved in their specified routes started from their respective receiving docks, and moved through storages and sub-assembly stations to the main assembly stations. The parts routing information of each part and assembly was based on the factory visits made by the author, where she made detailed observations of the material movement, interviewed production personnel and viewed video-recordings made during the data collection. However, the routing information of the components from the suppliers to receiving dock or from the shipping dock to the dealers is not taken into consideration.

Along with the routing information, the material-handling device used to carry the part and the volume carried per trip for each part was noted. For instance, the axle idlers that were used in the Frame Assembly in Station -1A, were received from the Receiving dock-1 and carried to the Storage-1 by a fork-lift carrying 25 axle-idlers per trip and this was noted and incorporated in the part-routing information. Table 4.6 represents the part-routing information for all the components used in Frame Assembly in Station-1A. The part-routing for all other components and assemblies is provided in the Appendix-E. However, small parts, like nuts, screws, staples etc; were assumed to be carried in batches and the part volume information were not specified with a definite number. The routing information forms an extremely useful part for making layout decisions.

Table 4.7: Part-Routing Information for Frame Assembly
(Based on the case-study)



4.5.4 Material Handling Equipment Information- (*Cost Factor*)

The material handling equipment information is required to determine the cost of material handling between the stations or the facilities within the house manufacturing plant. This information is basically the data related to the number and types of material handling devices used in the factory, their investment, maintenance and operation cost, labor costs, efficiency, and the method by which the material is handled. All the material handling equipment data, related to the case study was collected on the basis of detailed discussion with the production personnel and the maintenance department, video recordings and some useful guesstimation by experienced plant personnel.

Table 4.8: List of the Material Handling Devices Used in a Manufactured Housing Factory
(Based on the case study)

Description	Quantity
1/ 3 ton Electric Hoist	3
2/ 2 ton Electric Hoist	24
3/ 6000lb Capacity Fork Lift Type 1	1
4/ 6000lb Capacity Fork Lift Type 2	1
5/ 6000lb Capacity Fork Lift Type 3	1
6/ 6000lb Capacity Fork Lift Type 4	1
7/ 6000lb Capacity Fork Lift Type 5	1
8/ 6000lb Capacity Fork Lift Type 6	1
9/ 5000 lb Capacity Fork Lift Type 1	2
10/ 5000 lb Capacity Fork Lift Type 2	2
11/ 5000 lb Capacity Fork Lift Type 3	2
12/ 5000 lb Capacity Fork Lift Type 4	1
13/ 5000 lb Capacity Fork Lift Type 5	3
14/ Hydraulic Pumps	5
15/ Hand Trolleys Type A	6
16/ Hand Trolleys Type B	8
17/ Pellets Type A	As Required
18/ Pellets Type B	As Required

The Table 4.8 shows the list of all material handling equipment that is being used in the plant. For detailed information on each of the material handling device, please refer to the appendices. Table 4.9 shows the detailed information of a forklift and presents the sample data collection format for all the other material handling equipment.

Table 4.9: Data Collection Format for the Material Handling Device
(Based on the case study)

ITEM	VALUE
Equipment Name	Fork Lift Toyota
Equipment Type	Lift Truck
Location	Floor & Wall Area
Quantity	1
Fixed Cost	\$ 250 per year
Investment cost	\$21,500
Maintenance cost	\$ 20 per month
Labor Cost	\$18.50
Available Time	115200 min
Load activity	Fork Load
Unload Activity	Fork Unload
Material Handling Activity	Load, Unload, Transport
Average Speed	15-20 feet per minute
Maximum Allowable Utilization	85%
Travel Effectiveness	50%
Transfer Angle	CIMFF_ACTPATH
Layer	5

4.5.5 Material Handling Activity Information-(Time Factor)

The material handling activity information provides the necessary data to calculate the time factor for the material flow, while the material handling equipment information primarily provides us with the cost factor of the material flow within a facility. The material handling activity time is primarily calculated in five steps, as mentioned below (EDS 2002).

4.5.5.1 Total available time for an equipment

This information was collected on the basis of the time available to the operator of the equipment, efficiency of the operator, and the working hours of the factory in the case-study.

For example, let us consider the available labor time for a fork-lift. The author assumes the available time for each truck driver, after subtracting lunch, breaks and allowances from an 8 hours shift, is 6.5 hrs per shift. Since the plant operates 5 days per week, the total hours the equipment is available for operation per week is (5×6.5) hrs or 32.5 hrs per week. Now if we multiply this by the efficiency factor of the fork-lift, (assuming 85% efficiency), then the availability time of the fork lift further reduces to 27.625 hrs per week.

The availability time data for all the other material handling devices were collected and calculated in the similar fashion. The information was based on the figures given by the maintenance and production division at the case study factory.

The factory in the case study had multiple levels mezzanine, first floor etc. FactoryFLOW allows single level analysis at a given time. As a result, the layout analysis was done on a single level. These shortfalls were corrected by changing the time factor i.e. by increasing the load and unload time for multiple level activities according to the readings observed.

4.5.5.2 Time to load the material to the equipment

The time taken by the material handling device to load any material was based on the type of material, nature of the equipment, mode of loading and operator efficiency. The time taken for loading 40 tires by a forklift was less than the time taken for loading $14' \times 2'' \times 10''$ -96 pieces of wood lumber. Even though, the forklift carried a greater bulk of material faster, in congested aisles moving small volume materials by hand-trolley proved to be more efficient. Moreover, the same forklift takes less time to load the same material from the same level rather than from the mezzanine level. For example, the

forklift will take less time to receive material from Storage –1, which is in the same level as Storage-18 which is at the mezzanine level in case-study factory. Finally, the more skilled the operator, the smoother the operation.

However, the time taken for each material loading varied each time the operation was performed, and there were many data points to refer to. In order to arrive at an almost accurate time, the author performed time study. For the load activity of each material the author observed the same operation 8 times and noted down the times. Three instances of each of the material load activity were videotaped. The observed readings along with video-clippings as references were averaged out to get the load activity time for each material. The outliers, for example, an operator leaving the equipment during load-activity for the lunch-break, were ignored.

4.5.5.3 Time Taken by the Loaded Equipment to Travel from the Receiving Point to the Dropping Point

The time taken by the devices to carry material from each point to another were noted. When high volume and heavy materials were carried, the speed of the carrier device automatically slowed down. This time also varied with the travel distance between the receiving points to the dropping points of the materials. In addition, the aisle width and congestion also affected the travel-time.

The travel time readings were also taken in a manner similar to the load-activity time, averaging out the 8 time readings observed for each operation and 3 videotaped instances. The outliers were ignored.

4.5.5.4 Time to Unload the Material from the Equipment

The time taken to unload material from the material handling equipment was noted in similar fashion.

4.5.5.5 Time Taken by the Empty Equipment to Travel from the Receiving Point to the Dropping Point

The time taken by the empty equipment after the unloading activity was comparatively the simplest. The time was calculated by multiplying the travel distance with the average speed of the equipment per hour. However, the speed of the equipment was reduced by a 15% factor to account for the congestion of the aisles, and this factor was based on the feedback provided by the experienced production personnel.

Based on the information collected in sections 4.4.5 and 4.4.6, the effectiveness and the availability of the material handling devices and their investment, the maintenance cost per week can be estimated. In some specific cases the total time taken by the forklift to load and unload and travel is also broken down for the purpose of the analysis.

4.6 Quantitative Modeling In Layout Evaluation Software (FactoryFLOW)

Chapter III discusses how the FactoryFLOW program manipulates the input data to calculate costs, distance, and time requirements for a project. However, before starting to input data within the software, one needs to understand the FactoryFLOW data structure.

4.6.1 Understanding The FactoryFLOW Data Structure

In order to perform the calculations, as already mentioned in Chapter III (Section 3.4.8), and generate the output, FactoryFLOW combines a layout drawing with a database of

production and facility information. A FactoryFLOW database may be defined as the *“..database file that contains all textual data for an analysis project, both input data and calculation results.”* (EDS 2002). The project file has a .FLO filename extension. Although, the .FLO database file format is compatible with Microsoft Access, it does not require any external database application.

The data can be entered into the .FLO database using several means. Some of the procedures of the data entry are listed below (EDS 2002).

- Migrating data files from an earlier release of FactoryFLOW
- Importing data from an appropriately structured Microsoft Excel workbook
- Entering the data using FactoryFLOW graphical data editor.

The quantitative data entry for analyzing the facility layout problem of the manufactured housing plants in FactoryFLOW was done by using the Methods II and III mentioned above. The step-by-step data entry process in FactoryFLOW is explained in the following sections.

The input data in the FactoryFLOW can be classified into the following categories shown in Table 4.10 (EDS 2002).

Table 4.10: The Categorization Of FactoryFLOW Input Data
(EDS 2002)

This data category	Applies to this type of data
Company Standard Data	Data must be the same in FactoryFLOW Projects, or studies, that will be compared with each other, including: Activity Equations Activity Templates Container Types Containers Activity Point Types Global Activity Assignment Matrix
Facility Specific Data	Studies for a given facility include the same activity points and material handling equipment . Analysis projects are normally limited to only one facility per .FLO file.
Study Specific Data	Study-specific data mainly comprise part routings for the analysis areas or assemblies being studied. Routing data for multiple product, assemblies or other part groupings can be contained in a single.FLO file, and can be selectively included in analysis

The stepwise procedure for setting up of a quantitative model in FactoryFLOW for the case-study is described in the following section.

4.6.2 AutoCAD Plant Layout Drawing

The preparation of the AutoCAD plant layout drawing is the first step in getting started with the FactoryFLOW study of the facility layout problem. The AutoCAD is opened and a layout drawing of the case study is prepared and saved under the name *fcad layout.dwg* is prepared.

4.6.3 Starting FactoryFLOW

Once the AutoCAD, installed with EDS factory bundle, is opened, it shows the *Factory* menu (refer to the figure 4.19). The *Factory* menu has a pull down menu, from which (refer figure 4.20) *FactoryFLOW* is selected.

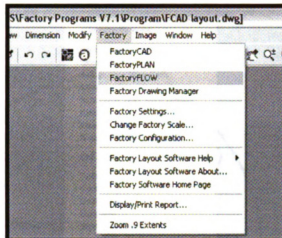


Figure 4.19: Opening Factory Menu In AutoCAD

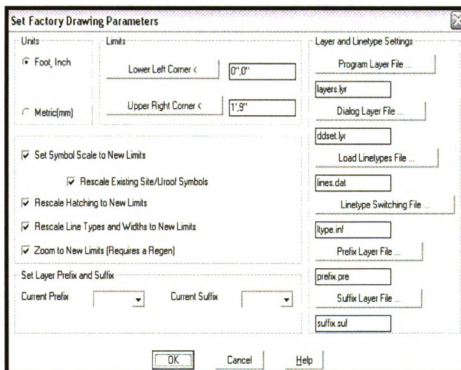


Figure 4.20: Starting FactoryFLOW

The *Factory.FLO* editor from the *FactoryFLOW* menu is selected and the *FactoryFLOW* application is started. The .FLO file is named as *fcad layout.FLO* and opened. The process of starting *fcad layout.FLO* is illustrated in the following Figures 4.21 and 4.22.

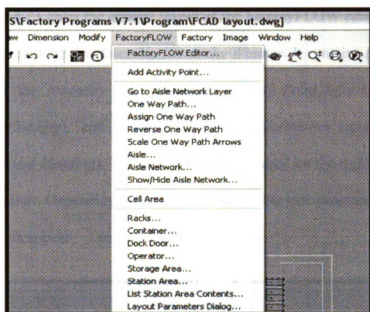


Figure 4.21: Starting Fcad layout.FLO Database in FactoryFLOW (Step 1)

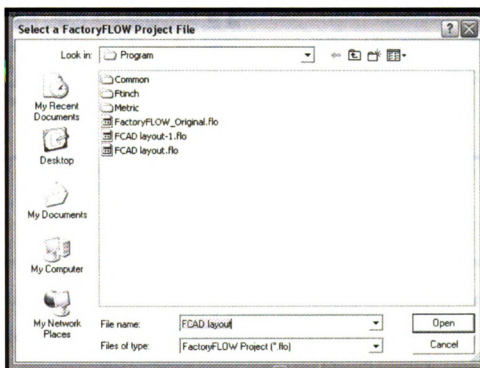


Figure 4.22: Starting Fcad layout.FLO Database in FactoryFLOW (Step 2)

Since a new file name was selected, FactoryFLOW creates a new file based on a default standard database named FactoryFLOW.FLO. This file is found in the *program* folder within the folder where the factory programs are installed (EDS 2002).

Figure 4.23 gives the general layout of the FactoryFLOW *editor*. The left hand side of the editor displays the *Assembly Hierarchy Window*. It contains *Product and Part Structure* (under the *Assembly Data Heading*), *Activity Point Information* (under the *Activity Point Heading*), and *Material Handling Information* (under the *Material Handling Equipment Heading*). The data window is situated on the right hand side of the FactoryFLOW editor. Depending on what is selected in the tree structure of the editor the corresponding data appear in the window.

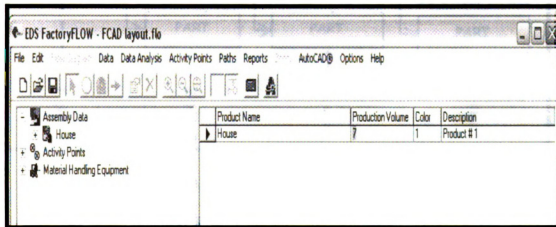


Figure 4.23: The Factory Flow Editor Window

4.6.4 Tree Diagram Or Product Structure

In order to explain the concept of Tree-Diagram, the author has made use of the definition of a generic Tree Diagram. A product is made up of a number of parts and assemblies, the assemblies; in turn are broken down into their respective subassemblies and components, and the subassemblies can be further subdivided into sub-sub-

assemblies and parts, and so on. This kind of product structure can be illustrated with the help of a figure and this figure may be defined as a *tree diagram* (refer to the Figure 4.24).

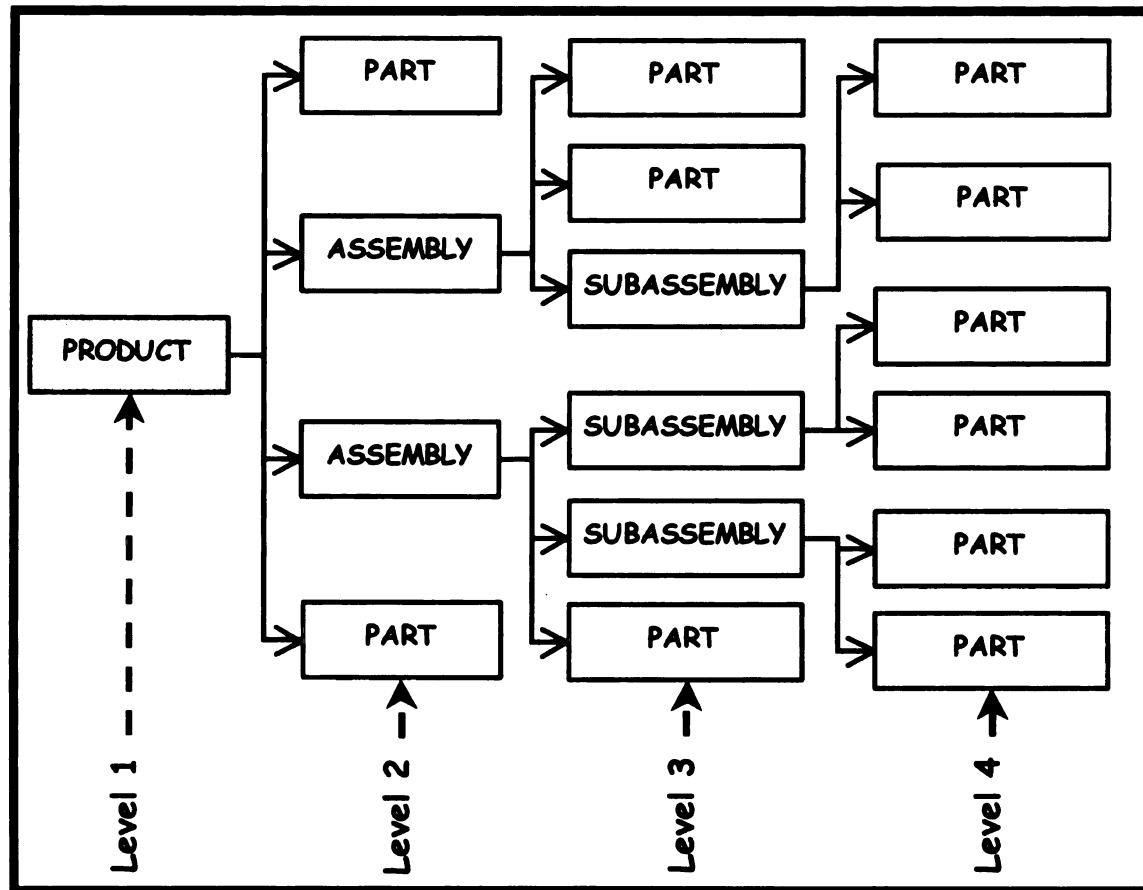


Figure 4.24: A Generic Tree Structure

All required parts, assemblies and the routing data were documented and translated into the FactoryFLOW format. Table 4.2 and appendices describe the parts and the assemblies of a typical house at the case-study factory. Based on the above-mentioned definition of a Tree-Diagram, the house was broken down into assemblies, sub-assemblies and parts upto the 17th level. The Figure-4.25 illustrates the Product –Tree Structure of a house to the 4th level. The complete Tree-Diagram Structure is provided in Appendix-C.

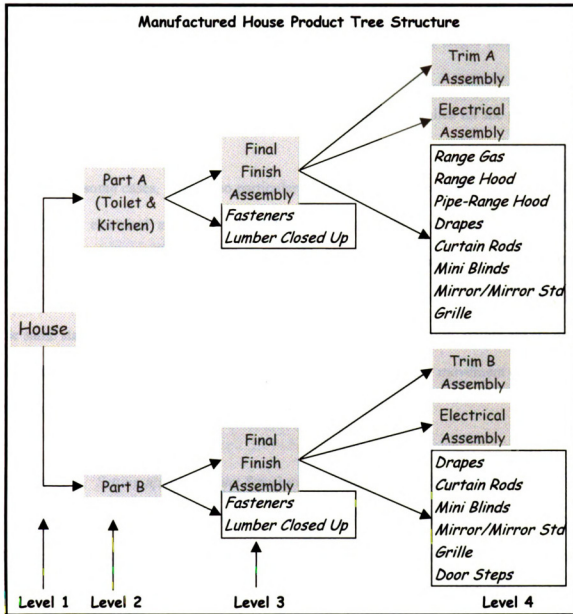


Figure 4.25: The Product Tree Structure of a Manufactured House up to the 4th Level

(Based on case study)

FactoryFLOW models the material handling flow within a manufacturing facility in such a manner that all parts come to a station and then form an assembly, and the assembly leaves the station as a whole. However, in the case of the manufactured home factory, many of the assemblies are distributed over several stations. For example,

the Trim Assembly takes place in several stations like Station 18, 28, 30 etc. The Trim Assembly for the purpose of modeling has been divided into three stages like Trim A1, Trim A2, Trim A3. Similarly the Electrical Assembly, Frame Assembly and Roof Assembly have been subdivided into several parts and sub-assemblies for the purpose of modeling.

In some cases, there is no particular station where the assemblies are done. For example the electrical assembly takes place simultaneously along with interior wall assembly, roof assembly and exterior and final finish assembly. However the FactoryFLOW software does not treat a part as an assembly if it does not take place in the same station. To overcome this problem dummy stations or activity points are created in the same location in a manner that ensures that the material flow movement or the cost of the material handling equipments is not affected.

4.6.4.1 Setting up the Product Structure in FactoryFLOW Editor

Once the Product-Tree was developed, the FactoryFLOW Editor window was opened and The Assembly Data Heading in the tree structure was right-clicked. A pop-up menu appeared and a new Assembly was chosen from the fly-out as illustrated in Figures 4.26, 4.27 and 4.28.

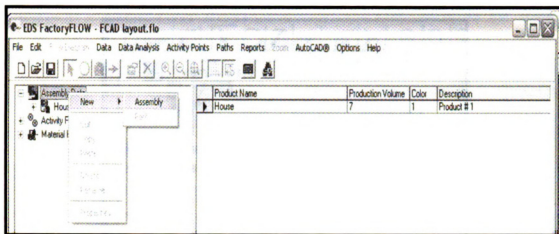


Figure 4.26: Setting Up Product Tree Structure (Step 1)

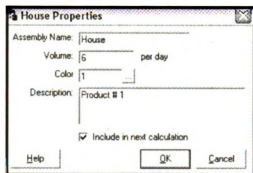


Figure 4.27: Setting Up Product Tree Structure (Step 2)

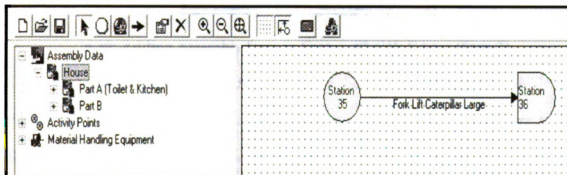
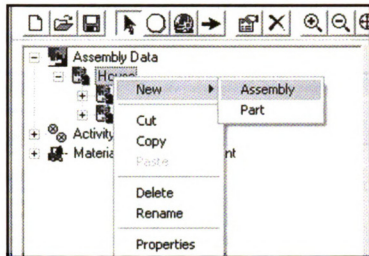


Figure 4.28: Setting Up Product Tree Structure (Step 3)

The new assembly was named as *House*. The *properties* of the *House Assembly* was chosen by double-clicking on the *House Assembly*. Six-units-per-day information is entered in the volume text box. The procedure is explained in the Figures 4.29 and 4.30.



4.29: Adding Assembly Data to FactoryFLOW Editor (Step-1)



4.30: Adding Assembly Data to FactoryFLOW Editor (Step-2)

The next step is to right click on “House”. Again the *New*, and then the *Assembly* from the fly-out menu is chosen. The name of the first assembly is chosen as *Part-A* (with Kitchen & Toilet). Similarly, a second assembly is chosen as a new assembly and is named as *Part-B*. This process is continued for all the sub-assemblies and parts provided in the Tree-Structure of the “House”. For the parts, *New Parts* are selected instead of *New Assembly*. For example, when the new subassembly named *Part-B* is chosen, two *New Parts*, namely, *fasteners* and *Lumber Closed Up* and a *New Assembly*, *Final Finish*

Assembly-B, is added. Please refer to Figures 4.31, 4.32,4.33,4.34 for the stepwise explanation of the procedures.

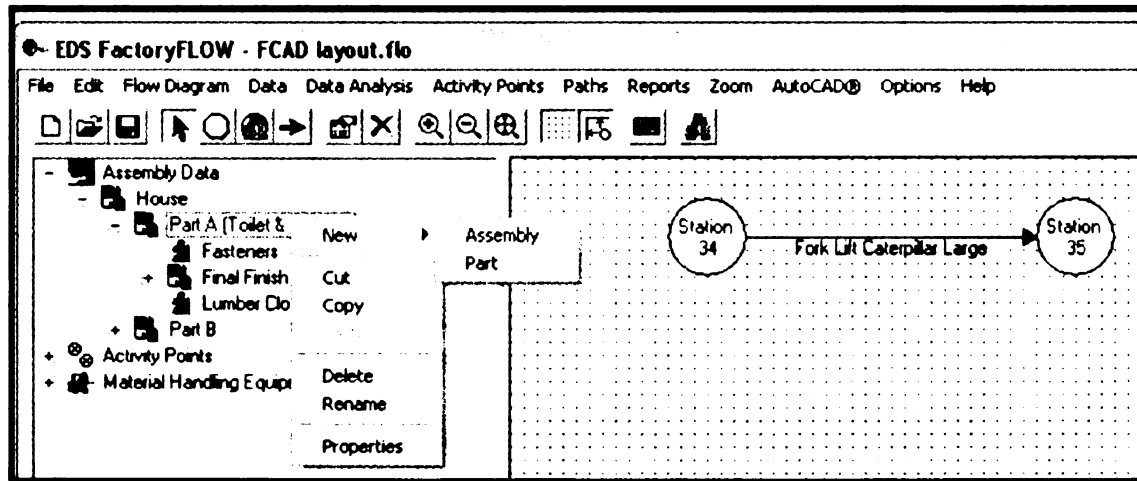


Figure 4.31: Adding Subassembly to the Assembly (Step-1)

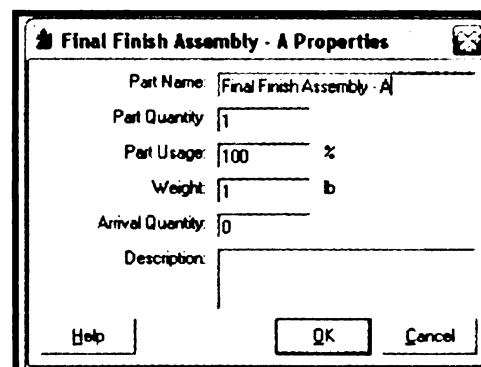


Figure 4.32: Adding Subassembly to the Assembly (Step-2)

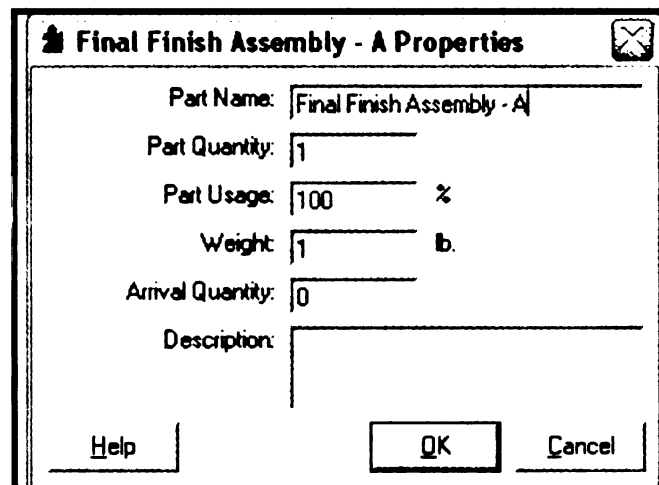


Figure 4.33: Adding Part to the Sub-Assembly (Step-1)

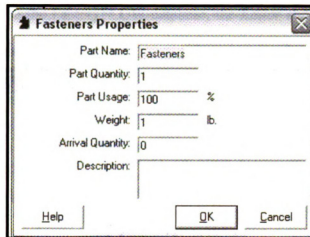


Figure 4.34: Adding Part to the Sub-Assembly (Step-2)

Once the product structure has been entered, the next input is part quantities per product. This is done by either double-clicking on the part and assembly names, or right clicking and choosing *Properties* to bring up the properties of that item. By default, all part quantities are set to one. For the parts and assemblies that needed to be modified, the *part quantity* field was changed to the correct number as according to the Product-Quantity Information (example: part quantity field for fasteners for Product-A was 44). But it should be noted that, for the *Part Quantity* in a subassembly, the input number of subassemblies should be the number that are needed to make the product. Again, for parts that make up a subassembly, the numbers of parts needed to make the subassembly are entered. For example, in the case of the Sub-Assembly “Cabinet Assembly-A”, there was a requirement of seven sub-assemblies per product. So during the data-input process the part-volume of each part of the “Cabinet Assembly” were entered as 1, while the number of “Cabinet Assembly” was entered as 7. Since for the house parts, both the toilets and kitchen are in the Part-A, the distribution of electrical wires and conduits are broken down into 80 to 20 ratios in between the Parts-A and B. Once the complete product-tree

Activity Points

Receiving Dock-1

Receiving Dock-2

Receiving Dock-3

Receiving Dock-4

Receiving Dock-5

Receiving Dock-6

Receiving Dock-7

Receiving Dock-8

Receiving Dock-9

Station 10

Station 11

Station 12

Station 13

Station 14

Station 15

Station 16

Station 17

Station 18

Station 19A

Station 19B

Station 19C

Station 19D

Station 1A

Station 1B

Station 20A

Station 20B

Activity Point Default Properties

Activity Point Name: Station 1A

Activity Point Type: Assembly

Coordinates

X: 3675.07

Y: 1698.48

Z: 0.00

Area Dimensions

Length: 0

Width: 0

Height: 0

in.

Description:

Chassis Assembly

Figure 4.37: Defining Activity Point-Station-1A in FLOW Window

4.6.6 Material Handling Devices

As mentioned earlier, the cost of maintenance for the material handling equipments like fork lift and hoists were variable. The author has used the feedback from the maintenance division, production personnel and information maintenance workbooks, and the average market rates for deriving the cost of operation and maintenance of this equipment. Also, for some of the material handling devices like fork-lifts and hand pellets, the standard rates in the existing FactoryFLOW database were used for cost calculation and analysis purpose. The list of the Material handling devices used in the case-study factory are given in the Table 4.8.

While adding the material specifications to the FactoryFLOW database the following assumptions were made.

- Parts per trip field were assumed to represent the parts per trip. This is accomplished by having containers per trip equal to one.
- Since FactoryFLOW does not allow for the simultaneous handling of different products using the same material handling equipment, the author has broken up each of such trips of multiple products into unit sub-trips, and the cost and time has been adjusted accordingly to account for this assumption, such that the overall outcome remains the same. For example, the labor rates and the maintenance operational cost of the material handling devices are divided into a smaller ratio proportional to the number of devices used. If 1 forklift, which costs \$4500 per year and \$18.5 of labor-hr is broken down into 10 forklifts for the purpose of analysis, then each forklift is assumed to have a maintenance cost of \$450 per year and \$1.85 labor-hr (refer to Table 4.11).
- The electric hoist is not a part of the existing factory flow database. So the electric hoist was categorized as a special material handling equipment and had the activity equations customized for this purpose.
- Also, the activity equations and activity templates were formulated according to the procedures and the readings in the case study.

**Table 4.10: Number of Material Handling Equipments, Labor & Equipment Rates
Assumed During Modeling In FactoryFLOW**

Description of Equipments	Actual	Actual Cost	Actual Labor Cost	# of Equipments Assumed Software	Manipulated Equipment Cost	Manipulated Labor Cost
Forklift Toyota	1	500	18.5	5469	0.0914	0.0034
Forklift Mitsubishi	3	500	18.5	6435	0.2331	0.0086
Forklift Ingersollrand	4	600	18.5	2801	0.8568	0.0264
Forklift Caterpillar	7	600	18.5	5791	0.7253	0.0224
Forklift Caterpillar Large	1	800	18.5	9	88.8889	2.0556
Electric Hoist A	21	300	18.5	176	35.7955	2.2074
Electric Hoist B	4	450	18.5	28	64.2857	2.6429
Electric Hoist C	2	600	18.5	2	600.0000	18.5000
Hand Trolley/Pellets	100	60	18.5	8909	0.6735	0.2077
Human	100		18.5	8891	0.0000	0.2081

4.6.6.1 Specifying Material Handling Devices in FactoryFLOW

The *Material Handling Devices* heading in the *Assembly Hierarchy* is selected and a pop-up menu appears. *New Material Handling Device* from the pop-up menu is chosen and a window appears as shown in Figure 4.38 below and the information fields are filled out.

Figure 4.38 shows the entry of the information on the forklift *Toyota*. In a similar manner, the specifications for the remaining material handling devices were added to the FactoryFLOW database.

Material Handling Equipment Properties	
Equipment Name:	Fork Lift Toyota
Equipment Type:	Lift truck
Quantity:	70
Fixed Cost:	50 per year
F/P/M Cost:	5 per hr
Labor Cost:	15 per hr
Available Time:	115200 min per year
Load Activity:	Fork Load
Unload Activity:	Fork Unload
Material Handling Activity:	
Avg. Speed:	290 ft./min
Acceleration:	0 ft./sec ²
Deceleration:	0 ft./sec ²
Max. Allowable Utilization:	85 %
Travel Effectiveness:	50 %
Transfer Angle:	0 degrees
Layer:	CIMFF_ACTPATH
Color:	1
Update Properties Show Parts Delivered By This Device	

Figure 4.38: Adding Material Handling Equipment Information in FactoryFLOW

4.6.7 Quantitative Modeling of the Case Study in Software

The preceding sections explained how to enter the data to the FactoryFLOW database. This section will focus on the methodology of relating the different data entered in the database with each other and develop the quantitative model for the analysis.

4.6.7.1 *Creating the Process Flow Diagram*

Once the assembly, subassembly and parts appear on the tree structure, each of the parts are selected and the *FLOW diagram* window for each of the corresponding selected part or assembly is displayed on the right hand side of the editor. Then the stations that are visited by the respective part are added to the window by selecting the *Flow Diagram* menu and the *Add Activity Point* command. This procedure is explained with the help of

Figures 4.39, 4.40 and 4.41, where the routing information of the Frame Assembly A is shown.

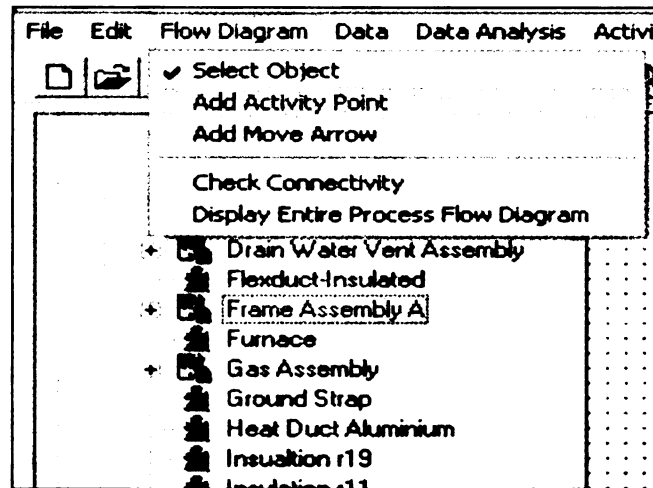


Figure 4.39: Adding Part Routing Information for Frame Assembly A (Step 1)

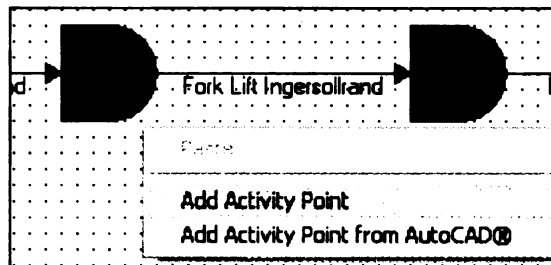


Figure 4.40: Adding Part Routing Information for Frame Assembly A (Step 2)

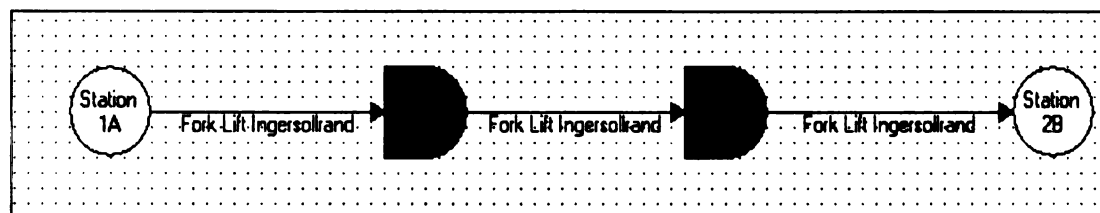


Figure 4.41: Adding Part Routing Information for Frame Assembly A (Step 3)

The next step is to establish the route between the activity points added to the *FLOW* window. This is done by selecting the *Add Move Arrow* Command from the Flow Diagram Menu. During this process a pop-up window appears, where the information

about the material handling device, and the volume per trip carried is specified. This process is explained by the following figures 4.42 and 4.43 for the Frame Assembly A.

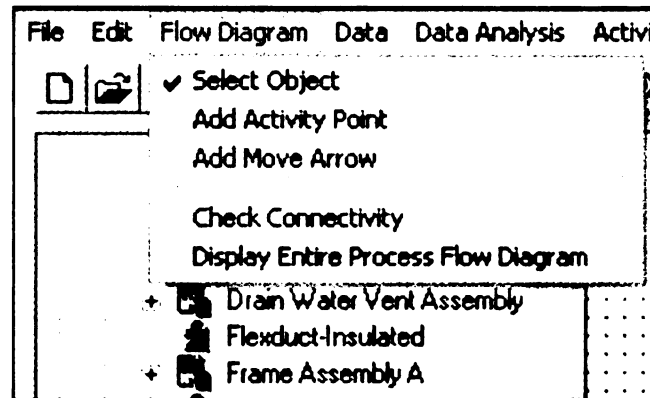


Figure 4.42: Connecting the Activity Points (Step 1)

This process of developing the product tree structure and routing information was done for each and every parts, sub-assembly and assembly based on the part routing information provided in the appendices.

 A screenshot of a dialog box titled 'Part Name: Frame Assembly A'. It contains the following fields and controls:

- 'From: Station 18' and 'To: Station 2A'
- Tabs: 'Flow Data', 'Load Activity', 'Unload Activity', 'Pass Through Points' (the first is active)
- 'Flow Percentage: 100 %'
- 'Material Handling Equipment: Fork Lift Ingersollrand' (dropdown menu)
- 'Container: Standard Pallet' (dropdown menu)
- 'Container Storage Quantity at Destination: 0'
- 'Parts per Container: 1'
- 'Containers per Trip: 1'
- 'Container' section with radio buttons for 'Full' (selected) and 'Empty'
- 'Use Specified Distance: ' (checkbox) followed by a text field and 'ft.'
- 'Classification: Part' (dropdown menu)
- Buttons at the bottom: 'Help', 'OK', and 'Cancel'

Figure 4.43: Connecting the Activity Points (Step 2)

4.6.7.2 *Adding Activity Points to the Drawing*

This stage involves the linking of the FactoryFLOW database with the AutoCAD layout drawing. This is done by selecting *Add Missing Activity Points To The Drawing* from the *Activity Points* menu in the FactoryFLOW editor. Once this command is given, then the Activity Points are placed in the correct areas in the AutoCAD layout drawing.

Once these steps are performed, the FactoryFLOW is ready for the analysis. The following section gives an overview of the reports and calculations generated by FactoryFLOW.

4.6.8 Production of Analysis Reports & Diagrams and Verification of the Existing Layout (Case Study)

As already discussed in Chapter III, given the input and a layout drawing, FactoryFLOW calculates distances, costs, intensity (frequency of path use), material handling activities, and is able to diagram the material flow. The latter part of this chapter explains the process of generating the above-mentioned outputs.

4.6.8.1 *Performing a Euclidian Calculation*

Once the data have been entered in the FactoryFLOW, and the activity points are placed in the drawing, a *Euclidian* calculation of material flow is performed. As explained in Chapter III a Euclidian analysis is a straight-line analysis and does not require an aisle network. This calculation is performed and a *Calcualtion Log-File* is created and the *Euclidean Flow Paths* are displayed in the AutoCAD drawing. While performing the material flow calculations, if the material handling device capacity is too small for the required moves (i.e. busy minutes per day is greater than available minutes per day), the program displays a dialog box for adjusting the number of devices. This gives an

opportunity to manipulate the number of material handling devices used for certain movements and to perform “what-if” analysis. During the calculation process, the equipment utilization calculation results are also displayed in the Material Handling Equipment Utilization report.

Calculation Log-File

The calculation log-file is created based on the FactoryFLOW equations discussed in section 3.4, and calculates the distance, cost, time and material handling utilization reports on each of the parts and the subassemblies used in building the house. Since there are a great number of parts, assemblies and sub-assemblies used to build a house, the calculation log-file created forms a thousand page report. As it is not possible to include the whole report in this thesis, only the log file for the major assemblies are provided in the Appendix-B. The calculations for the main product *House* is given in Table-4.10 below. These calculation are based on the *Actual Path* calculation that is described in the latter sections.

Table 4.12: Calculation Log File Report

Product:	House	
Production Volume:		7
Seq. #:1	From: Station 35 [Assembly]	To: Station 36 [Packaging]
MH Device Name:		Fork Lift Caterpillar Large [Lift truck]
MH Device Speed:		290.00 [ft./min]
Total Travel Time (adjusted for effectiveness):		20.33 [min]
Travel Time (adjusted for effectiveness):		2.90 [min]
Point-to-Point Distance:		421.19 [ft.]
Distance (adjusted for effectiveness):		842.38 [ft.]
Container:	Standard Pallet [Pallet -- Full]	
Load/unload time: [per trip, delivery, container, part]		555.80 [min]
Load Time:		162.40 [min]
Load Template: Fork Load [using material handling device default.]		
1.Load Activity [Per trip]	1.00 *	7.00 = 7.00 [min]
2.Elect- Hoist Unload		
3.Hoist Load [Per trip]	15.00 *	7.00 = 105.00 [min]
4.Load Activity [Per part]	5.00 *	7.00 = 35.00 [min]
5.Unload Activity [Per trip]	1.00 *	7.00 = 7.00 [min]
6.Hoist Load [Per trip]	1.20 *	7.00 = 8.40 [min]
Unload Time:		393.40 [min]
Unload Template: Fork Unload [using material handling device default]		
1.Unload Activity [Per trip]	1.20 *	7.00 = 8.40 [min]
2.Elect- Hoist Unload		
3.Hoist Load [Per trip]	15.00 *	7.00 = 105.00 [min]
4.Hoist Load [Per part]	5.00 *	7.00 = 35.00 [min]
5.Hoist Load [Per part]	35.00 *	7.00 = 245.00 [min]
Frequency:		7.00 [trips]
Parts Moved:		7.00 [parts]
Parts per Container:		1.00 [parts]
Containers per Trip:		1.00 [containers]
Total Time:		576.13 [min]
Total Cost:		227.38 [\$]
Fixed Cost:		1.72 [\$]
Variable Cost:		225.65 [\$]

The figures displayed in this log-file will help us to figure out the material flow movements which can be made more cost-efficient or time-efficient by changing the layout. Later, in Chapter V the author will illustrate how the figures presented in the Calculation log-file were used to develop alternative layout designs.

Euclidean Flow Paths

Figure 4.44 shows the Euclidian Flow Paths for the material movements in the facility layout of the case study factory. The thickness and the density of the flow paths will help the analysts to decide the necessary changes to be made in the layout and develop the alternatives. However, the *Actual Path Calculations* and *Actual Path Flow Diagram* reports were used in the analysis for developing the layout alternatives in Chapter V.

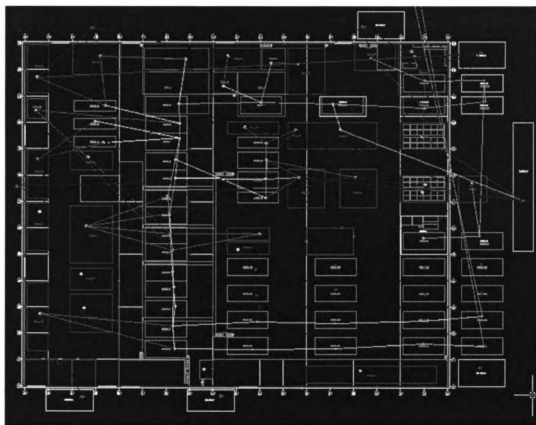


Figure 4.44: Euclidian Flow Path Diagram For the Factory-1

4.6.8.2 Querying a material flow path

The querying of a material flow-path exercise also helps to query a material flow path in order to find information such as the part being moved, the total cost of the move, the total distance of the move, or the total frequency. Figure 4.45 displays the results of querying of a material Flow path between Station 5 and Station 5A.

Query Flow Path	
Query Flow Path Results:	

Number of paths queried:	2

Product:	House
Part:	Shingles
MH Device Name:	Human
From:	Storage 16
To:	Station 11
Unit Cost:	0.51 [¢ per ft.]
Total Cost:	269.62 [¢ per day]
Distance:	\$27.75 [ft. per trip]
Total Distance:	91,828.46 [ft. per day]
Trip Frequency:	87.00 [trips per day]

Figure 4.45: Querying a Material Flow Path Report

4.6.8.3 Filtering the Material Flow Path

With a large number of material flow paths between the activity points, concentrating on just one flow path or group of paths coming from, or going to, any particular workcenter is difficult. The FactoryFLOW uses the *Flow diagram Filter* command that shows only the selected material flow paths. Figure 4.46 shows the example of using the Flow Diagram Filter for the assemblies Frame Assembly A and Frame Assembly B.

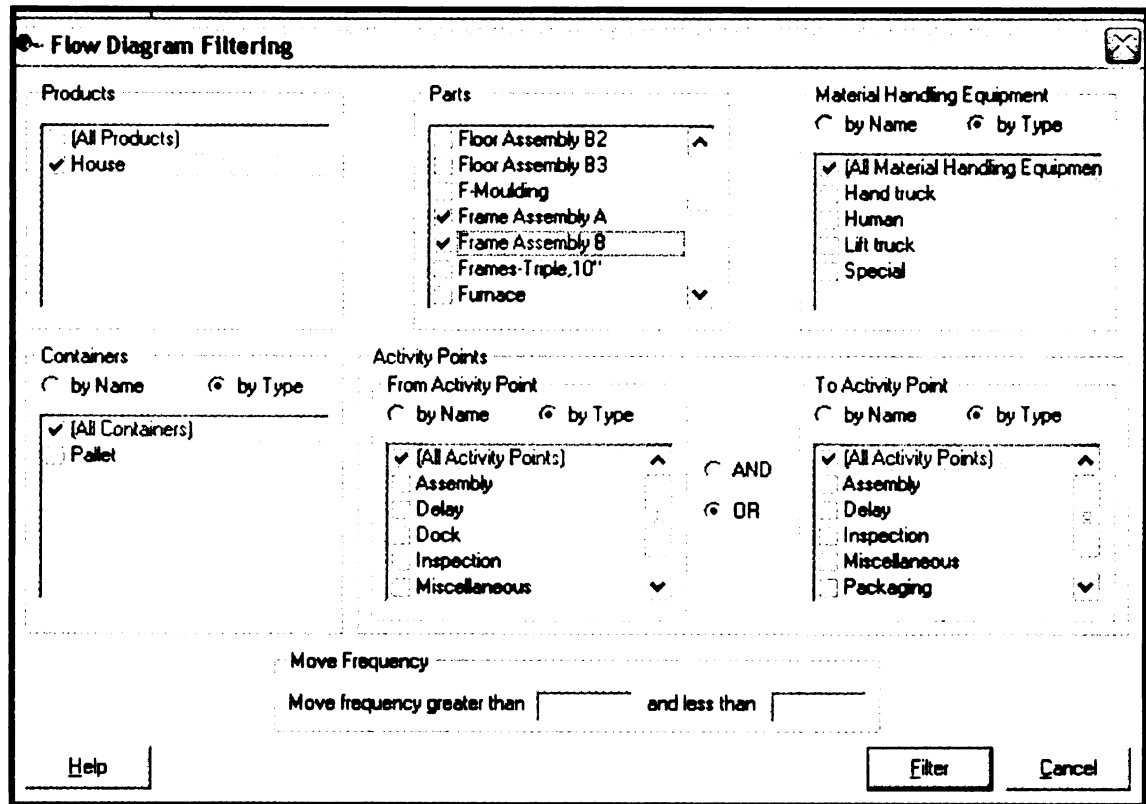


Figure 4.46: Filtering the Material Flow Path

4.6.8.4 Creating an Aisle Network

In order to perform an actual path calculation, an aisle network is drawn by using the AutoCAD lines in the “Aisle Network layer” to create an aisle network: The “Aisle Network layer” is the default layer used by FactoryFLOW for aisle network lines. Using the AutoCAD line, command, lines are drawn down the center of the aisles. Care must be taken to ensure that line intersections are connected. If the aisle lines are not connected, FactoryFLOW will not perform the actual path calculations properly. Figure 4.47 displays the layout drawing of Factory-1 with aisle network lines.

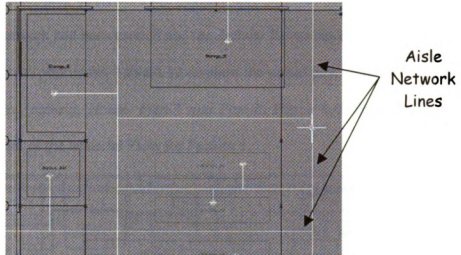


Figure 4.47: Partial Factory-1 Layout Drawing with Aisle Network

Joining Activity Points to the Aisle Network

After the aisle network has been created, the activity points are joined to that network. They are joined using *AutoJoin* command in the FactoryFLOW Activity points menu. Figure 4.48 displays the Factory 1 layout where the activity points are joined to the aisle network.

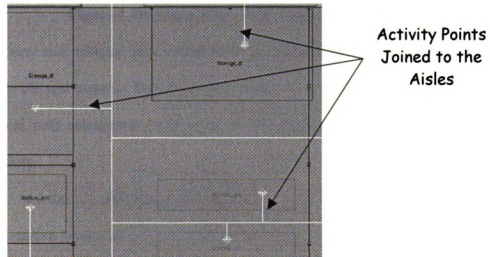


Figure 4.48: Partial Plan For Factory-1- Aisle Network Joined with the Activity Points

4.6.8.5 Performing an Actual Path Calculation

Once the aisle network had been created and the *Activity Points* has been joined, an actual path calculation was performed. Table 4.12 displays the actual path material flow reports on the assemblies, namely, *House, Part-A and Part-B*. Figure 4.49 displays the actual Flow Path diagram of the Material Flow for Factory 1.

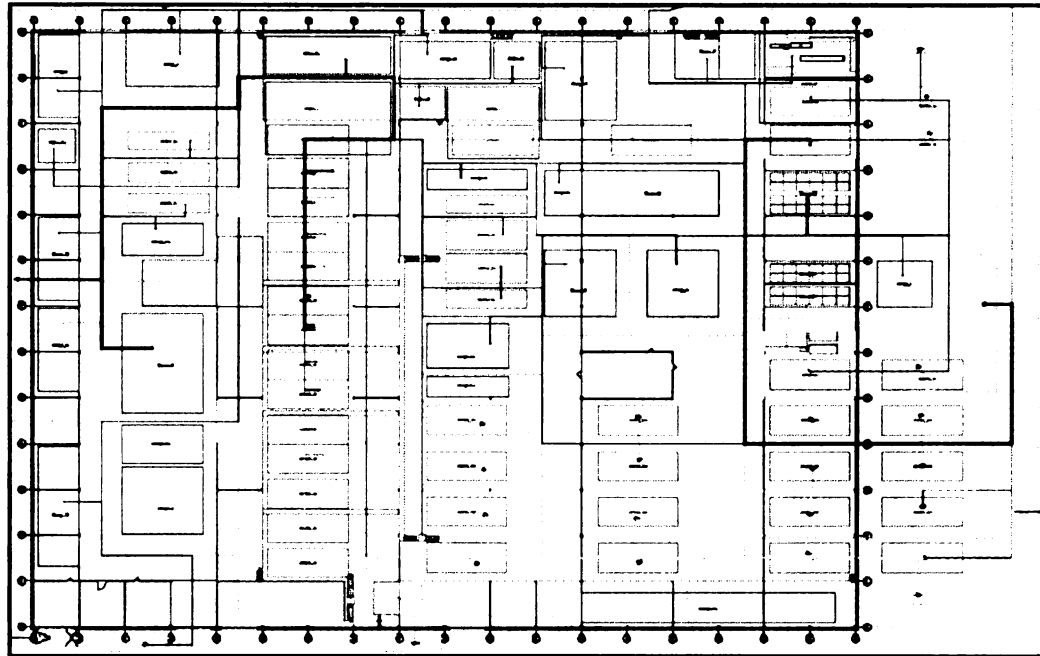


Figure 4.49: Actual Flow Path Diagram In Factory-1

The reports and material flow calculations generated from the actual path calculations resemble the real material flow more closely than the Euclidian calculations. As a result, the actual path calculations were used for the layout analysis and developing layout alternatives.

4.6.8.6 Moving an Activity Point

The alternative layouts of the case-study factory were developed by changing the location of the activity points. In doing this, some of the activity points were relocated from their existing positions to the new positions. Once the activity points had been shifted, the

activity points were joined to the network and all the reports and calculations described in the previous sections were performed. Once the analysis was performed, the results of the layout with changed activity point location were compared with the results of the existing layout. The steps of this analysis are described in Chapter V.

4.6.8.7 Creating Charts and Reports

An actual path analysis is the most accurate description of the material flow in a facility. This analysis is typically used to create charts and reports available in FactoryFLOW. As explained in the previous section, the aisles are drawn using AutoCAD drawing so that the calculations are made based on the actual travel distances and not on the Euclidian distances. Below are description of some of the reports that can be generated based on the actual path calculations.

Aisle Congestion Diagrams

This diagram maps the traffic associated with each section of the aisle network. It helps the planner to identify the congested aisles in the facility layout system based on the frequency of material movements and material flow intensity. Figure 4.50 shows the Aisle Congestion Diagram for the Factory 1.

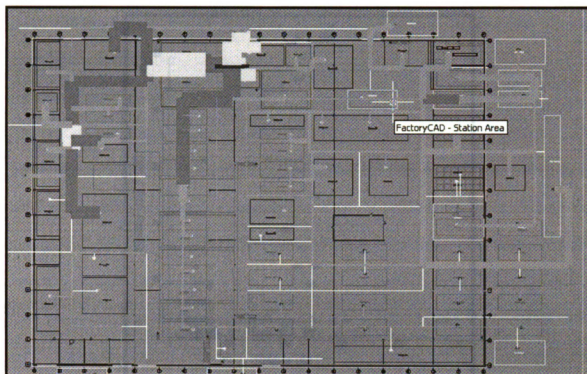


Figure 4.50: Aisle Congestion Diagram for the Factory 1.

Based on the information contained in the aisle congestion diagram, the facility layout alternatives that can maximize the savings and efficiency can be developed.

Distance Intensity Charts

Distance-Intensity (DI) Charts in FactoryFLOW generates the distance-intensity data and draws the chart. This is a scatter chart, which graphically represents the paths' length versus its intensities (number of moves along the path). In an optimal layout, the points will be close to the X and Y axes, which implies that high intensity moves will have short travel distances and vice versa. FactoryFLOW uses the existing data in database to compute distances and intensities. However, the DI charts are not dynamic, and they have to be updated everytime the database is updated. Figure 4.51 shows the DI chart for the existing factory layout.

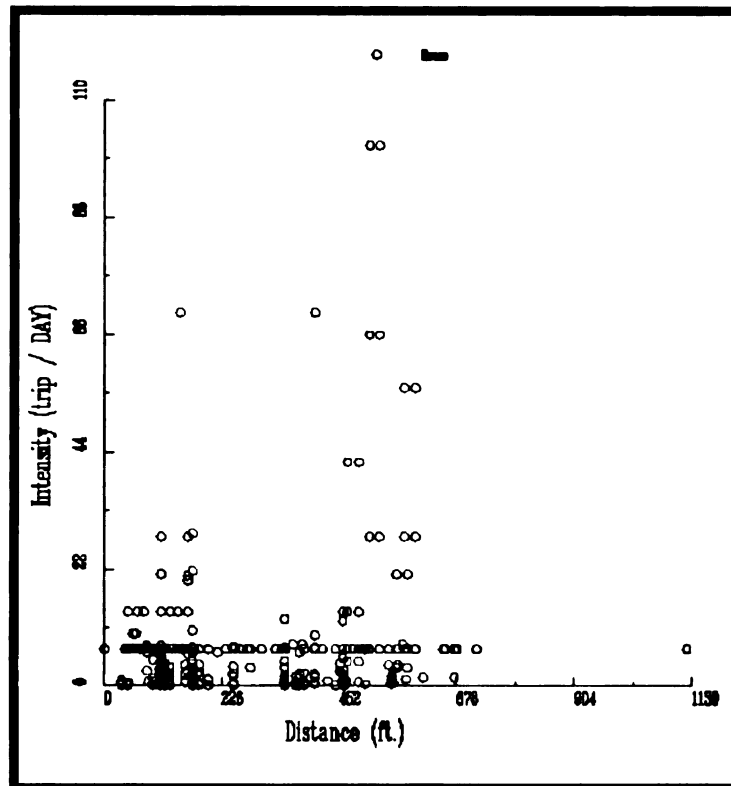


Figure 4.51: Distance Intensity Chart for the Existing Factory Layout

The figure 4.51 displays several points that represent the distance-intensity of each path. With the help of *Query a Distance-Intensity Point* one can select point to see the intensity path of a single flow path.

Product Quantity Chart

FactoryFLOW's product quantity (PQ) chart is a bar graph that shows the relative quantity of products manufactured. FactoryFLOW takes direct information from the product file (.FLO database) to develop the chart. Similar to the Distance-Intensity charts, PQ charts have to be regenerated every time there is any change in the .FLO database. The product quantity chart is useful for grouping products into similar volume categories. Different volume categories tend to require different methods of plant layout. High volume products lend themselves to a mass production type of layout, i.e., production line. Since this research focuses on the facility layout design of the manufactured housing

plant, and not on the product design of the house, the product design charts are not considered during analysis.

Distance Cost Reports

The Distance-Cost Reports can be generated from the *Reports* Menu in FactoryFLOW. The Distance-Cost report presents information about the total distance traveled by each part, sub-assembly or assembly between two stations, specifies the material handling device used; and also reports the total material movement cost incurred by each part, sub-assembly or assembly in a day. Table 4.13 represents a partial section for the Distance – Cost report for some of the materials in the case-study factory (refer to the Appendix-E for the complete report). The report is used in this research, for the purpose of cost analysis and evaluation of the various layout alternatives developed. The outputs of this report is based on the following equation (refer to section 3.4.1 in Chapter III).

$$\sum_a \sum_i \sum_j c_{ij} f_{ij} d_{ij}$$

The above expression represents the material movement cost for the manufactured housing plant for a given day. The *Cost Per Day* column in Table 5.1, is the product of unit cost, distance traveled and number of trips for a given material (refer to the *Part Description* column) in a day.

Table 4.13: Partial Distance Cost Report
(Based on case study and FactoryFLOW analysis)

Part Description (a)	From (Station-I)	To (Station-J)	Material Handling Unit	Distance Travelled d_{ij}	Cost/Day $c_{ij} f_{ij} d_{ij}$
27" Overhead Assembly	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Adapter	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.08
Adapter Cleanout	Receiving Dock-3	Station 2E	Fork Lift Mits	424.51	\$0.00
Adapter-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.39
Adapter-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-D	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-E	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-Swivel Trap	Receiving Dock-3	Station 2E	Fork Lift Mits	424.51	\$0.00
Axle Brake	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
Axle Idler	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
Backsocket	Receiving Dock-4	Storage 4B	Fork Lift Mits	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mits	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mits	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05

The charts and reports generated by FactoryFLOW are based on the mathematical model of the *Layout Evaluation Criteria* explained in section 3.3.1 in Chapter III of this thesis. For quantitative modeling purpose, it adopts the ABSMODEL-2, also explained in section 3.3.1.1. Moreover, the calculations for the cost, distance-traveled and the frequency of the trips for the material movement are based on the equations explained in section 3.5.3 in Chapter III.

4.7 Summary

This chapter presented the product and the production process of a manufactured housing facility based on the literature review and a case study. The author visited the manufactured housing factory multiple times over six weeks and collected the required data for space requirements, part volume, part routing and material handling system information through interviews, observations, and video-recordings. This chapter also presented the process of documenting the data collected during the above-mentioned factory visits for a quantitative analysis of the facility layout problem of the manufactured housing industry. The quantitative matrices based on the material flow between the stations within the factory were developed and the FactoryFLOW software was selected as the quantitative analysis solution. The process of adding data to the software database and developing the quantitative model of the facility layout problem in the FactoryFLOW environment was illustrated. The final section of this chapter discussed the various reports and charts that were generated in FactoryFLOW based on the quantitative model developed. The results obtained from the FactoryFLOW analysis in this chapter will be used as the benchmark, on which the alternative facility layout designs will be developed and evaluated in Chapter V.

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**MATERIAL FLOW-BASED ANALYSIS OF MANUFACTURED HOUSING
PRODUCTION PLANT FACILITY LAYOUT**

VOLUME II

By

Deblina Banerjee

A THESIS

Submitted to
Michigan State University
in the partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Construction Management Program

2003

CHAPTER FIVE

**MATERIAL-FLOW BASED DEVELOPMENT AND
EVALUATION OF ALTERNATIVES**

5.1 Introduction

In this chapter, the author provides an analysis of the results and reports obtained from FactoryFLOW software that was used for the material-flow based-quantitative facility layout modeling of the case-study factory described in the previous chapters. The author identified the critical points in the Distance-Cost reports and the Distance-Intensity charts and performed “what-if” scenarios based on the critical points and generated reports to compare them with the existing layout. The results for most of the alternatives generated through “what-if” scenarios showed significant difference from the existing layout. In the latter part of this chapter, the author developed a quantitative model of the facility layout based on the case study performed during earlier research (Senghore 2001, Mehrotra 2002). Considering a typical house as a product and the production process as a generic production process, the author performed quantitative analysis of the different facility-layout alternatives, which were qualitatively evaluated during the earlier research (Mehrotra 2002). In the final section of this chapter, the author proposes the recommended sequence of process steps required for evaluating the facility layout alternatives and material-handling system for a given manufactured housing plant, after incorporating the inputs, and suggestions from the industry personnel and professional layout designers.

5.2 Development of “What-If” Scenarios for the Case-Study Plant

Once a material-flow-based quantitative model of the facility layout of the case-study plant was developed in FactoryFLOW, the software analyzed the model, and generated several diagrams and reports as illustrated in the earlier chapter. The FactoryFLOW-

generated diagram and reports are primarily based on the material flow and aisle congestion paths, and readily present the flow information graphically in the layout drawing (refer to Figure 5.1) and graphs (refer to the Distance-Intensity chart in Figure 5.2), and numerically in material-flow reports (e.g. Moves-Cost-Distance report of each parts, assemblies and sub-assemblies in the Appendix-E). The material-flow calculations are based on the ABSMODEL-2 (refer to section 3.3.1.1 in Chapter III) and the equations explained in section 3.5.3 in Chapter III.

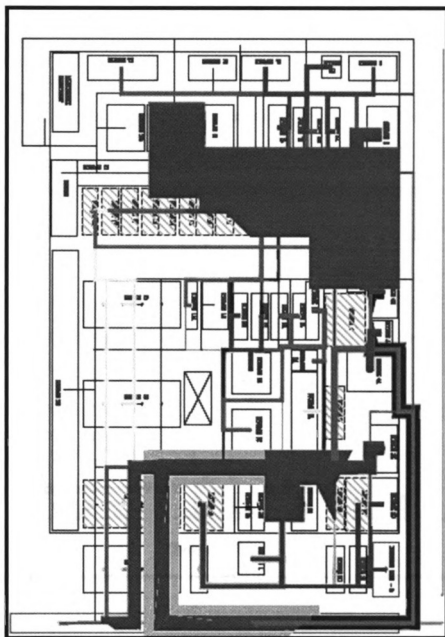


Figure 5.1: Factory-1 Layout: Actual Material Flow-Paths in FactoryFLOW Analysis
(Based on case study)

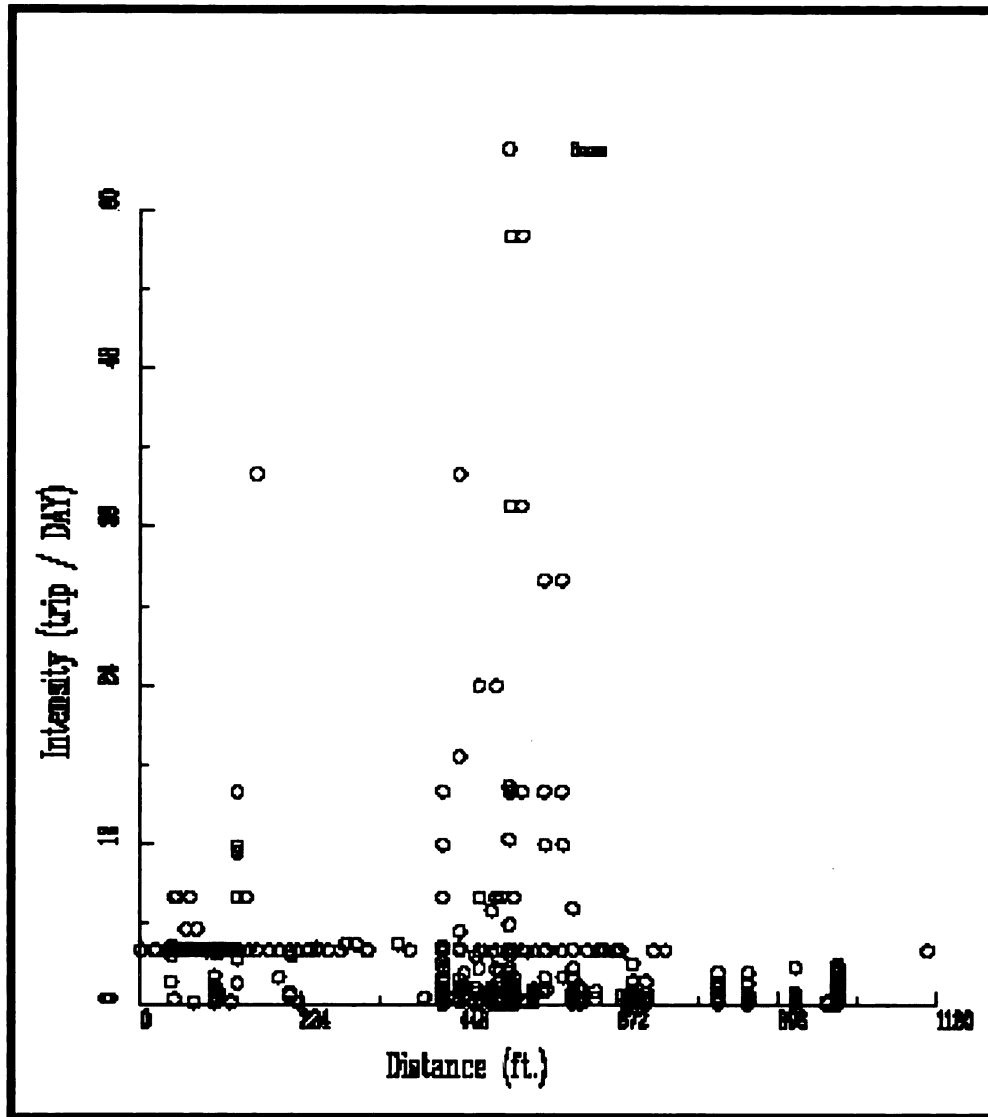


Figure 5.2: Distance Intensity Chart
(Based on case study)

5.2.1 Selection of Distance-Intensity Charts and Moves-Distance Cost

Reports for Layout Alternative Evaluation

The reports and diagrams generated by FactoryFLOW, as already described in detail in Chapter IV, help to readily identify the critical paths for the material movement, the potential material-flow bottlenecks, the production flow efficiency, the storage space requirements and the material-handling requirements. This information is useful during

planning or for improving the layout of a single work cell, a production line, a department, or a plant; working to improve the material flow efficiency of a product, a part, or groups of parts or products, calculating storage requirements and material handling system requirements; changing product mix, adding new production, or working to improve plant efficiency; implementing new production philosophies, such as Just-In-Time or Group Technology, and presenting layout alternatives (EDS 2002). The process of selecting the reports depends on the nature and the purpose of the layout analysis.

Moreover, the facility layout alternatives can be developed based on the layout design (e.g. by changing the location of the stations or the aisle network system design), the material handling system design (e.g. by changing the equipments or the part routings), or the product design (e.g. by changing the part groupings). For the purpose of evaluating the layout design alternatives, the congestion diagrams, distance-cost reports or the distance intensity charts are most effective while for evaluating the product design, the work-center utilization charts, and product-intensity charts are more helpful. As stated earlier, the purpose of this research is to evaluate the layout design alternatives based on the material flow. In order to perform the analysis the author has selected one graphical report, namely, the Distance-Intensity Chart; and one numeric report, namely, the Distance-Cost report, from the various reports that were generated during the FactoryFLOW analysis.

5.2.1.1 Distance-Cost Reports

The Distance-Cost report presents information about the total distance traveled by each part, sub-assembly or assembly between two stations, specifies the material-handling device used, and also reports the total material movement cost incurred by each part, sub-

assembly or assembly in a day. This report helps to find the cost of moving each material from one station to another. Table 5.1 represents a partial section for the Distance–Cost report for some of the materials in the case-study factory (refer to the Appendix E for the complete report).

Table 5.1: Partial Distance Cost Report
(Based on case study and FactoryFLOW analysis)

House	27" Overhead Assy	Station 4B	Station 4	Electric Hoist A	113.84	\$0.486
	Adapter	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.026
		Storage 15	Station 6A1	Hand Trolley	108.7	\$0.047
		Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.079
	Adapter Cleanout	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.005
	Adapter-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.393
	Adapter-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.026
	Adapter-C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.026
	Adapter-D	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.026
	Adapter-E	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.026
	Adapter-Swivel Trap	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.004
	Axle Brake	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.001
		Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.002
		Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.001
		Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.002
	Axle Idler	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.003
		Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.003
		Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.003
		Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.003
	Backsocket	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.001
		Storage 4B	Station 4B	Human	41.94	\$0.046
		Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.003
		Storage 4B	Station 4B	Human	41.94	\$0.096
		Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.001
		Storage 4B	Station 4B	Human	41.94	\$0.046
		Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.003
		Storage 4B	Station 4B	Human	41.94	\$0.096
		Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.001
		Storage 4B	Station 4B	Human	41.94	\$0.046
		Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.002
		Storage 4B	Station 4B	Human	41.94	\$0.071

The annual material movement related cost for the case-study factory was derived from the daily material movement cost given by the distance-cost report. This report came up with an annual cost figure that was later verified by the case-study factory

personnel, thus validating the soundness of the quantitative FactoryFLOW modeling of the facility layout. The process of validation is described in details in the later part of this chapter.

5.2.1.2 Distance Intensity Chart

The Distance-Intensity graph presented in figure 5.2, enables one to specify the distance traveled versus the intensity of trips for a particular part, assembly or sub-assembly, along with the material handling devices used. As already explained in chapter-IV, an optimal layout will have the points close to X and Y axes. Figure 5.3 presents the Distance-Intensity Chart for the case-study manufactured housing plant. The descriptions of the points marked in the figure 5.3 were viewed with the help of *Query Distance-Intensity* command.

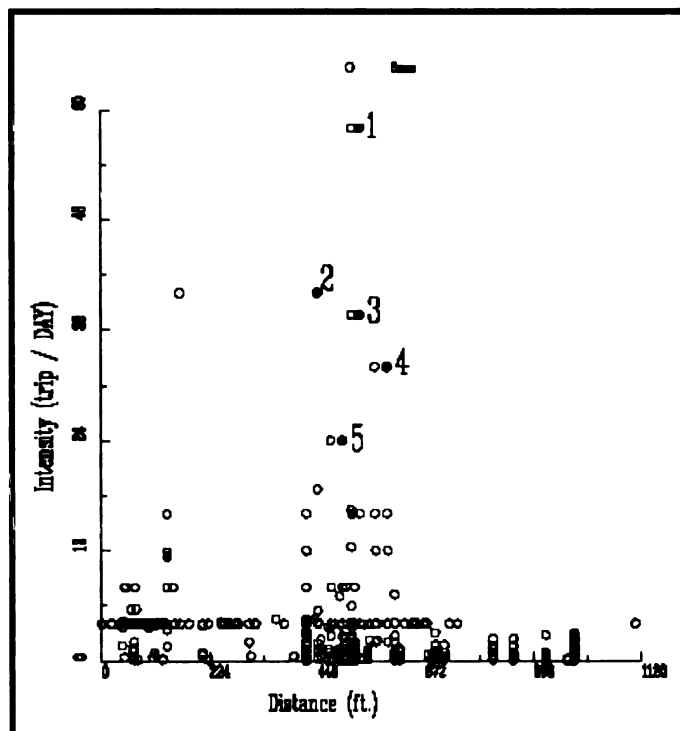


Figure 5.3: Distance Intensity Chart with the Critical Points
(Based on case study and FactoryFLOW analysis)

5.2.2 Analysis and Identification of Critical Factors in the Layout Design For the Case-Study Model

The Distance-Intensity charts and Distance-Cost reports provide information about the cost of moving materials, number of trips and the distance traveled. The next step is to analyze the reports and the charts in order to find ways to improve the facility layout by reducing cost, distance traveled or number of trips. In doing this, one has to evaluate and identify those material movements which, when revised either by changing the location of the stations or by changing the mode of traveling (e.g. material handling devices), can bring about a remarkable reduction in the total material movement cost or the total distance traveled. For this reason, the most costly material movement (from Distance Cost reports) or the movements having maximum number of frequencies (from Distance-Intensity charts) were selected to perform the “what-if” scenarios by developing the facility layout alternatives.

5.2.2.1 Critical Points in the Distance-Cost Report

The Distance-Cost report, for the existing facility layout of the case-study factory generated by FactoryFLOW was reviewed, and some of the most costly material movements were selected as the critical points. The details of the chosen critical material movements are provided in Table 5.2.

Table 5.2: Details of Material Movements selected for “What-If” Analysis from Distance-Cost Reports

The Material Movements Selected for the “What-If” Analysis

Point #	Part	From	To	Mat. Hand Equipment	Distance	Cost/Day
1	Sheathing Goldguard	Storage-16	Station-12	Hand Trolley	555.11 ft	\$28
2	Wire A & Wire B	Receiving Dock-5	Storage-15	Hand Trolley	853.77 ft	\$21
3	Lag	Storage-2D	Station-2B	Human	305.69 ft	\$17

5.2.2.2 Critical Points in the Distance Intensity Chart

As already explained in Chapter IV, the points representing the parts, assemblies and subassemblies, should always be closer to the X-axis or the Y-axis, for an optimized facility layout for a given manufactured housing plant (e.g. high intensity moves will have short travel distances, and long distance moves will be limited to moves with low intensity). According to this principle, in order to make the layout design more efficient, the five points highlighted in the Distance-Intensity chart in figure-5.3 were chosen, as they were distant from both the axes. The details of the selected points are given in table 5.3. After selecting the points, a “what-if” analysis was performed by developing facility layout alternatives or by changing the mode of material movement. Once the material flow was changed, the model was again analyzed in FactoryFLOW, and Distance-Intensity Charts and Distance-Cost Reports for each alternatives, were generated for analysis. The results of the analysis are explained in the following section.

Table 5.3: Details of Material Movements selected for “What-If” Analysis from Distance-Intensity Charts

Query Distance Intensity Information For The Critical Points

S. No	Part	Part Routing		Material Handling Device	Travel Distance	Intensity (# of trips/day)
		From	To			
1	Shingles	Storage-16	Station-11	Human	536 ft	58
2	Novodeck 96x168	Receiving Dock-1	Storage-2C	Fork Lift Ingersollrand	448.08 ft	40
3	SGL Underlayment	Storage-16	Station-11	Human	536.11 ft	37.6
4	Ceiling Light	Storage-22	Station-32	Human	592.28 ft	32
5	Door	Storage-28	Station-30	Human	499.79 ft	24

5.3 Generation of Alternatives Based on “What-If” Scenario for the Case-Study

Plant

Once the critical points were identified from the charts and reports in the earlier section “what-if” scenarios were developed in the FactoryFLOW model, either by changing the location of the stations or by changing the material handling device, with an aim to reduce the distance, cost and frequency of trips. The alternatives thus developed were re-evaluated in FactoryFLOW, and the reports generated were compared to see the effect of the changes.

5.3.1 Alternatives Based on Distance/Cost Reports

The costliest material movements were identified as the critical points (refer table 5.x), and various “what-if” scenarios were developed and evaluated in FactoryFLOW. The scenarios and their outcome are developed and analyzed in the following section.

Scenario 1

Scenario-1 is based on the quantitative model of the existing layout of the case-study factory. The other layout scenarios were developed based on the output of Distance-Cost Reports generated in scenario-1.

Scenario 2

This alternative was based on the critical point-1 identified from the Distance-Cost Report (refer to table 5.2). It showed that the daily cost of moving the part *Sheathing-Goldguard* (for External Finish Assemblies) by using *Hand Trolley* as the material handling equipment, from *Storage-16* to *Station 12* was \$28. In the second alternative, the material handling equipment *Hand Trolley* was replaced by *Hand Trolley (Large)*, which carried 2400 units per trip instead of 1200, and thus reduced the number of trips. When the distance-cost report for the second alternative was generated it presented a yearly cost savings of 4.9% (refer to Table 5.5). However, in suggesting this alternative, it was assumed that a single equipment *Hand Trolley* was replaced by the new *Hand Trolley (Large)*, and the cost incurred for keeping the older unit was not taken into consideration.

Scenario 3

This alternative was also based on the critical point-2 identified from the Distance-Cost Report (refer to table 5.2). It was noted that the components *Wire-A* and *Wire-B* traveled a total distance of 854 feet daily from *Receiving Dock-5* to *Storage-15*. The layout of the factory was altered in this alternative by shifting the position of the *Receiving Dock 5* (refer to figure 5.4). The Distance-Cost report for the scenario-3 was generated, and it was found the travel distance was reduced by 142 feet for the parts, *Wire-A* and *Wire B*.

Moreover, the reports also showed that the total travel distance for all materials was approximately reduced by 95,000 feet per day. Table 5.5 shows that there would be an annual cost-savings of 5% if this change was incorporated, along with the change suggested in the scenario-2.

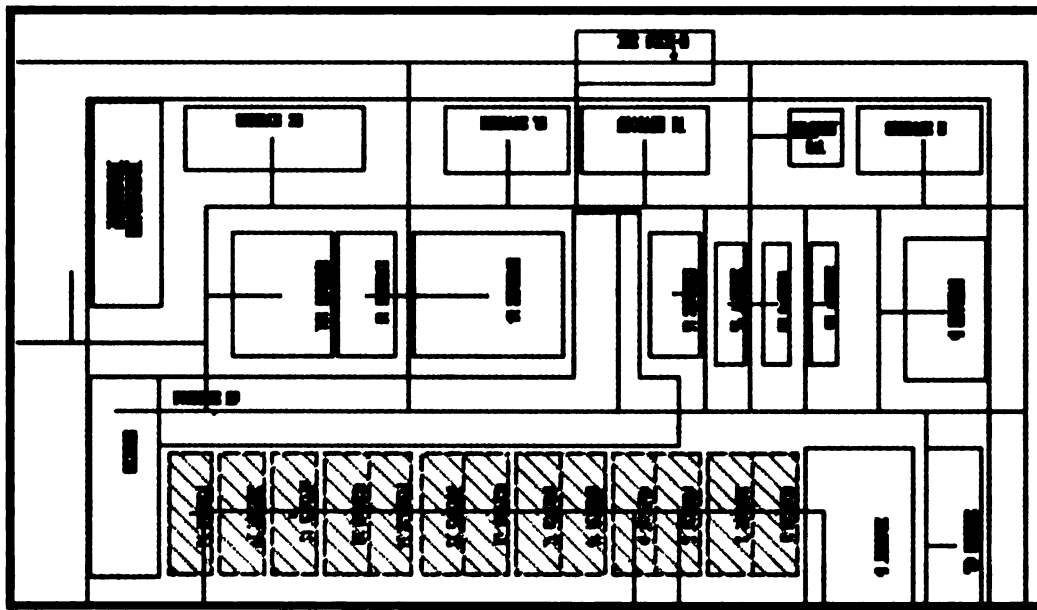


Figure 5.4: Partial Layout of Factory-1 Showing Layout Change in Alternative Developed in Scenario-3

Scenario 4

Scenario 4 was a modification of scenario 3 (based on the critical point 2 in table 5.2) where the material handling equipments for carrying the parts *Wire-A* and *Wire B* from the *Storage-15* to the *Station-6A1* were changed from *Human* to *Hand Trolley (Large)*. A cumulative annual savings of 11.4% was recorded (refer to Table 5.5). However, if the revision done in scenario-4 is done without the change marked in scenario-3, there will be an annual cost savings of only 3%.

Scenario 5

The critical point-3 in table 5.2 was the movement of the part *Lag* from *Storage-2D* to *Station 2B* (for the Floor Assembly) by human and the daily cost of the movement is \$8.00 and the distance traveled was around 305 ft per day. The *human* was replaced by *Electric Hoist* and the reports were generated. It was noted that there is an increase by 20% in the annual material movement cost, however the total distance traveled has been reduced significantly (refer to table-5.4). From this report, it can be easily concluded that, though the travel distance was reduced, the cost of the *Electric Hoist* was greater than the savings achieved by reducing the travel distance. However, in order to see whether any cost savings can be achieved by changing the material handling device that is being used for carrying the part *Lag*, a “what if” scenario was performed by using the various material handling equipments available in the plant. The results of the “what if” scenario analysis are provided in Table-5.4. As evident from the results, the existing system of carrying the *Lag* with *Human* works out to be the cheapest.

Table 5.4: Comparison Chart for the Results “What-If” Scenarios of Part-Lag Based on Distance-Cost Reports

"What-If" Analysis with Various Material Handling Equipment

Part	From	To	Mat. Hand Equipment	Cost/Day
Lag	Storage-2D	Station-2B	Human	\$17
	Storage-2D	Station-2B	Electric Hoist	\$24
	Storage-2D	Station-2B	Hand Trolley	\$20
	Storage-2D	Station-2B	Fork lift	\$21

5.3.2 Alternatives Based on Distance-Intensity Charts

The scenarios based on the critical points identified in table 5.3 from the Distance-Intensity charts, were developed, and analyzed in FactoryFLOW. The Distance-Intensity chart for each option was generated, compared and analyzed. The objective during this analysis was to move the critical points closer to X-axis or Y-axis, or both. This implied that the movements had either reduced distance (if moved towards X axis) or reduced number of trips (if moved towards Y axis).

Scenario 6

The movement of the part *Shingles* from *Storage-16* to *Station-11*, was identified as the critical point-1 (refer to figure 5.3 and table 5.3) as the number of trips as well as the distance between the stations traveled were higher. In this case, the material handling device *Human* was replaced by *Hand Trolley (large)*, and the number of parts handled per trip was increased from 20 to 80. FactoryFLOW evaluated the scenario, and provided the new Distance-Intensity chart (refer to figure 5.5), where the new position of point 2 is nearer to the Y-axis. The point was queried through the *Query-Distance command* in FactoryFLOW, and the report showed that the number of trips was reduced to 15 trips (refer to Table 5.6) from 58 trips.

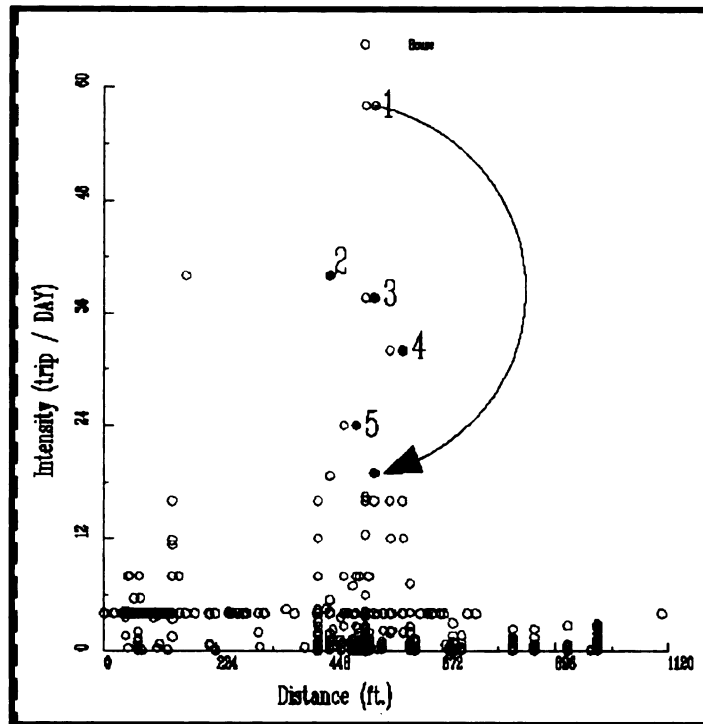


Figure 5.5: Distance –Intensity Chart for Scenario-6

Scenario 7

Scenario-7 was developed on the basis of the critical point-2 identified from figure 5.3. This point represented the movement of *Novodeck-96x128* from *Receiving Dock-1* to *Storage-2C*. In this scenario the routing of the part was changed instead of changing the material handling equipment. The author observed that in the layout, *Receiving dock -2* is nearer to the *Storage-2C* (refer to Figure 5.1). So the part routing was changed from *Receiving dock -1* to *Receiving dock -2*. The distance-Intensity report for the revised layout showed that point-2 has moved towards the X axis (refer to Figure 5.6), and detailed query confirmed that the travel-distance has reduced to 128.8 feet from the earlier 448.08 feet (refer to Table 5.6).

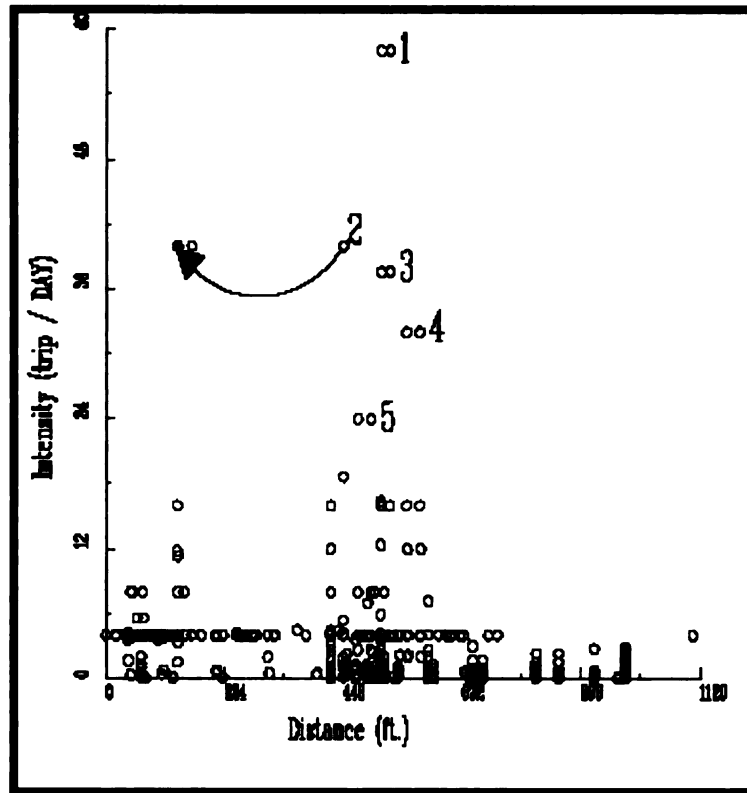


Figure 5.6: Distance –Intensity Chart for Scenario-7

Scenario 8

Similarly scenario-8 was developed on the critical-point-3 (in Figure 5.3), where *SGL Underlayment* traveled from *Storage-16* to *Station-11* by *Human*. In this case, the material handling device, viz. *Human*, was changed to the *Hand Trolley(large)* and the parts carried in each trip were increased from 200 to 600. The Distance-Intensity chart developed for this scenario showed that point-3 has moved towards the Y-axis, and detailed report indicated that the number of trips was reduced to 12.5 per day (refer to Figure 5.7).

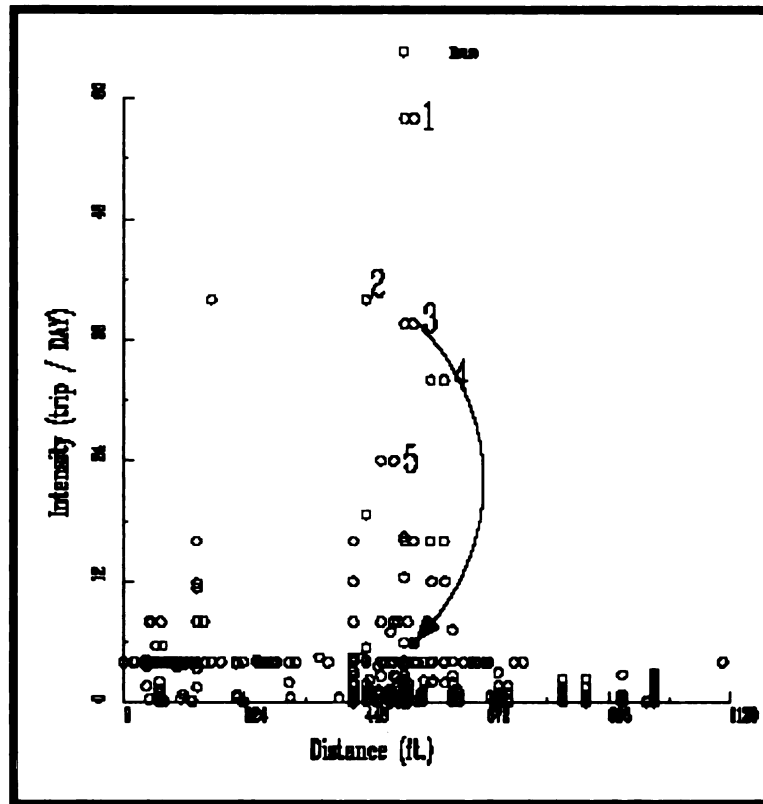


Figure 5.7: Distance –Intensity Chart for Scenario-8

Scenario 9

Scenario-9 was developed on the basis of the critical point-4 identified from the figure 5.3. This point represented the movement of *Ceiling Light* from *Storage-22* to *Station-32*. In this scenario, similar to scenario-7, the routing of the part was changed instead of changing the material handling equipment. The author observed that in the layout, *Storage-25* is nearer to *Station-32* (refer to Figure 5.1). So the part routing was changed from *Storage-22* to *Storage-25*. The Distance-Intensity report for the revised layout showed that point-4 has moved towards the X-axis (refer to Figure 5.8), and detailed query confirmed that the travel-distance has reduced to 25 feet from 592.28 feet (refer to Table 5.6).

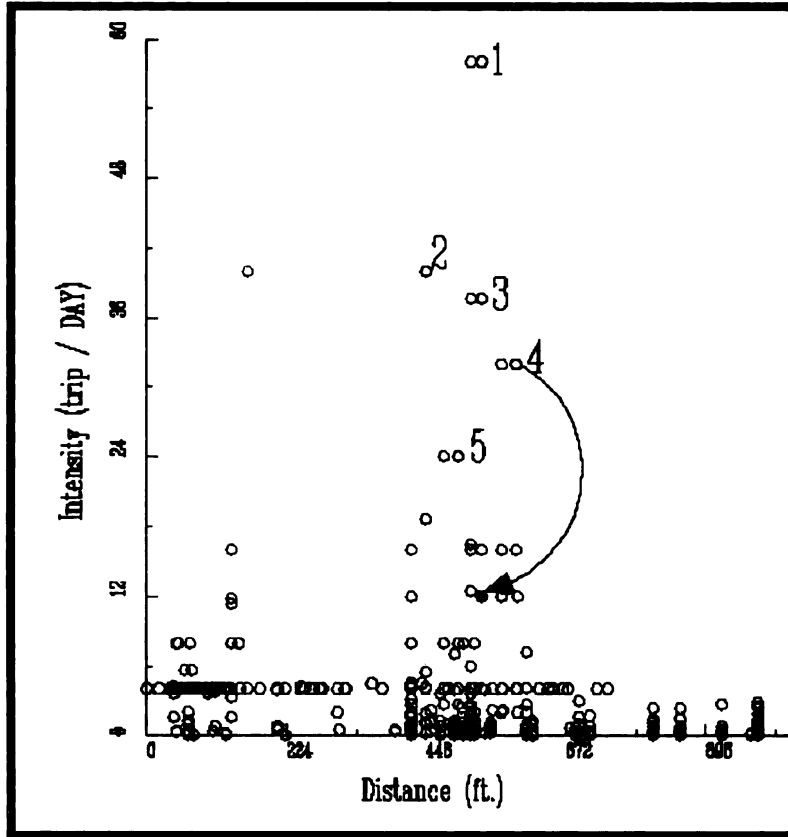


Figure 5.8: Distance –Intensity Chart for Scenario-9

Scenario 10

Scenario-10 was developed on the critical-point-5 (in Figure 5.3), where *Door* travel from *Storage-28* to *Station-30* was by *Human*. In this case, the material-handling device e.g. *Human* was changed to the *Hand Trolley (large)* and the parts carried in each trip was increased from 1 to 2. The Distance-Intensity Chart developed for this scenario showed that the point-5 has moved towards the Y-axis, and the detailed report indicated that the number of trips were reduced to 12 trips per day from 24 trips per day (refer to Figure 5.9).

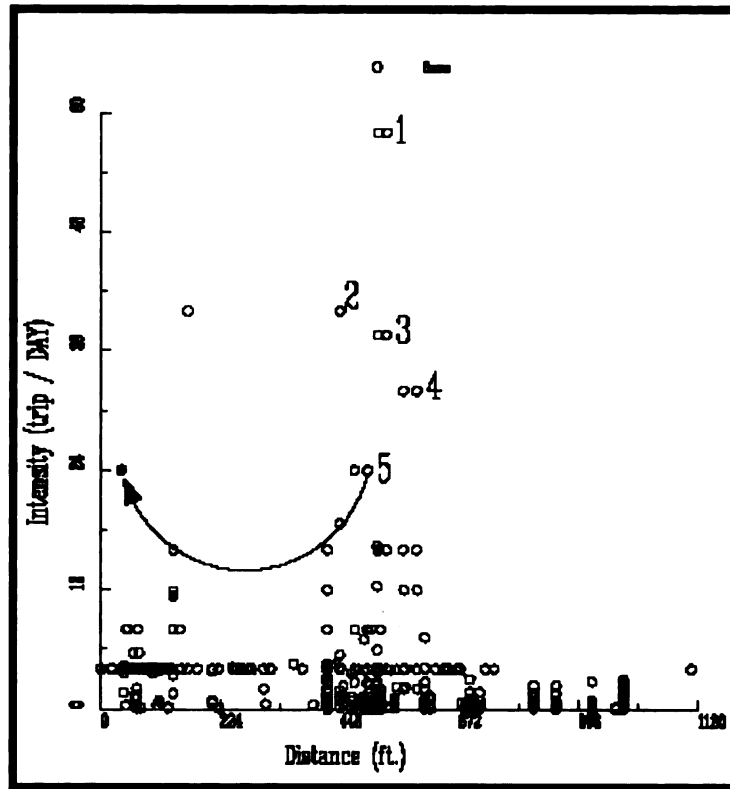


Figure 5.9: Distance –Intensity Chart for Scenario-10

5.3.3 Comparison & Analysis Of The Alternatives

In this section the results of the “what-if” analysis are presented, and the differences in total cost and the total distance traveled are noted, compared and analyzed. The subsequent FactoryFLOW analysis for the proposed layout alternatives in most of the cases showed substantial reduction in the material movement cost (refer to Table 5.5), travel distance and the frequency of the trips between the stations (refer to Table 5.6).

Most of the scenarios, prepared on the basis of the critical points identified from the Distance-Cost reports showed remarkable cost-savings (refer to Table 5.5). Table 5.5 presents both the individual and cumulative cost-savings of the individual scenarios

(Scenario 1-5). However, in scenario-5 the result was not favorable from a cost-savings perspective. This result can be treated as a sort of eye-opener for a designer in realizing that the most obvious option for cost-savings does not always work in a particular way. There are several factors that contribute to the material movement cost incurred within a manufactured housing plant. Reducing the total distance can save time, but it does not necessarily mean that it will save money too. The analysis in software is useful in these cases, where the designers can try each and every “*Apparently Cost-Saving*” option to find whether they are truly cost-saving or not. The judgment and experience-based knowledge of the design team while evaluating the layout alternatives are also crucial during the time of the analysis.

Similarly, the analysis based on the Distance-Intensity charts generated for the scenarios 6 to 10, clearly outlined the process of fine-tuning the basic layout for a new or existing manufactured housing plant by changing part routes, station locations or the material handling devices. However, once the distance-versus-trips analysis is done and the favorable options are selected, they should be further evaluated through the cost reports to see the effect of the changes on the total material flow cost. Due to the limited thesis scope, this exercise was not performed by the author.

The two cases of material movement analysis, one cost based and another distance-trip based, provide the planners with the flexibility to plan the facility layout of a manufactured housing plant according to the resources available. For the manufactured housing plant (new or existing) where the available finance is the main constraint, the designers can fine-tune the layout by selecting each of the cost-incurring movements, perform “what-if” and analyze the results in FactoryFLOW, and suggest the selected

revisions and implement the changes in the layout. Sometimes, the availability of space or site-layout is a major concern. In such cases, the designers should opt for the Distance-Intensity chart-based alternatives, which highlight the distance traveled versus the frequency of trips. Ideally, both the form of analysis should be used to find out how the cost-savings option matches with the distance-trip-saving option, and the optimum alternative should be selected.

Table 5.5: Comparison Chart For The Results “What-If” Scenarios Based On Distance-Cost Reports

Results of “What-If” Scenarios Based on Distance-Cost Report

Scenario	Distance travelled per day (in feet)		Cost/Day		Cost/year		Total Savings Based on Scenario		% \$ Savings Based on Scenario	
	Cumulative	Separate	Cumulative	Separate	Cumulative	Separate	Cumulative	Separate	Cumulative	Separate
1-exist'g	589,320	-	\$124.8	-	\$259,602	-	-	-	-	-
2 (pt-1)	588,763	588,763	\$118.6	\$118.6	\$246,779	\$246,779	\$12,823	\$12,823	4.9%	4.9%
3 (pt-2)	494,430	495,678	\$112.2	\$118.8	\$233,426	\$247,085	\$26,177	\$12,517	10.1%	5%
4 (pt-2)	493,429	498,207	\$110.6	\$120.7	\$229,952	\$251,149	\$29,650	\$8,453	11.4%	3%
5 (pt-3)	493,318	493,458	\$134.0	\$149.8	\$278,808	\$311,584	-\$19,205	-\$51,982	-7.8%	-20%

Table 5.6: Comparison Chart for the Results Of “What-If” Scenarios Based On Distance-Intensity Charts

Scenario	Parts	Material Handling Devised		Part Routing		Distance between Stations traveled (ft)		% Reduction		# of Frequency of Trips		% Reduction
		Original	Proposed	Original	Proposed	Original	Proposed	%	%	Original	Proposed	
6 (pt-1)	Shingles	Human	Hand Trolley large	Storage-16 to Station-11	-	536	-	-	-	58	15	74%
7 (pt-2)	Navadeck 96x168	Fork Lift Ingersollrand	-	Rec Dock-1 to Storage-2C	Rec Dock-2 to Storage-2C	448.08	128.8	71%	-	40	-	-
8 (pt-3)	SGL - Underlarm	Human	Hand Trolley large	Storage-16 to Station-11	-	536.11	-	-	-	37.6	12.5	67%
9 (pt-4)	Ceiling Light	Human	-	Storage-22 to Station-32	Storage-25 to Station-32	592.28	25	96%	-	32	-	-
10 (pt-5)	Door	Human	Hand Trolley large	Storage-28 to Station-30	-	499.79	-	-	-	24	12	50%

5.4 Quantitative Analysis of the Various Layout Design Alternatives Based on the Case-Study Used for Earlier Qualitative Layout Analysis

The earlier researches on production process (*Production And Material Flow Process Model For Manufactured Housing* by Senghore 2001); and facility layout design of a manufactured housing plant (*Manufactured Housing Production Plant-Layout Design Process* by Mehrotra 2002) were based on the data collected from the same case study plants. The author in this research has developed the quantitative model of the case-study factory based on the production process and facility layout design of the earlier research works. However, the author, due to the limited scope of this thesis was unable to collect the required information about the product design, aisle network layout of the plant and the material handling system design in the case-study plant used during the earlier researches. The following part of this section explains the methodology as well as the assumptions that were made while developing the quantitative model for the facility layout system of the case-study plant used in previous research works. Moreover, the concluding part of this section presents the quantitative analysis reports and comparative evaluations of the five different layout patterns, namely, S-shaped, Z-shaped, L-shaped, U-shaped and Straight line, which were qualitatively evaluated in the earlier developmental research work for a given case-study plant (Mehrotra 2002).

5.4.1 Developing The Quantitative Model

The following steps were followed during the quantitative modeling of the facility layout for the case-study home manufacturing plant in the earlier research works. For the convenience of the readers, the author from this point onward will refer to the case-study of the earlier researches as case-study A.

5.4.1.1 Defining the Product Structure of the House Produced in the Case-Study A Plant

Owing to the limited scope of the thesis, the author was unable to collect detailed information about the houses that were produced in the case-study-A factory. However, based on the understanding of the earlier researches and author's knowledge about the components and assemblies that are generally used to produce a typical double-section manufactured house and the typical design of the floor plans, it was assumed that the product structure was more or less similar to the product that is produced in the factory that the author used as the case study. Given this assumption, for the purpose of modeling, the product tree structure and the product volume information formats developed in Chapter IV (also refer to Appendix-B) were used.

The production numbers, i.e. the number and the type of houses produced per day were based on the information provided by Senghore in his research work on production process modeling (Senghore 2001). According to the information provided in the thesis, case-study A produced approximately 600 to 625 homes per year, i.e. 6 houses per day. As a result, during the modeling process in this thesis, the production number was specified as six units per day.

5.4.1.2 Understanding the production process in the Case-Study A

The production process in the case-study A is defined in the figure 5.10. It represents a typical manufactured house production process in the plant with major clusters like the floor cluster, wall cluster, roof cluster, exterior cluster, and the finishes cluster. Table 5.6 provides a detailed list of the stations in each cluster and the activities performed in each cluster. As shown in the production process model in figure 5.10, the assembly line in a

manufactured housing production plant consists of many different types of stations. Not all the stations on or beside the assembly line in a production plant conform to one standard or are of one particular type. The stations can be classified into main assembly stations, sub-assembly stations, feeder stations, and internal and external storage areas (refer to Chapter-II), based on the type of activity taking place at that station/area.

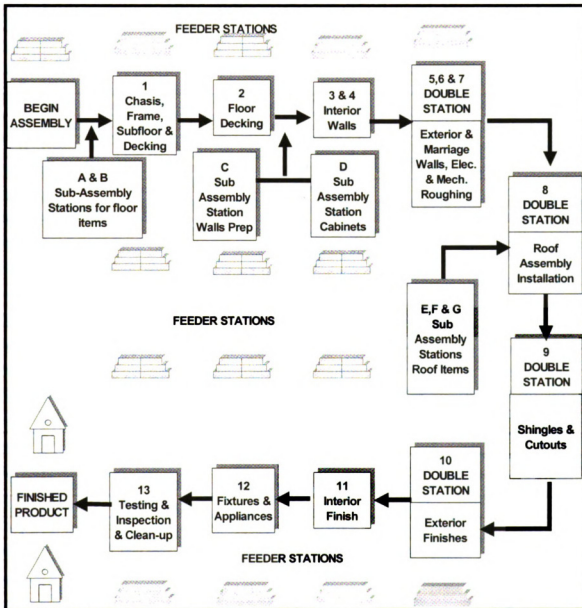


Figure 5.10: Manufactured Housing Production Process
(Mehrotra et al 2003)

Table 5.7: List of the Main Assembly, Sub-Assembly and Feeder Stations
(Activity Points)
(Mehrotra et al 2003)

No.	Description of Stations
I-Main assembly stations	
1	Chassis on wheel and axle pulled into the factory.
2	Place assembled floor frame with insulation, ductwork and wiring over the chassis
3	Placement of interior walls (studs with panel on one side only),
4	Placement of cabinets, toilet compartment, bathtub, kitchen sink.
5	Placement of exterior walls
6	Rough electrical and mechanical, and final exterior walls installation
7	Installation of all electrical and mechanical equipment
8	Roof installation
9	Installation of shingles on the roof and cut outs for doors and windows
10	Exterior wall finishes and installation of side shingles. Installation of door& windows,
11	Begin interior finishes- install foam for carpeting, complete interior drywall finish
12	Install carpet, final electrical and plumbing finishes, install marriage walls.
13	Interior Finishes and Cleanup, Testing & Inspection
II-Sub-assembly stations	
A	Fabrication and storage of ductwork and plumbing, and placement of tires.
B	Assemble floor frame- place black sheet, place insulation, place floor joist, place wire and duct work, staple black sheet to the floor joist
C	Sub-assembly of interior walls
D	Assembly of cabinets, kitchen, and toilet sinks
E	Sub-assembly station for roofing main activity stations.
F	Fabrication of roof truss, installation of ceiling board, painting, drying and finishing
G	Installation of loose and rigid insulation
III-Feeder stations	
a	Storage of ductwork and plumbing pipes
b	Storage of cabinets
c	Storage of drywall panels
d	Storage of drywall, doors and windows, and sheathing.
e	Storage of roof shingles
f	Storage of foam and carpet and drywall (marriage)
g	Storage of wall boards and tools
h	Storage of mirror, and appliances.
i	Storage of drapes and appliances.
j	Storage of toilets and materials to be shipped to the site for onsite installation
k	Storage of drywall panels and wooden members for roof frame fabrication

5.4.1.3 Preparing the layout Design in AutoCAD and Identifying the

Stations (Activity Points) in the Case-Study A

The layout design prepared in AutoCAD in the previous research (Mehrotra 2002) was used as the basic layout and modified for the purpose of the quantitative modeling. The activity points or the stations described in Table 5.7 were added to the layout drawing.

Figure 5.11 presents the existing layout of the case-study A plant.

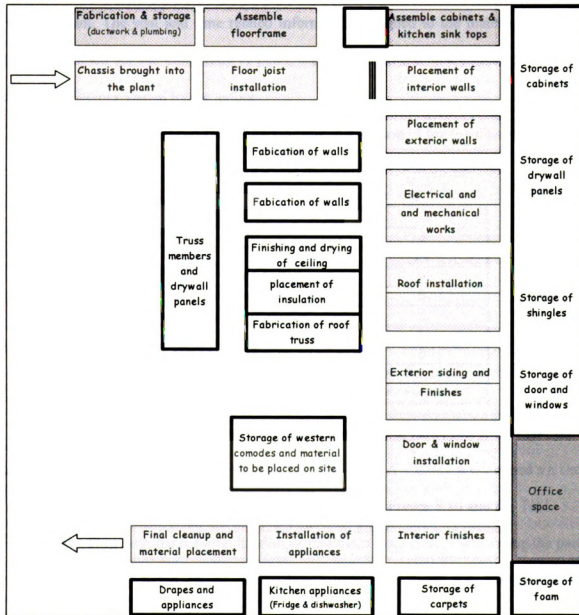


Figure 5.11: Existing Layout for Case-Study A Plant
(Modified from Mehrotra 2003)

5.4.1.4 *Defining the Material Handling System Design in the Case-Study A Plant*

Once again, due to limitations in scope of this thesis, the author had to assign a material handling system based on the existing literature and personal understanding of the material movement process within a manufactured housing plant. Table 5.8 presents the list of the material handling equipments which are typically used in a manufactured housing plant. The cost and time related information assigned to the material handling system assumed for the case-study A plant, were based on the data collected from the case-study factory visited by the author.

Table 5.8: List Of Material Handling Equipments Assumed for the Case-Study A Plant
(Based on the case study)

List of Material Handling Equipments used:

	Description	Quantity
1	3 ton Electric Hoist	3
2	2 ton Electric Hoist	24
3	6000lb Capacity Fork Lift Type 1	6
4	5000 lb Capacity Fork Lift Type 2	8
5	Hydraulic Pumps	5
6	Hand Trolleys Type A	6
7	Hand Trolleys Type B	8
8	Pellets Type A	As Required
9	Pellets Type B	As Required

Moreover, the part routing charts developed for the parts, assemblies and sub-assemblies of the houses manufactured in the case-study A factory were based on the production process and the list of the stations presented in Figure 5.10 and the Table 5.7 respectively. However, the material handling equipments described in developing the part routing charts were based on the information presented in Table 5.8. The procedure

adopted for developing these charts was similar to the methodology presented in Chapter IV.

5.4.1.5 Data Input & Quantitative Modeling in FactoryFLOW

The quantitative facility layout model of case-study A was developed in a manner similar to the facility layout of the present case-study factory. The detailed steps for formulating the quantitative model is explained in Chapter IV. After developing the complete model, FactoryFLOW analysis was done, flow calculations were performed and the Distance-Cost Reports for the existing facility layout for case-study A were generated.

5.4.2 Assumptions Made for Quantitative Modeling of the Facility Layout of Case-Study A

As explained earlier, due to the unavailability of certain information, the following assumptions were made during the FactoryFLOW modeling and analysis of the facility layout for the case-study A manufactured housing plant.

1. The production process for producing the manufactured house described in the model was based on the production processes described in case study A during the earlier researches (Senghore 2001, Mehrotra 2002).
2. Due to the lack of sufficient information about the houses manufactured in case-study A, product structure and the product tree structure were assumed to be similar to the products of the manufactured housing factory visited by the author. Moreover, the parts per volume and part routing information were also considered similar to the case-study plant.
3. The production volume quantity was based on the earlier research on manufactured housing production process (Senghore 2001).

4. The material handling system design and the use of the material handling devices were considered to be almost similar to the case-study factory visited by the author.
5. Cost and time data associated with the material handling equipments assigned for the case-study A plant were assumed to be similar to the manufactured housing plant visited by the author.
6. During the modeling, the aisle network system for the case-study A factory could not be developed owing to the lack of information. As a result, actual aisle distances between the stations were not considered. Moreover, for the flow-path calculations during FactoryFLOW analysis the Euclidean distance was considered. Therefore, the actual distances for the material movement between the stations were not considered during the quantitative analysis of the facility layout alternatives for the case-study A manufactured housing plant. Once the actual aisle networks and routes are considered, the total cost for the material movement may vary as the distances traveled by the material handling devices will vary.

5.4.3 Analyzing Layout Design Alternatives Developed for Qualitative Analysis in the Earlier Research Work

In the research paper *Manufactured Housing Production Plant - Layout Design Process* the author prepared the relationship charts (as described in Chapter IV), developed five alternative facility layout patterns for the case-study A plant, and evaluated them qualitatively in the FactoryPLAN software. Figure 5.12 presents the alternative layout patterns explored. The results of the qualitative analysis of the five layout patterns

mentioned above, are presented in Table 5.9 and the interpretation of the scores mentioned in the table are explained in the following paragraph.

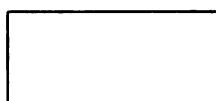
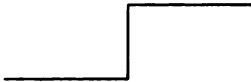
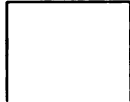
Nos.	Name	Pattern
1	Straight-line layout	
2	L Shaped layout	
3	Z Shaped layout	
4	U Shaped layout	
5	S Shaped layout	

Figure 5.12: Alternative Layout Patterns
(Modified from Mehrotra 2002)

Table 5.9: Effectiveness Scores for Layout Alternatives of Case-Study A Plant
(Modified from Mehrotra 2002)

Straight-line layout	351612	870	78.6	1320	67.5
L - Shaped layout	309125	940	76.8	1480	63.5
Z - Shaped layout	258139	800	80.3	1320	67
U - Shaped layout	279823	500	87.7	1170	71.2
S - Shaped layout	258608	420	89.7	810	80

Interpretation and Analysis of the Proximity Scores for the Case-Study A Plant

FactoryPLAN provided the effectiveness score of each layout pattern based on the input data including the specified relationships. The scores of the layout alternatives (Table 5.9) were evaluated based on the following calculations (EAI 1999).

- The Weighted column in Table 5.9 shows the layout score, which is the sum of the relationship line values, each of which is computed using the formula:

$$\text{Length} \times \text{Weight}$$

Where

Length= length of the relationship line

Weight= relationship weight for the level of relationship

- The E-Score column in Table 5.9 shows the sum of the relationship weight values of those relationships whose Euclidian distance (the length of a single segment line directly connecting the station point locations) falls outside the specified maximum/minimum distance values. The best possible score is “0”, (i.e., all relationship distances fall within the respective maximum/minimum distance values).
- The E% Score column in Table 5.9 shows the layout’s percent of optimal quality, when all relationships would fall within respective maximum/minimum distance values. An E% Score of 100 would correspond to an E-Score of 0.
- R-Score and R% Score are similar to E-Score and E% Score, with the exception that relationship line length is calculated as rectilinear distance (the length of a two-segment line, one segment horizontal, one segment vertical) between the workcenters.

The analysis for selection of the best layout was based on all the scores defined in Table 5.9. The “S” shaped layout was identified as the best layout as it has the highest E% score.

Based on the facility layout patterns explored for the qualitative evaluation of the layout design for the case-study A plant, and the quantitative model developed in FactoryFLOW, the quantitative analysis for each pattern was performed. The results and analysis are described in the next of this section. The following figures (figure 5.13 to figure 5.17) represent the *Material Flow Diagram (Euclidian)* for each of the alternative layout pattern.

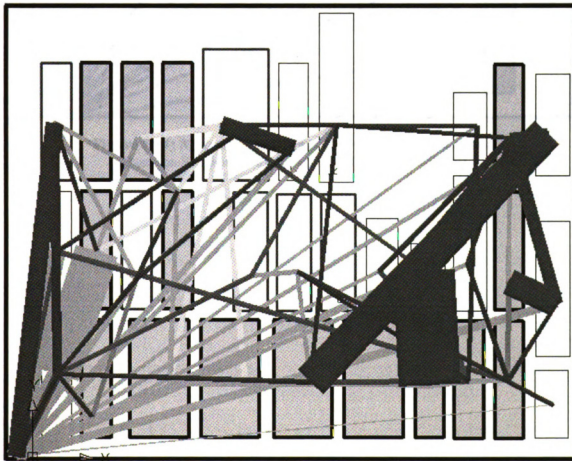


Figure 5.13: Material Flow Diagram for S-Shaped Layout
(Based on Senghore 2001, Mehrotra 2002 and Case-Study)

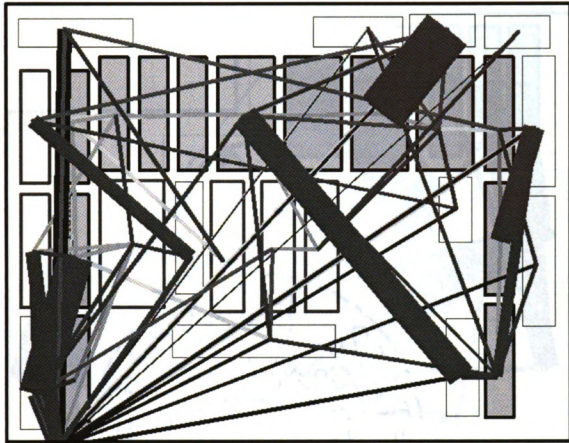


Figure 5.14: Material Flow Diagram for U-Shaped Layout
(Based on Senghore 2001, Mehrotra 2002 and Case-Study)

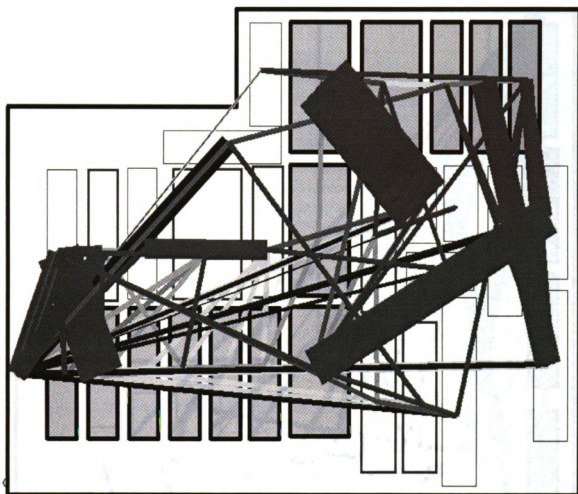


Figure 5.15: Material Flow Diagram for Z-Shaped Layout
(Based on Senghore 2001, Mehrotra 2002 and Case-Study)

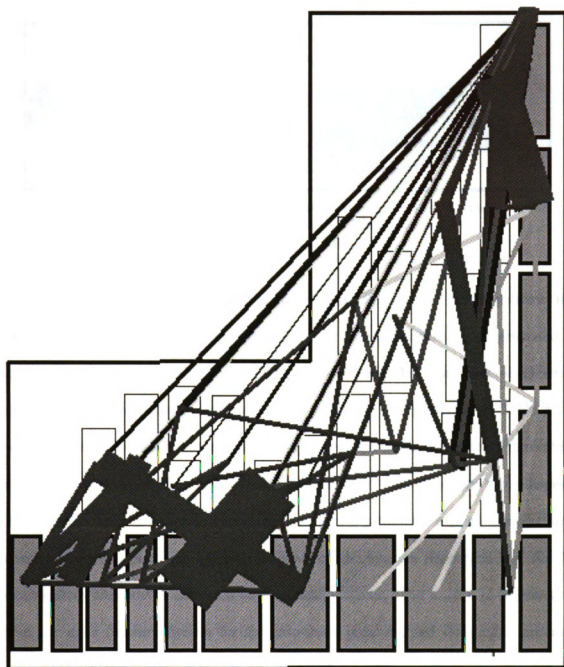


Figure 5.16: Material Flow Diagram for L-Shaped Layout
(Based on Senghore 2001, Mehrotra 2002 and Case-Study)

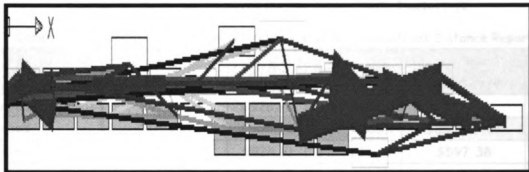


Figure 5.17: Material Flow Diagram for Straight Line Layout
(Based on Senghore 2001, Mehrotra 2002 and Case-Study-)

5.4.4 Comparison of the results

Based on the Euclidian material flow path calculations in the above layout patterns, the Distance-cost report for each layout was generated. Once the reports were generated, a comparative analysis between the distance traveled and the total cost of material movement for the various layout designs was performed and presented in Table 5.10. From the table, it is clear that the S-shaped layout has the minimum material movement cost, while the Straight line Layout incurs the maximum cost. Based on the efficiency scores and the material movement cost, the basic layout pattern for a given manufactured housing production plant can be chosen. However, the material movement cost for the layout pattern alternatives are based on Euclidean distances (due to lack of information about the *Aisle Network System* for the case-study plant-A), and for a more accurate analysis the actual distance based material-flow cost should be considered.

Table 5.10: Comparison Table for the Material Movement Cost of the Various Layout Pattern Alternatives for the Case-Study Factory-A

Comparison Chart For Various Layout Alternatives Based on Moves Distance Report

Layout Pattern	Distance travelled per day (ft)	Cost/Day	Cost/year	Savings Based on Existing Layout	% savings
U-Shaped (existing)	281,633	\$926.98	\$192,810.84		
S-Shaped	216,159	\$806.35	\$167,720.47	\$25,090.37	13.0%
L-Shaped	244,065	\$924.10	\$192,213.47	\$597.38	0.3%
Straight Line	439,625	\$927.48	\$192,914.84	-\$104.00	-0.1%
Z-Shaped	202,075	\$880.50	\$183,144.00	\$9,666.84	5.0%

5.5 Input from Industry and Professional Designers

Once the FactoryFLOW quantitatively evaluated the layout alternatives and the results were compared, the next step was to prepare a recommended sequence of process steps as an outcome of this complete analytical exercise of preparing quantitative models of facility layout design and analyzing them. The recommended sequence of process steps were based on the results of analysis, and this presented a comprehensive methodology that needs to be followed by the decision-makers while designing the facility layout for a given manufactured housing plant. Once the preliminary process steps were developed the input from industry personnel and professional practitioners were solicited. Based on the feedback received, the author developed the final process steps.

5.5.1 Validating the Scenarios and Layouts by Construction Plant

Managers

Initially the author presented the comprehensive quantitative model developed based on the case-study factory to the factory personnel. Prior to the model, the plant managers had very little awareness about the material flow within the stations and the cost incurred due to the movement within the plant. The quantitative facility model that was generated helped the managers to identify the problem areas. The plant managers also provided the

author with information on the annual material movement cost for the case-study plant and it varied between \$200,000-\$ 270,000. The model developed in FactoryFLOW also calculated the similar cost of material movement of \$259,000 and hence the model was validated.

Once the alternatives were developed and evaluated, the author developed a preliminary process steps, based on the results, to outline the complete procedure of facility layout analysis. The process steps were also discussed with the plant managers and their suggestions were incorporated into the final process steps. The industry personnel agreed with the overall proposed process steps.

5.5.2 Evaluating The Scenarios, Layouts and Process Steps by Professional Design Consultants

Professional facility designers were consulted and their opinions for the proposed comprehensive process steps were also solicited. These professionals are primarily design consultants for “Mobile Home Factories” that are used for large home-developing complexes. The consultants expressed their agreement with the overall process steps and also the content proposed in this thesis. The suggestions from the consultants are listed below, and some of them were incorporated in the final process steps. (For the detailed review, please refer to the Appendix-F.)

- The proposed process steps were very comprehensive and addressed the facility layout evaluation problem for a manufactured housing facility, in the most rational sequence.

- As a tool for use by a profit-oriented entity (house manufacturing industry), the analysis process steps must present some kind of conclusion to decision makers (e.g how to reach the final goal).
- Adequate product definition is essential (e.g. kind of house to be manufactured), to be able to maximize the accuracy of the evaluation of the facility layout alternatives for a given manufactured housing plant. Maintaining a database for the products, and production processes can also be very useful for this purpose.
- The output reports and tables should be tied to the process steps, while defining and presenting the various process steps in the proposed methodology, in order to make the process steps more comprehensive to the user.

5.6 Recommended sequence of Process Steps for Facility Layout Design of Manufactured Housing Facilities (Quantitative Approach)

This research is a part of the second phase of the National Science Foundation (NSF) funded project, named, *Manufactured Housing Production Process Analysis and Facility Layout*. As a part of the later phase of the process for the Phase II, the author visited several manufactured housing production plants and found that the industry did not follow a systematic process for plant layout. Even though an exploratory research work has been done in the field of facility layout design of the manufactured housing production plant, it only considered the qualitative analysis of the facility layout. As a result, one of the objectives of the present research work was to prepare comprehensive process steps for evaluating the layout alternatives and select the optimal layout design. These process steps will guide the manufacturers through a series of steps or procedures

to either evaluate new layouts designs or to improve existing layouts. A basic *Process Flow Diagram* method was adopted for the presenting the sequential process steps for the layout design alternatives evaluation of a manufactured housing production plant.

5.6.1 Process Flow Diagram

The Process Flow Diagram is a structured chart diagram that illustrates the organization of stepwise procedures to perform a certain task. By developing a pre-specified model of a process, the process becomes repeatable, manageable, measurable, and less likely to be forgotten. The diagram is useful as it represents the processes in an explanatory visual format and is primarily used for developing software process models. The process flow diagram can be developed into two formats, namely, Milestone Process Model and prototypes (GATECH 2003).

This Milestone Process Model helps to split the activities/methods into several process phases in a milestone format, required to achieve the defined goal. Figure 5.18 illustrates an example of the basic milestone process model.

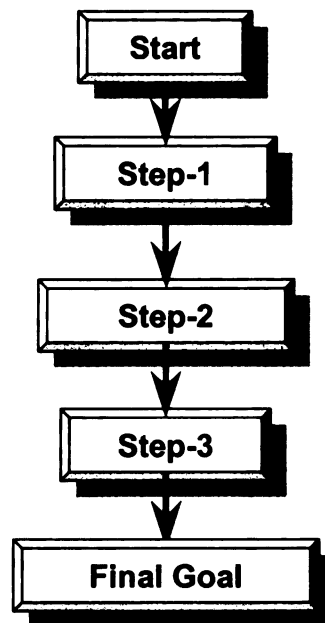
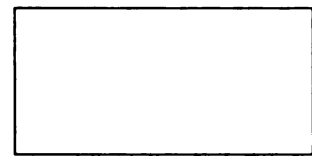
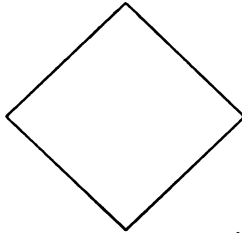


Figure 5.18: Illustration of Milestone Process Model
(Modified form GATECH 2003, Mehrotra 2002)

The Prototype Process Model breaks down each major activity step presented in the milestone model into detail steps where each step corresponds to either technical activity or a management step. This kind of model is a standard practice in the field of engineering and resembles a flow-chart (Mehrotra 2002) structure. Figures 5.19 presents some of the standard symbols that are primarily used in a flow-chart.



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



Decision point: Diamond. A diamond is put at the point in the process at which a decision must be made.



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

Figure 5.19: The Standard Flow Chart Symbols Used to Develop Prototype Process Models

(Modified from GATECH 2003, Mehrotra 2002)

5.6.2 Process Steps for Evaluating Facility Layout Alternatives for Manufactured Housing Plants

With the objective of developing a Process Flow Diagram for the required steps that need to be followed while analyzing the facility layout design alternatives for a given manufactured housing plant, Figure 5.20 was developed. The figure presents the major process steps, or the milestones, for the complete facility layout analysis procedure. The detailed breakdown structure for each major step is given in Figure 5.21 in the prototype model structure. Each of the major milestone steps are elaborated in the following section.

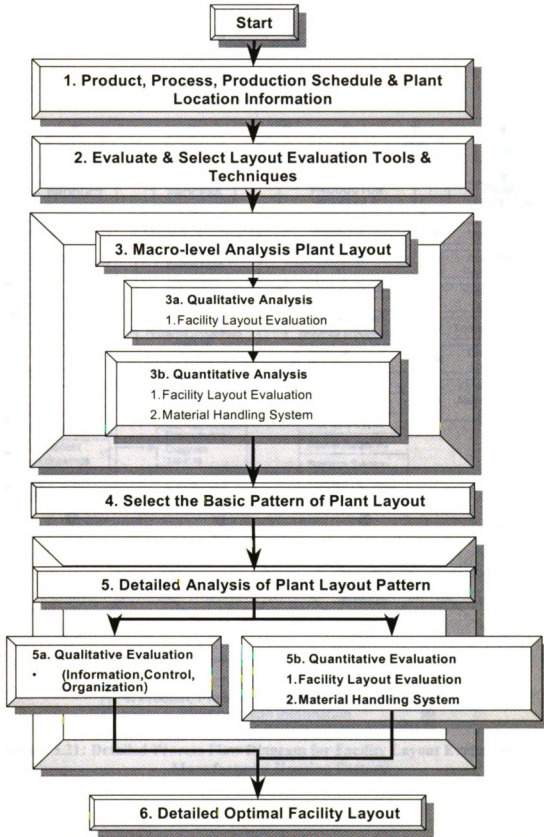


Figure 5.20: Milestone Process Steps for Facility Layout Evaluation for a Manufactured Housing Factory

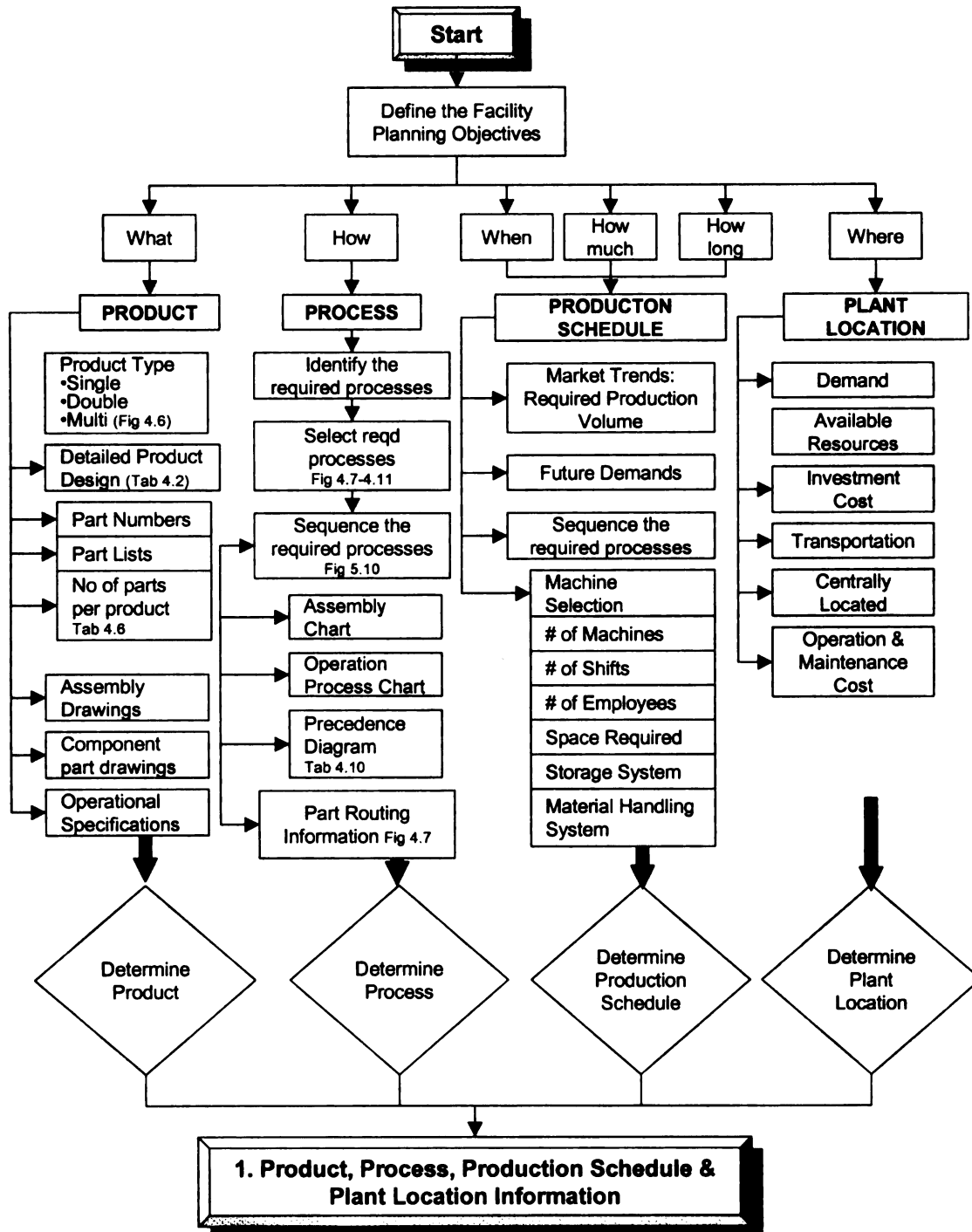


Figure 5.21: Detailed Process Flow Diagram for Facility Layout Evaluation for a Manufactured Housing Factory

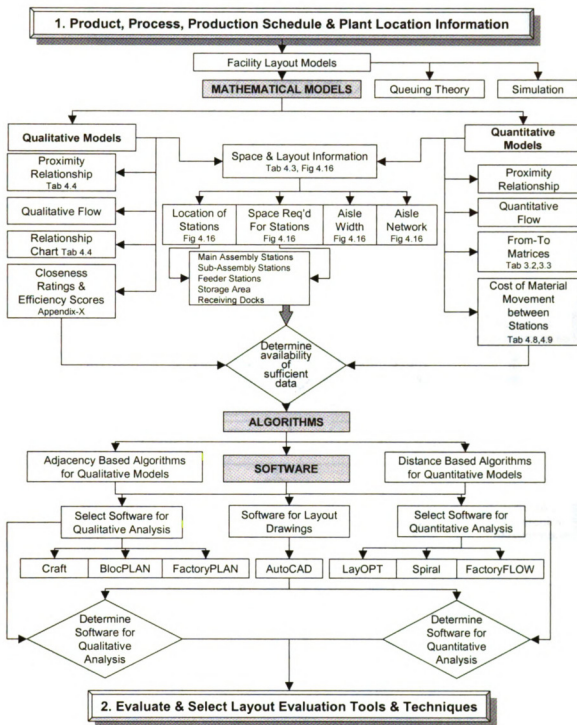


Figure 5.21(contd): Detailed Process Flow Diagram for Facility Layout Evaluation for a Manufactured Housing Factory

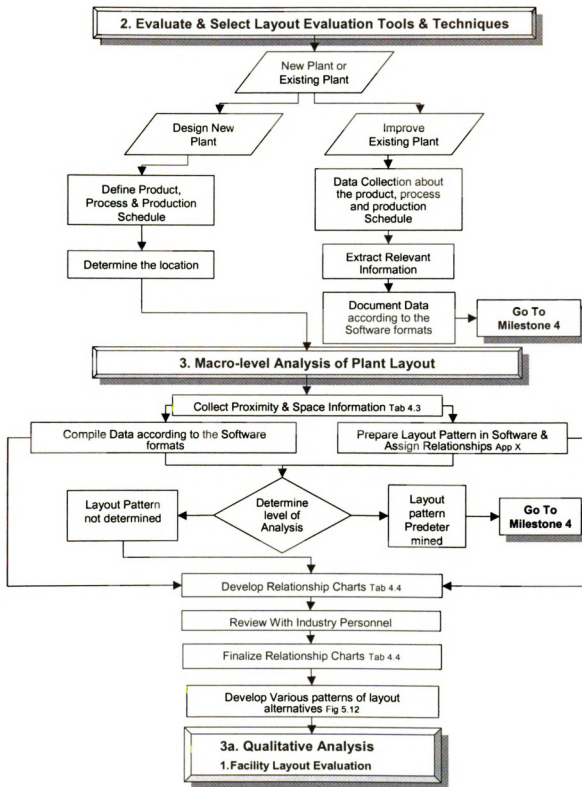


Figure 5.21(contd): Detailed Process Flow Diagram for Facility Layout Evaluation for a Manufactured Housing Factory

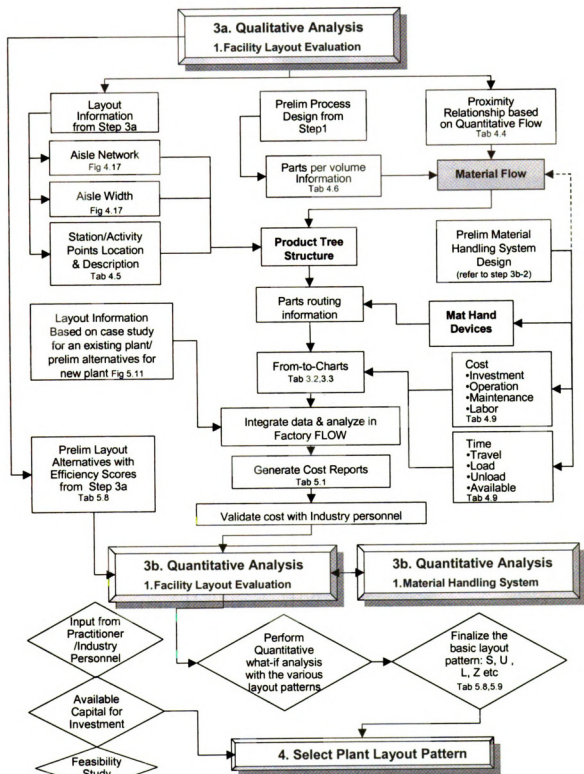


Figure 5.21(contd): Detailed Process Flow Diagram for Facility Layout Evaluation for a Manufactured Housing Factory

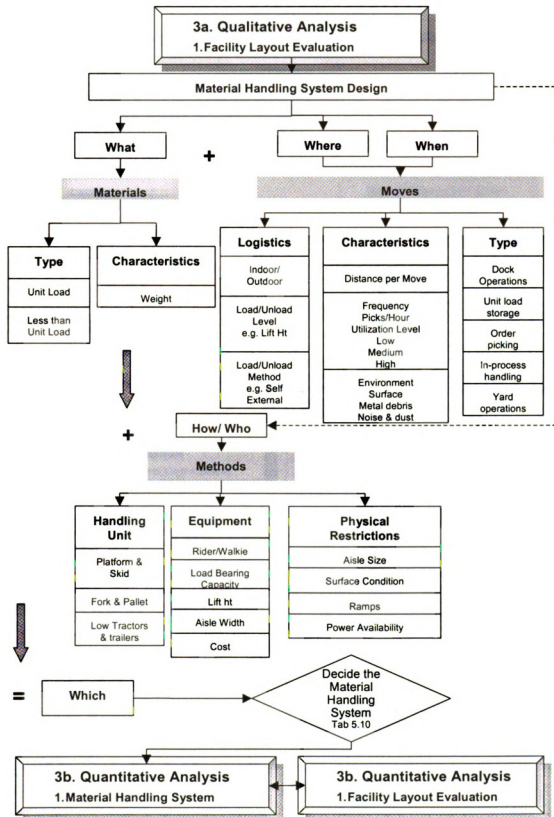


Figure 5.21(contd): Detailed Process Flow Diagram for Facility Layout Evaluation for a Manufactured Housing Factory

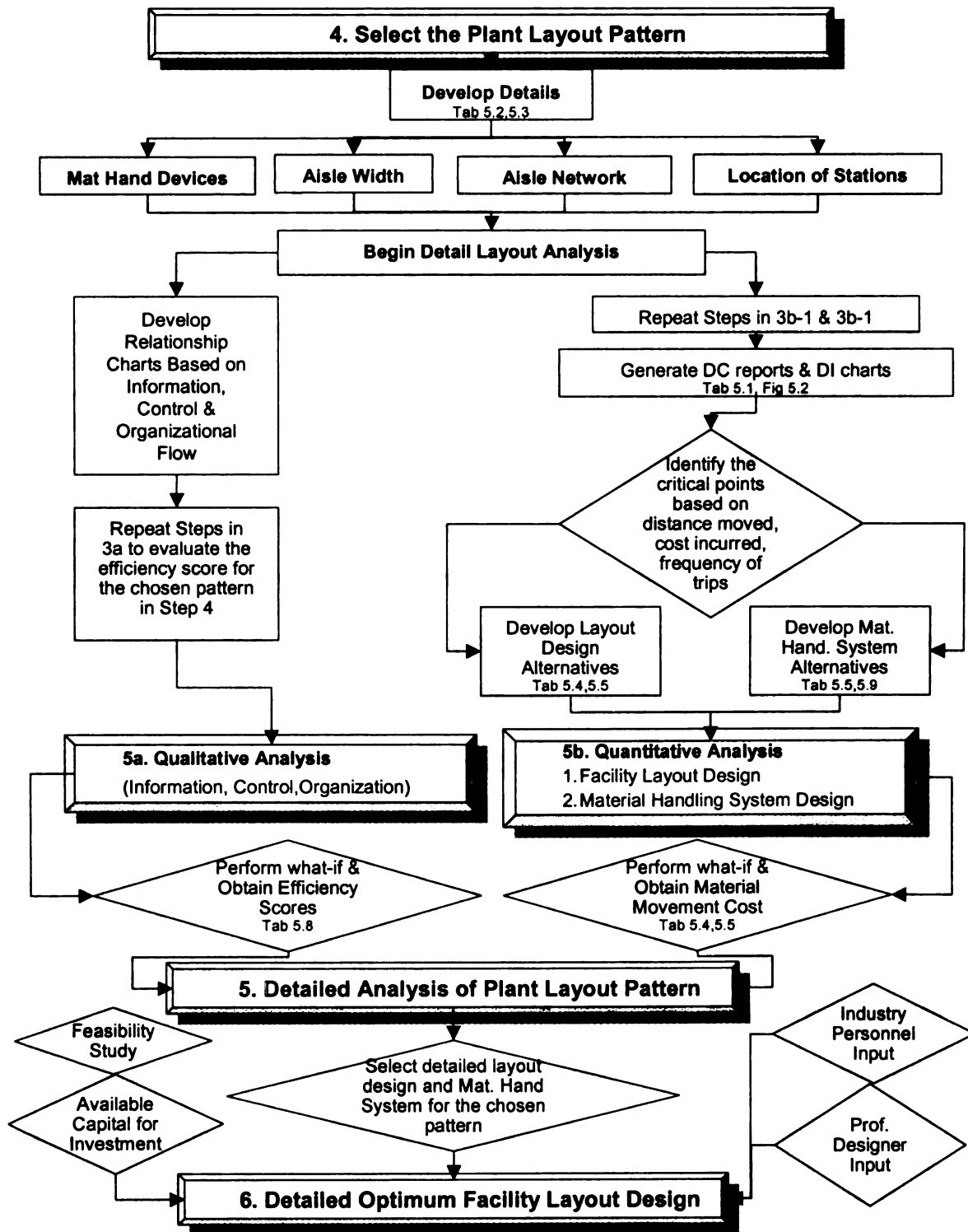


Figure 5.21(contd): Detailed Process Flow Diagram for Facility Layout Evaluation for a Manufactured Housing Factory

5.6.2.1 Product, Process, Production Schedule and Plant Location

Information

The first milestone emphasizes the fact that high quality facility layout is an outcome of excellent product, process and production design. A well-defined process for developing a facility layout for a manufactured housing facility should always begin with an analysis of the production volume of the products with process sequences and machine requirements. A designer should be very familiar with the types of products, production processes and assembly of manufactured homes, as he/she will be required to select proper production processes and equipment that are most suitable for manufacturing the defined types of houses. Once the type of houses to be produced and the manufacturing processes are determined, along with the production schedule, the designer can start with the process of developing the facility layout. For developing a new house-producing factory, the finalization of the plant location is also a major step in this milestone. Refer to figure 5.21.

5.6.2.2 Evaluate and Select Layout Evaluation Tools & Techniques

Once the product, process and production schedule information for a given manufactured housing factory is determined, the designer can begin developing layouts through a systematic flow evaluation process. Initially the designers have to define the level of analysis to be done. For an existing home factory it will be an improvement process, while for new facilities, the initial stage will be the layout pattern selection process. Considering this, the methodology proposed is developed in two stages, namely, macro-level analysis of layout pattern alternatives and detailed analysis of layout design alternatives.

After determining the level of analysis, information related to the space requirements for each station and the aisles, aisle network system and flow between the stations can be collected and layout drawing can be prepared in a CAD software. The flow data can be divided into qualitative flow (relationship charts) and material flow based quantitative flow (From-To charts). Figure 5.21 explains the data collection process for each kind of flow. The process of collecting and analyzing qualitative data is briefly explained in this thesis based on the exploratory research work (Mehrotra 2002). As for quantitative analysis, the author explained the detailed procedure of collecting quantitative flow data based on material flow for the given case-study factory in this thesis. Owing to the limited scope of this research, other flows, like information, process and organization were assumed to be a part of qualitative flow and were not included as a part of the quantitative data collection process.

Once the data are collected and documented in proper formats, the next step is to select the software for developing and evaluating qualitative and quantitative models. While selecting the facility-layout evaluation software tools, the analyzing power and the compatibility with the design software should be the major criterion.

5.6.2.3 Macro-Level Analysis of Plant Layout

After selecting the software for analyzing the layout alternatives, the layouts can be analyzed in two steps as illustrated below.

5.6.2.3.1 Qualitative Analysis: Facility Layout Evaluation

For the purpose of the qualitative analysis of the layout of a manufactured housing plant, one has to develop a qualitative model using the selected software, based on the space information of the stations and the relationship charts. The relationship charts are

developed based on the A, E, I, O, U relationship between the stations explained in Chapter IV. Once the model is developed, several alternative layout patterns can be generated and evaluated to derive the efficiency scores (Table-5.8). This thesis considers five basic layout patterns, namely, S-shaped, U-shaped, L-shaped, and straight line for qualitative analysis.

5.6.2.3.1 Quantitative Analysis: Facility Layout Evaluation and Material Handling System Evaluation

Simultaneously, the quantitative modeling of the facility layout for a given home factory can be carried out using the selected software based on the material flow. The material flow is the primary activity that outlines the basic layout of a manufactured housing factory, as it has a large volume and number of materials moving between the stations. An ideal layout for such a plant would have smooth and short flows with minimum backtracking and crossover. Material moves are illustrated by *Material Flow diagram* (refer Figure 5.1). Besides material flow, the designer needs to collect data on the aisle network, material handling equipments used and their related cost (e.g. labor, investment, operation etc.), and the time required for various material movement activities. A quantitative evaluating tool like FactoryFLOW software will help the designer to generate a variety of diagrams from the same set of product and process data, and as a result, helping the designer to focus on the different aspects of flow to find the critical points. The designer can evaluate both the facility layout as well as the material handling system for a given manufactured housing factory plant with the help of the reports generated in the evaluating software.

Facility Layout Evaluation: The reports and charts generated primarily provides the material movement cost, total distance traveled and the frequency of trips between stations. If some of the movements show a large distance traveled by a material between any two particular stations, then the layout design can be changed to ensure that the stations are placed near to each other. Once the change is done, the revised layout can be re-evaluated in the software to see the overall effect of the revision. This process of “what-if” analysis using the software should help the designer find the effects of the proposed change and save both time and money.

Material Handling System Evaluation: While designing the material handling system for the manufactured housing facility, the designer should adopt a questioning attitude. Besides addressing the basic questions of why, what, when, where, how, who and which, one should always develop a questionnaire which will include all the possible factors that can affect the cost, efficiency and flexibility of a material handling system design. The factors which are to be considered in analyzing the material handling problem include the types of materials, their physical characteristics, the quantities to be moved, the sources and destinations for each move, the frequencies or rates at which the moves must be made, equipment alternatives, and the unit-loads to be handled from others (refer to process step 3b-2 in Figure 5.21). The list of questions that should be presented before starting the design process are listed below.

Table 5.11: Checklist for Material Handling System Design
(Modified from Tompkins et al 1996)

Checklist For Designing Material Handling System For A Manufactured Housing Plant	
Why	is handling required
	are the operations to be performed as they are
	are the operations to be performed in the given sequence
	is material received as it is
	is material shipped as it is
	is material packaged as it is
What	is to be moved
	data are available and required
	alternatives are available
	are benefits and disadvantages for each alternative
	is the planning horizon for the system (future expansion)
	should be mechanized/automated
	should be done manually
	criteria should be used to evaluate alternative designs
Where	exceptions can be anticipated
	are the new technologies/equipment and concepts
	is the material handling system required
	do material handling problem exists
	should a particular material handling equipment to be used
	will future changes occur
	can operations be eliminated, combined, simplified
When	can assistance be obtained
	should material be stored
	should material be moved (JIT, Lean concepts)
	should equipment be automated
	should material be consolidated
	should a particular trip/movement/equipment be eliminated
	should the suppliers be contacted

Table 5.11 (contd): Checklist for Material Handling System Design
(Modified from Tompkins et al 1996)

Checklist For Designing Material Handling System For A Manufactured Housing Plant	
How	should the material be moved
	do the material handling problem be analyzed
	do the best suited one from the available alternatives be chosen
	do the performance of the material handling system be measured
	should the exceptions/changes be accommodated
	to make the system flexible
Who	should be handling the material
	should be involved in the design system
	should be involved in evaluating the system
	should be involved in installing the system
	should be the supplier of the equipments
	should be maintaining the system
	should be responsible for the system
	has faced similar problems-market study/case study
Which	operations are necessary
	problems should be attacked first
	persons should "pick their brains" for layout design
	type of equipment should be considered
	material flows should have real-time control
	material flows should have real-cost control
	alternative is preferred

5.6.2.4 Select the Basic Pattern of Plant Layout

After developing the qualitative and quantitative models for the basic layout design of a house manufacturing factory and after evaluating them, the designer gets the efficiency scores and material cost for each alternative developed. Based on the analysis results available and input from the experienced facility planners, industry personnel and, managerial constraints (e.g. available budget, company philosophy etc.), the basic layout

pattern is selected (refer to process step 4 in Figure 5.20). The selected basic layout pattern is further fine-tuned in the later step to make the layout more detailed, cost effective and more efficient.

5.6.2.5 Detailed Analysis of Plant Layout Pattern

The selected basic layout pattern is further re-evaluated using the quantitative analysis software as shown in process step 5b, in Figure 5.20, for a micro-level analysis of each material flow in order to make the layout design and the material handling system more efficient. The generated reports guide the designer to develop the “what-if” scenarios and help to improve the layout.

5.5.2.6 Detailed Optimal Facility Layout

The effectiveness of the final milestone process step (refer to the step 6 in Figure 5.20) can be defined as the outcome of several technical activities as well as managerial decision steps. Soundness of the layout technique is hugely dependent on the level of analysis, combined with a thorough product, process, equipment and material handling system analysis. Layout projects that do not contain detailed relationships and material flow studies often result in a weaker analysis and fail to attain the goal of optimization. Besides the factors mentioned above, financial reasons as well as the experience of the industry personnel and the professional practitioners involved in this process, also play a vital role during this major decision-making step. The optimized layout is selected not only on the basis of the software evaluation reports (e.g. efficiency scores or the material movement cost) but also depends on the input from the design team and the people involved during the layout evaluation process for a given manufactured housing plant. Moreover, while selecting the basic layout pattern and the detailed layout and material

handling system, the feasibility study for the chosen alternative should be performed, before finally selecting an alternative.

The process steps discussed in this section are based on the author's knowledge and understanding of the manufactured housing production process and facility layout. These are the recommended steps, validated by the industry personnel and professional practitioners. However, these process steps should be recommended as guidelines only after applying them in real-world scenario.

5.7 Summary

This chapter outlined the process of evaluating the layout alternatives for a given manufactured housing plant. The author presented the methodology of evaluating the basic layout patterns for a home manufacturing facility, based on both qualitative and quantitative flow, using FactoryPLAN and FactoryFLOW software. Moreover, the author explained the process of evaluating an existing facility layout and material handling system design, using the case-study manufactured housing plant as an example, and also illustrated the process of identifying alternatives (again using the given plant) to make the existing layout more cost-efficient and productive. The industry personnel evaluated the results of the “what-if” analysis and provided their feedback. The author developed the comprehensive process steps for layout alternative evaluation of a manufactured housing plant, implementing the tools and technologies adopted in the research for layout evaluation process, as the final outcome of this thesis. The proposed methodology was accepted by the professional designers and is similar to the one carried out in designing manufacturing facilities in industrial engineering.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

6.1 Introduction

This research was primarily intended to initiate the implementation of the advanced tools and techniques, adopted in field of industrial engineering for a facility layout evaluation process, into the manufactured housing industry. In order to achieve this, one of the major objectives was to understand the available tools and techniques. The research also sought to show how these can be used to evaluate facility layout design alternatives for a given manufacturing plant in order to select the optimum layout design. To attain this objective, the author utilized a comprehensive software for evaluating the layout design alternatives for the case-study manufactured housing plant, performed micro-level and macro-level analysis, and recommended detailed process steps for the evaluation of facility layout alternatives. The following paragraphs provide the outline of each chapter to summarize the methodology followed during the research.

Chapter II presented the review of existing and ongoing research and literature in the field of facility design and planning and manufactured housing industry. It briefly outlined an overview of the latest studies in the facility-planning field. Existing research and literature were classified into three categories, namely Production Process and Material Management in the Manufactured Housing Industry; contemporary Facilities Layout design concepts and techniques in Industrial Engineering; and facility layout design concepts in Manufactured Housing plants.

In Chapter III, the author outlined the major contemporary tools and techniques that are used for planning, developing, evaluating and presenting facility layout design alternatives in manufacturing facilities. The chapter also provided examples of certain types of quantitative models that can be used to develop an alternative facilities plan. The

chapter explained the role of the computer in facilitating the generation of facility layouts; the chapter also gave a detailed description of the FactoryFLOW software, that had been used for data analysis and development of factory layout design alternatives. Moreover, Chapter III also presented various facility layout concepts, algorithms and models that are used for developing computer software for designing facility layouts. At the same time, the author emphasized material flow and material handling systems as the major quantitative elements in facility planning. Various activity relationships and flow relationships were described in this chapter. Among the flow relationships, the quantitative flow relationship and the From-To charts were used, as the research focused on the quantitative relationships within the stations and substations of a manufactured housing plant.

In Chapter IV, the author explained the methodology for modeling the facility layout problem of the manufactured housing factory using a quantitative approach. This chapter also re-introduced the FactoryFLOW software and implemented the software for the quantitative analysis of the facility-layout design problem for the manufactured housing industry case-study plant. The author also described the manufactured housing plant that has been used as a case study for the quantitative analysis of the facility layout problem. In addition, this chapter documented the details of a manufactured house, the production process, materials used and their flow, and the material handling system and devices used for the manufactured housing facilities (based on the case study manufacturing plant). The analysis of the data collection, development of the product-tree structure, and identification of the activity points and their interrelationship with material handling system necessary for the formulation of the quantitative model in the software,

were also explained in this chapter. It also briefly outlined the qualitative analysis of the facility layout problem of the manufactured housing plant (Mehrotra, 2002). Finally, the reports and diagrams of the quantitative model based on existing layout of the manufactured housing factory were generated using the FactoryFLOW software. Among the various reports generated, the author selected the Distance-Intensity chart (graphical report) which provided frequency of trips for each part, sub-assemblies and assemblies; and the Distance-Cost report (numerical report), which provided the material movement cost and the distance traveled.

Chapter V provided the evaluation of the selected reports obtained during FactoryFLOW analysis of the facility layout problem in the case-study factory. Based on these reports, the critical points were identified (*i.e. most cost incurring material movements, the material movements having greater frequency of trips*), and “what-if” scenarios were developed (*by changing either station locations or material handling equipment*). These scenarios were developed with a view to minimize the cost or reducing the distance traveled. The next step was building a quantitative model of the facility layout, of the case-study plant, that was already evaluated qualitatively in an earlier thesis (Mehrotra 2002). In the above-mentioned developmental thesis, five different facility layout patterns were generated based on various qualitative assembly flow patterns and were evaluated qualitatively. The author in this thesis evaluated the five basic layout patterns (e.g. S-shaped, U-shaped, L-shaped, Z-shaped and Straight line), proposed in the earlier thesis, and analyzed them quantitatively in the factory FLOW software. Based on the exercises performed to understand the manufactured housing production process, and techniques developed to define the proximity relationships of

various assembly flows for qualitative analysis and quantitative analysis of the facility layout design, the author produced the sequential process steps to evaluate the facility layout design alternatives for a manufactured housing plant. The recommended process steps were validated and critiqued by the industry personnel, and their suggestions were incorporated in the final proposed steps. The process steps will guide the facility planner in evaluating the various facility layout alternatives and deciding the best layout for a given production process in a manufactured housing plant.

6.2 Summary of the Research Objectives

The overall goal of the proposed research is to analyze the impact of material-flow on the facility layout of a manufactured housing production plant, and to outline the process steps for evaluating the layout-design based on the material-flow.

6.2.1 Develop the quantitative model for the facility layout based on the material-flow

The following steps were carried out to achieve objective I.

Step-1: To understand the facility layout design and production process of the manufactured housing production plant

To achieve the above mentioned step, the manufactured house as a product was defined and the production process was studied in details. Moreover, the material management process, and material handling system design prevalent in the manufactured housing industry were also reviewed, in order to get a better understanding of the material flow movement within the plant.

Step-2: To review existing literature and to acquire information about the latest theories and technologies implemented during layout planning and designing of other manufacturing facilities.

The author reviewed the existing literature in order to understand and present the new perspectives, expertise and significant advances in facilities planning

Step-3: To acquire and understand appropriate designing, modeling and evaluating techniques and software for the analysis of facility layout problems

The author investigated the factors (e.g. qualitative flow and quantitative flow) that affect the facility layout designs during this step. Various techniques that can be implemented for facility layout problem analysis were also studied. Simultaneously, the software solutions for facility layout alternatives evaluation, both qualitative and quantitative were also investigated in this step. Finally, FactoryFLOW software, a quantitative analysis tool was selected for this research

Step-4: To collect data by visiting the case-study factory and to analyze the data in order to compile the process details of manufactured housing production plant

The author followed a sequential step-by-step approach for gathering the relevant data from the case-study housing plant to develop the quantitative model for the facility layout by watching the production process, videotaping the material movement and material handling activities, noting down the timings, interviewing the factory-floor personnel, such as production managers, supervisors, workers and maintenance division people. After the data collection process was completed, various basic formats like Layout Drawings in AutoCAD and From-To charts were developed.

Step-5: To develop a comprehensive quantitative model of the facility layout based on the material flow using FactoryFLOW software.

Once the FactoryFLOW software data structure was understood, the existing layout design of the case-study factory was prepared in AutoCAD. Following this, the activity points (e.g. stations) were identified and the quantitative model was developed in FactoryFLOW with the help of product-tree structure, part-routing information, product-volume data and material handling system design. After completing the model, Distance-Intensity Charts and Distance-Cost Reports were generated and the results were validated with the industry personnel.

6.2.2 Computer Aided Analysis of the quantitative model, including development and evaluation of the alternatives

The following steps were carried out to achieve objective II.

Step1: To identify the critical factors from the reports generated and develop alternatives based on “what-if” analysis.

After evaluating the quantitative model in FactoryFLOW, distance cost-reports and distance intensity charts were generated, and the critical factors were identified. Based on these critical factors, “what-if” analysis was performed and the layout alternatives were generated. The alternatives were evaluated, compared and analyzed by studying the reports and charts.

Step 2: To formulate a quantitative model of a typical production process model based on the earlier researches and evaluate various design layout alternatives proposed by Mehrotra (2002) in her developmental research work.

The author developed a generic quantitative model of the facility layout based on the production process of the case study in the earlier researches on a manufactured house production process and facility layout design (Senghore 2001, Mehrotra 2002). The design layout patterns (based on qualitative flow), proposed by Mehrotra in her developmental research work (Mehrotra 2002), were quantitatively evaluated in FactoryFLOW. The results generated in the form of Distance-Cost reports were compared, and patterns were evaluated based on the total material flow cost and the distance traveled by the materials between the stations.

6.2.3 Outline the process steps required to analyze the facility layout based on the material flow for a Manufactured Housing Production Plant.

The following steps were carried out to achieve objective III.

Step1: Develop an outline of comprehensive process steps for the facility layout design of a manufactured housing industry

Based on the modeling, evaluation, and analysis process carried out during the earlier steps, it was concluded that a facility layout problem can be analyzed in a two-stepped approach: namely, macro-level and micro-level. In order to do this, it is necessary to produce both the qualitative and quantitative models for the layout problem. The qualitative analysis provided the efficiency scores, while the quantitative analysis provided the material flow cost. Based on the efficiency scores and cost, the basic layout pattern can be chosen, which can be further detailed in a micro-level through quantitative

analysis. Primarily following this concept, the comprehensive process steps were proposed for evaluating and selecting the optimum facility layout design of a manufactured housing factory.

Step 2: Collected feedback/recommendations from the manufactured housing industry personnel

The author interviewed the industry managers for the validation of the quantitative model of the facility layout for the case-study factory. The comments and suggestions on the method of generating and evaluating the layout design alternatives were incorporated in the final process steps.

Step 3: Collected feedback/recommendations from the professional design consultants

The author visited professional design consultants who design mobile factories for building homes and collected their input on procedures that need to be adopted to select the optimum facility layout design for a given house-manufacturing facility.

6.3 Limitations of Research

One of the major limitations of this research is that the quantitative model is developed based on only the material flow between the stations of the manufactured housing plant. Due to the multiplicity of relationships involved, it is necessary to construct separate From-To quantitative matrices for every major flow involved. For example, different From-To or quantitative matrices can be developed for material, personnel, information, organizational, control, environmental, and process flow. However, the development of the individual matrices for each of the flow mentioned above for a home-manufacturing facility, which involves a huge movement of material,

people, information etc, can be a very demanding process and was beyond the scope of this Master's thesis.

Another major drawback was that the layout alternatives were evaluated quantitatively on the basis of the cost of the material movement between the stations. As a result, in this research the product structure, position of the stations, material handling system and devices were mainly considered for the process of evaluating the layout design alternatives. The results and conclusions were arrived at considering only the layout and material handling system design perspectives and do not take into account the changes in process and productivity management.

The research, owing to the thesis scope and hardware limitations, has focused on the 2-dimensional (e.g. length and width) analysis of the layout alternatives. The author has not taken into consideration the 3-dimensional (e.g. length, width and height) aspects of layout planning. However, FactoryFLOW software has the capability of analyzing 3-dimensional layout alternatives, and this can be an area for future research.

In addition, the FactoryFLOW software used in this thesis is primarily an optimization tool, which can only evaluate alternative scenarios but cannot come up with the best solution for a given facility layout problem. This necessitated the two-step approach proposed in this thesis. The basic layout pattern for new manufactured housing facility is selected using a qualitative approach (e.g. intuition, product type, information, management concepts etc), and then it is fine-tuned using a quantitative approach (using FactoryFLOW software) to come up with an optimal solution.

Finally, the thesis scope of research is limited to developing the process steps for evaluating facility layout alternatives based on material-flow for a given house

manufacturing plant. However, a recommendation of a single solution that can be identified as an optimal layout design is outside the scope of this research. Industry practitioners will have to collect data and carry out their own analysis to arrive at a decision. This research makes an attempt to show the practitioners a stepwise approach that needs to be followed to come up with the best layout for a given manufactured housing facility.

6.4 Conclusions

Any visitor with some understanding of a manufacturing process would likely be able to recognize the basic production process and assembly line in a manufactured housing factory. However, a visitor who has advanced concepts of robotics and highly automated systems, which are prevalent in all other manufacturing facilities, will be definitely disappointed by the basic operational methods of mid-70s that prevail in a manufactured housing plant (MHRA 2000). The manufactured housing industry lacks any information about the futuristic technologies associated with the process of facility layout design and material handling system design. This research provides the comprehensive process steps which, when followed, will help the layout-designers to adopt the contemporary techniques for the facility layout design process in the manufactured housing factory. The major conclusions, derived during the research work are presented in the following sections.

- Pricing and other market pressures have exerted a limit on the capital investments of manufactured housing facilities that has made it almost prohibitive to follow the footsteps that have revolutionized other manufacturing facilities, e.g.

automobile industries. Despite these limitations, the industry today is better positioned, possesses more resources and is more open to innovation and change. As a result, now is the ideal time for the manufacturers and designers of manufactured housing plants to learn and adopt new techniques.

- There is a narrowing of gap between the quality and the amenities available in the site-built and factory-built homes. But the manufactured homes continue to be much more affordable than their site-built counterparts. So it may be concluded that the demand for the manufactured homes can be increased, provided they are strategically marketed.
- The manufactured housing plants can be designed to meet variability in production by handling the material flow as efficiently as possible. In order to maintain an efficient material flow, the storage of the materials (e.g. inventory) should be kept at minimum level. This measure not only helps to provide more space, but it also helps the manufacturer to maintain the flexibility in production with a minimum of disruption. Therefore, it can be concluded that with more flexible production lines and sophisticated material handling techniques, the manufactured housing industry can not only increase their product variety, but also can offer a greater variety of products with higher quality.
- The FactoryFLOW software is an optimization software that makes the material travel distances and cost within a house manufacturing industry measurable and helps in benchmarking facility changes and their effect on strategic facility layout design improvements. Moreover, it runs interactively within a CAD system and the planners familiar with the manufactured housing production process will be

able to develop and redesign the manufactured housing facility visually and accurately. By considering the space requirements for each station in the AutoCAD drawing and the flow of materials between stations, potential layout problems can be identified. Troubleshooting of potential problem areas can thus be done prior to the implementation of a new layout. This greatly reduces the cost of implementation; e.g. the placing of a station in a wrong location could later result in thousands of dollars material movement cost.

- The industry personnel had very little knowledge of the exact parts-flow within the stations in the manufactured housing facility. The quantitative model of the manufactured housing factory developed in this thesis, based on material flow, was insightful, and the managers were able to identify problems and make suggestions as how those problems could be addressed.
- The implementation of advanced techniques in evaluating and selecting the facility-layout alternatives can lead to a substantial cost reduction. The alternatives can be modeled and analyzed on the basis of cost-parameters with the help of any advanced software solution (e.g. FactoryFLOW was used in this research). In addition, the layouts can also be made more effective by reducing the frequency of trips between stations, or the distance traveled, as the software analysis results also provide information about these factors. However, during the process of evaluation of layout and material handling system, the production process and throughput rates should also be considered.
- For an existing manufactured housing production plant, the layout can be improved without making any major investment or radical transformation. The

analysis reports provide information in such detail, that the facility planner can easily identify the scope and make several minor changes, which can help in a great deal of cost reduction and productivity improvement.

6.5 Future Research Areas

As mentioned earlier in the limitations, this research does not cover all the aspects related to facility planning and layout design process for a manufactured housing facility. Some of the related future research areas are mentioned in the following paragraphs.

6.5.1 Evaluation of Layout Design Alternatives based on Product Flow and Process Flow

The primary future research area, which may be defined as a continuation of this research is developing the process of a quantitative layout model based on the product flow and the process flow. Developing the quantitative formats for the layout alternative evaluation, after incorporating the product flow and the process flow, will enable the designers to analyze the facility layout designs for manufactured homes more effectively and comprehensively. However, this process will involve a detailed data collection process regarding the variety and the types of houses that are produced in the manufactured housing factory. This future research will also include the detailed study of the production process for each kind of product and will carefully identify the changes required in the production process to manufacture each product. This research will also need to develop an idea of the market and identify the future nature of the demand. Besides a detailed documentation of the product and the process flow, this research will need to interview the construction personnel and facility planners to evaluate the

effectiveness of each process flow based on material management, labor utilization, equipment utilization and effective use of other resources involved in the manufacturing process.

6.5.2 Incorporation of Lean-Flow Manufacturing Techniques in the Flow

Analysis during the Facility-Layout Design Process

This research takes into account the material flow within the stations of a manufactured housing facility in order to evaluate the layout alternatives quantitatively. However, it does not incorporate lean flow manufacturing techniques during the flow analysis to develop facility layout design alternatives. Application of the lean principles, while defining the layout design criteria, has the potential of further increasing the efficiency of the manufactured housing production process.

6.5.3 Innovative “Whole House” Production Process

Another possible scope of future research is the method of approaching the goal of “Whole-House Design Process” by exploring the possibility of finding an optimum combination of all the home production processes, namely site-built, panelized, factory-built and hybrid, that will produce a better quality home at a faster rate and lower cost. The researchers may consider all the various possible alternatives of the home-production process available, identify the best combination, and define the comprehensive approach for producing a “Whole House”.

Moreover, this research step may consider all the advanced technologies adopted in the home building processes. Any new expertise that has been introduced in the field of site-built, panelized, and factory-built-housing as well as the hybrid housing over the

models with the qualitative models proposed in earlier research (Mehrotra 2002), in order to evaluate facility layout alternatives and consequently select the most suitable layout for a given manufactured housing plant. Finally, the research presented the comprehensive process steps which will the designers to arrive at the optimal facility layout design for a manufactured housing plant, using advanced tools and techniques.

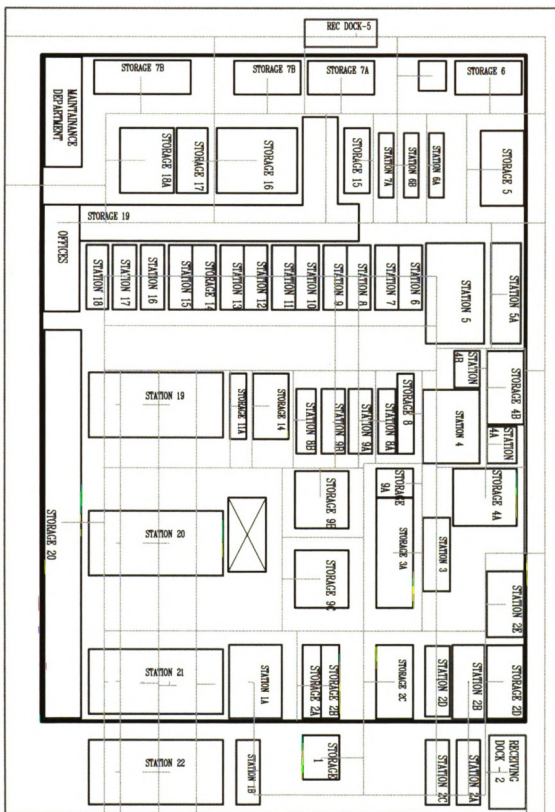
duration of the project might also be taken into account while proposing the new “Whole House” production approach. This initial research step may define the “Whole-House” production process. The next research step might be the implementation of the proposed system in a practical home-building situation. Finally, one can conclude with the analysis of the results and outcome and the recommendations. As a final step, the definitions of the various approaches and their possible effects on the home production process based on the results of the case study can be illustrated. The case study might also help to identify the weakness of the “Whole-House” production definition in the earlier research step. As a result, this may help in proposing a more realistic and feasible “Whole-House” production system.

6.6 Summary

The manufactured housing industry has shown a great potential to meet the increasing demand for affordable housing over the past two decades. However, the production process and the facility layout design techniques used in this industry are quite primitive and there is a need for introducing the advanced and futuristic technologies that are used in most other manufacturing industry. As a part of the research project funded by NSF-PATH Initiative, this research explores the tools and technologies used in other manufacturing facilities and describes the methodology in implementing them in the manufactured housing industry. The research develops a quantitative model of the facility layout of the manufactured housing factory based on the material flow, evaluates the model and various alternatives using optimization software, and analyzes the results. In addition, this research also presents the way of integrating the quantitative facility layout

APPENDIX-A

**DETAILED-ALTERNATIVE LAYOUT DRAWINGS FOR CASE-
STUDY FACTORY**



APPENDIX-B

**DETAILED PRODUCT BREAK-DOWN STRUCTURE &
PRODUCT QUANTITY INFORMATION IN CASE-STUDY
FACTORY**

Table B1: Product Breakdown Structure

House:Product Structure	
<u>Part A (with toilet & Kitchen)</u>	<u>Part B</u>
1 Frame Assembly	1 Frame Assembly
2 Floor Assembly	2 Floor Assembly
3 Gas Assembly	7 Electrical Assembly-B
4 Water Supply	7.1 Electrical Assembly Stage-B1
5 DWV Assembly	7.2 Electrical Assembly Stage-B2
6 Plumbing Fixtures	7.3 Electrical Assembly Stage-B3
7 Electrical Assembly-A	8 Interior Partition B
7.1 Electrical Assembly Stage-1	8.1 Interior Partition Type1
7.2 Electrical Assembly Stage-2	8.2 Interior Partition Type2
7.3 Electrical Assembly Stage-3	8.3 Interior Partition Type3
8 Interior Partition A	8.4 Interior Partition Type4
8.1 Interior Partion Type1	8.5 Interior Partition Type5
8.2 Interior Partion Type2	8.6 Interior Partition Type6
8.3 Interior Partion Type3	8.7 Interior Partition Type7
8.4 Interior Partion Type4	8.8 Interior Partition Type8
8.5 Interior Partion Type5	
8.6 Interior Partion Type6	9 Side Walls
8.7 Interior Partion Type7	10 End Wall Type-B
9 Side Walls-A	6.1 End Wall Type-A1
10 End Wall Type-A	6.2 End Wall Type-A2
10.1 End Wall Type-A1	11 Mating Walls-Type B
10.2 End Wall Type-A2	12 Ceiling Type B
11 Mating Walls-Type A	14 Exterior Roof Finish Assembly-B
12 Ceiling Type A	13 Exterior Finish Assembly-B
13 Exterior Finish Assembly-A	15 Trim -B
14 Exterior Roof Finish Assembly-A	15.1 Trim -B1
15 Trim -A	15.2 Trim -B2
15.1 Trim -A1	15.3 Trim -B3
15.2 Trim -A2	16 Final Finish-B
15.3 Trim -A3	19 Fasteners
16 Final Finish-A	
17 Cabinet Assembly-A	
17.1 Base Assembly-6"	
17.2 Base Assembly-19"	
17.3 Base Cabinet Assembly	
17.4 Corner Base Cabinet Assembly	
17.5 Sink Base Cabinet Assembly	
17.6 Bar Base Cabinet Assembly	
17.7 Bar Overhead Cabinet	
17.8 27" Overhead Cabinet	
17.9 Overhead Range Cabinet	
17.10 Corner Overhead Cabinet	
17.11 Reference Shelf	
17.12 21" Pantry Shelf	
17.13 Vanity Cabinet Module-A	
17.14 Vanity Cabinet Module-B	
17.15 Kitchen Counter Tops	
18 Fuse Panel Doors	
19 Fasteners	

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
1. Frame Assembly A1		1	EA
1	Frame s. triple, 10"	2	EA
2	Axle, idler, 99-1/2 recycled	4	EA
3	Axle, brake, 99-1/2 recycled	2	EA
4	Tyre, new 8-14.5/12ply	12	EA
5	Bolt, shakle, 1/2-13x3-1/2	24	EA
6	Lock, nut, 1/2-13, top notched	24	EA
7	Wire, 18-1, sae, primary red	116	LF
8	Wire, 18-1, sae, primary white	116	LF
9	Wire, 18-1, sae, primary black	116	LF
10	Wire brake, 14/2 sae red jacket	64	LF
11	Lug, ground 14-4 cu, 1/4 hole	2	EA
12	Wire, Bare Copper, 8sd	6	LF

Item		Part/Quantity	Unit
2. Floor Assembly A1		1	EA
1	Lumber, 2x6x14-1/2-cut, splice block	12	EA
2	Lumber, 2x6x19-1/2-cut, furnace block	2	EA
3	Lumber, 2x6x157-#2 btr	68	EA
4	Lumber, 2x6x29-3/4"	52	EA
5	Lumber, 2x6x12- # 3	15	EA
6	Bottom board, 176, ms1763	1349	SF
7	Insulation, r11, unf, 90"x75'	1012	SF
8	Insulation, r19, unf, 15"x39'2"	515	SF
9	Head Duct Aluminium- 5" x 12"	56	LF
10	Head Duct Aluminium- 5" x 12"	24	LF
11	Ground Strap' 4"x120"	2	EA
12	Insulation, r11, unf, 15"x93	112	SF
13	Strapping Steel, Crossover	4	EA
14	Boot, Register, 4"x10"x6"	6	EA
15	Register, 4x10, white	8	EA
16	Collar, start, 5"	2	EA
17	Flexduct, 5x10", insulated	30	LF
18	Tie Strap, 21" nylon, heat duct	4	EA
19	Boot, 4x10x5, inline	2	EA
20	Washer, 7/16x2-1/2, ga, rnd,ws	284	EA
21	Lag, 5/16x3, hex, s/l, waxed	328	EA
22	Furnace, Gas, pilot	1	EA
23	Plenum, 11.25x13	1	EA
24	Roof Jack, Std	1	EA
25	Ventilaire	1	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
3. Floor Assembly-A2		1	EA
1	Novodeck, 96x168, (trim 160)	1120	SF
2	Novodeck, 48x168, (trim 160)	112	SF

Item		Part/Quantity	Unit
4. Floor Assembly-A3		1	EA
1	Linoleum, 13'6"	40.5	SY
2	Carpet	61	SY
3	Carpet Pad	61	SY

Item		Part/Quantity	Unit
5. Gas Assembly		1	EA
1	Pipe, 1/2" black, 21'	21	LF
2	Pipe, 3/4" black, 21'	2	LF
3	Pipe, 1" black, 21'	1	LF
4	Tee, 3/4x1/2x1/2	1	EA
5	Coupling, 1x3/4,	1	EA
6	Dust Cap, Chain, 1"	1	EA
7	Elbow, 1/2, 90, Black	5	EA
8	Connector gas, 1/2x18	1	EA
9	Connector gas, 1/2x36	1	EA
10	Valve, Gas ball 1/2fpt	2	EA
11	Clamp, ground, 1/2 to 1 dc	3	EA
12	Vermin proofer	2	EA
13	Lug, ground, 14-4 cu, 1/4 hole	1	EA
14	Wire, Bare Copper	2	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
6. Water Supply		1	EA
1	Adapter, 3/4b	3	EA
2	Tee, 3/4 barb	1	EA
3	Elbow, 3/4 barb	1	EA
4	Connector, w/h	2	EA
5	Tee, 3/4x3/4x1/2, barb	10	EA
6	Tee, 3/4x3/2x1/2, barb	1	EA
7	Tee, 3/4x3/2x3/2, barb	1	EA
8	Tee, 1/2x1/2x3/4, barb	1	EA
9	Tee, 1/2", barb	5	EA
10	Elbow, 3/4x1/2 barb	19	EA
11	Elbow, 1/2Bx1/2fpt barb	6	EA
12	Elbow, 1/2 drop ear	3	EA
13	Nut, ballock	2	EA
14	Adapter	15	EA
15	Coupling, 1/2" barb	12	EA
16	Coupling, 3/4" barb	4	EA
17	Valve, 1/2, barb, fluidyne	2	EA
18	Tubing, 1/2x20" black	77	LF
19	Tubing, 1/2x20" red	84	LF
20	Tubing, 3/4x20" black	58	LF
21	Tubing, 3/4x20" red	29	LF
22	Crimp ring-1/2	120	EA
23	Crimp ring-3/4	50	EA
24	Vermin proofer-1/2	10	EA
25	Vermin proofer-3/4	3	EA
26	Vermin proofer-1 1/2	4	EA
27	Test plug-3/4	1	EA
28	Test cap-3/4 female	1	EA
29	Adapter, 3/4bx3	1	EA
30	Adapter, 3/4bx3/\$mpt	1	EA
31	Test plug-1/2 mpt	1	EA
32	Test cap-1/2 female	1	EA
33	Adapter, 1/2bx1/ swivel	1	EA
34	Adapter, 1/2bx1	1	EA
35	Sprinkler Head	1	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
7. DWV Assembly		1	EA
1	Pipe 1-2/2x20	53.5	LF
2	Pipe 2x20'	5	LF
3	Pipe 3x20'	29	LF
4	Tee, 3", dbl	1	EA
5	Wye, 3x3x2, Single comb	4	EA
6	Wye, 3", Single comb	3	EA
7	Bushing, 3x2 flush	3	EA
8	Bushing, 2x1 1/22 flush	5	EA
9	Elbow 3" 90 xlt	1	EA
10	Elbow 4x3 closet bend	1	EA
11	Flange, closet 4x3	1	EA
12	Flange, closet 4x3	1	EA
13	Dust cap, chain	1	EA
14	Elbow, 3" 22 1/2	1	EA
15	Elbow, 2" 45 lt	2	EA
16	Elbow, 2" 90 lt	2	EA
17	Tee, 2x1	2	EA
18	Wye, 1 1/2, single 45	3	EA
19	Plug Cleanout	3	EA
20	Tee 1/2 sant	6	EA
21	Vent 1 1/2 tailpiece	6	EA
22	Elbow, 1 1/2 45 street	5	EA
23	Elbow, 1 1/2 90	7	EA
24	Elbow, 1 1/2 45 lt	4	EA
25	Adapter, swivel trap	3	EA
26	P-trap A	3	EA
27	P-trap B	4	EA
28	P-trap C	1	EA
29	Plug, Cap	1	EA
30	Adaptor, cleanout	1	EA
31	Plug, cleanout	1	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
8. Plumbing Fixtures		1	EA
1	Bowl, toilet	1	EA
2	Bowl, tank	2	EA
3	Tank, toilet	2	EA
4	Seat, toilet	2	EA
5	Ring-wax	2	EA
6	Bolt-Closet	4	EA
7	Nut, open end	4	EA
8	E-gasket	2	EA
9	Tub corner, abs	1	EA
10	Filler-garden tub	1	EA
11	Plug-lift & turn-A	1	EA
12	Tub fiberglass	1	EA
13	Diverter, tub shower	1	EA
14	Shower head	1	EA
15	Plug-lift & turn-B	1	EA
16	Sink-kit	1	EA
17	Faucet	1	EA
18	Strainer basket	2	EA
19	Waste cont	1	EA
20	Lav	3	EA
21	Plug-cleanout	3	EA
22	Faucet-lav	3	EA
23	Water Heater	1	EA
24	Tube w/h overflow	1	EA
25	Vermin Proofer	2	EA
26	Box white plumbing	2	EA
27	Drain, 1/2" barb brass	2	EA
28	Valve, 3/4 barb	1	EA
29	Shower fiberglass	1	EA
30	Diverter, show chrome	1	EA
31	Shower head-kit chrome	1	EA
32	Strainer shower	1	EA
33	Shower door	1	EA
34	"F" moulding 98" brite	1	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
7.1. Electrical Assembly Stage-A1		1	EA
1	Load Center-100 amp	1	EA
2	Coupling-1 1/2	1	EA
3	Conduit 1 1/2 pvc	5	LF
4	Adapter 1-1/2 sch	1	EA
5	Breaker-25 amp	1	EA
6	Breaker-15 amp	1	EA
7	Breaker-20 amp	1	EA
8	Breaker-15 amp Pole	1	EA
9	Breaker 2p 30A	1	EA
10	Connector-romex	9	EA
11	Wire 14/2 w/ground	705	LF
12	Wire 12/2 w/ground	235	LF
13	Wire 10/2 w/ground	10	LF
14	Wire 10/3 w/ground	12	LF
15	Wire-bare copper 8sd	10	LF
16	Lug ground 14-4	1	EA
17	Wire-thermostat	30	LF
18	Connector-crossover	3	EA

Item		Part/Quantity	Unit
7.2. Electrical Assembly Stage-A2		1	EA
1	Box-2 gang	8	EA
2	Box-1 gang	28	EA
3	Box-plastic round	15	EA
4	Recept-gfi	3	EA
5	Recept-duplex	25	EA
6	Switch-grd screw	15	EA
7	Recept-dryer	1	EA
8	Plate-1g switch	5	EA
9	Plate-1g recept	19	EA
10	Plate 2g switch	5	EA
11	Plate-2g recept	3	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
7.3. Electrical Assembly Stage-A3		1	EA
1	Cover-waterproof recept white-A	1	EA
2	Cover-waterproof recept white-B	1	EA
3	Fixture ext light	2	EA
4	Jelly jar ext light	2	EA
5	Ceiling lite textured	13	EA
6	Globe-fluted ball	13	EA
7	Breeze bath fan	2	EA
8	Flex duct 3" dia	20	LF
9	Smoke detector	1	EA
10	Plate nail 1-1/2	33	EA
11	Sleeve wire	40	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
8. Interior Partition A		1	EA
8.1. Interior Partition Type1		1	EA
1	Lumber 2x3x8' stud	2	EA
2	Lumber 2x3x9' stud fj west	4	EA
3	Lumber 1x3xRL (cut from 14')	17.3	LF
4	Lumber 1x3xRL back (cut from 12')	6	LF
5	Gypsum-vinyl sussex	56.2	SF
6	Gypsum-vinyl Morroccan sand	98.8	SF
8.2. Interior Partition Type2		1	EA
1	Lumber 2x3x8' stud	4	EA
2	Lumber 1x3xRL back (cut from 12')	2.3	LF
3	Lumber 1x3xRL (cut from 14')	8	LF
4	Gypsum-vinyl sussex	32	SF
5	Gypsum-vinyl Morroccan sand	32	SF
8.3. Interior Partition Type3			
1	Lumber 2x3x8' stud	4	EA
2	Lumber 2x3xRL back (cut from 12')	3.7	LF
3	Lumber 1x3xRL (cut from 14')	8.5	LF
4	Gypsum-vinyl Morroccan sand	42	SF
8.4. Interior Partition Type4			
1	Lumber 2x3x8' stud	6	EA
2	Lumber 1x3xRL back (cut from 12')	17.3	LF
3	Lumber 2x3xRL (cut from 14')	12.6	LF
4	Gypsum-vinyl sussex	11.1	SF
5	Gypsum-vinyl Morroccan sand	101.1	SF
8.5. Interior Partition Type5			
1	Lumber 2x3x8' stud	7	EA
2	Lumber 1x3xRL back (cut from 12')	8	LF
3	Lumber 2x3xRL (cut from 14')	4	LF
4	Lumber 1x3xRL (cut from 14')	18	LF
5	Gypsum-vinyl sussex	66.4	SF
6	Gypsum-vinyl Morroccan sand	66.4	SF
8.6. Interior Partition Type6			
1	Lumber 2x4x8' stud	1	EA
2	Lumber 2x4x9' stud(cut from 10')	2	EA
3	Lumber 1x4xRL back (cut from 14')	6	LF
4	Lumber 1x3xRL (cut from 14')	9	LF
5	Gypsum-vinyl sussex	54	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
8. Interior Partition A		1	EA
8.7. Interior Partition Type7			
1	Lumber 2x3x8' stud	4	EA
2	Lumber 2x3x9' stud fj west	4	EA
3	Lumber 2x3xRL back (cut from 14')	5.4	LF
4	Lumber 1x3xRL (cut from 14')	25.4	LF
5	Lumber 1x3xRL back (cut from 12')	22.4	LF
6	Gypsum-vinyl sussex	53.6	SF
7	Gypsum-vinyl Moroccan sand	143.6	SF
Item		Part/Quantity	Unit
9. Side Walls-A		1	EA
1	Lumber 2x6x81-7/8' stud	66	EA
2	Lumber 1x6xRL back (cut from 12')	88	EA
3	Lumber 2x6xRL back (cut from 16')	88	EA
4	Lumber 2x6x14-1/2' cut from 16'(splice blocks)	12	EA
5	Lumber 2x6x30-1/2' cut from 16' (Header)	6	EA
6	Lumber 2x6x46-1/2' cut from 16' (Header)	4	EA
7	Lumber 2x6x7-1/4' cut from 16' (Crip)	19	EA
8	Lumber 2x6x11-1/4' cut from 16' (Crip)	15	EA
9	Lumber 2x6x44-1/4' cut from 16' (Crip)	4	EA
10	Lumber 3/4x3/4/10' #3 btr	104	LF
11	Insulation r19 unf	444.2	SF
12	Gypsum-vinyl sussex	107.3	SF
13	Gypsum-vinyl Moroccan sand	504.7	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
10. End Wall Type-A		1	EA
10.1. End Wall Type-A1			
1	Lumber 2x6x8 # 3	10	EA
2	Lumber 2x6x10' # 4	11	EA
3	Lumber 2x6xRL back (cut from 16')	51.7	LF
4	Lumber 2x6x14-1/2' cut from 16'(splice blocks)	4	EA
5	Lumber 2x6x30-1/2' cut from 16' (Header)	4	EA
6	Lumber 2x6x46-1/2' cut from 16' (Header)	2	EA
7	Lumber 2x6xRL back (cut from 16')	18.2	LF
8	Lumber 2x6x11-1/4' cut from 16' (Crip)	10	EA
9	Insulation r19 unf 15x39.2"	188.1	SF
10	Gypsum-vinyl Morroccan sand	231.4	SF
10.2. End Wall Type-A2			
1	Lumber 2x6x8 # 3	11	EA
2	Lumber 2x6x10' # 4	10	EA
3	Lumber 2x6xRL back (cut from 16')	51.7	LF
4	Lumber 2x6x14-1/2' cut from 16'(splice blocks)	4	EA
5	Lumber 2x6x30-1/2' cut from 16' (Header)	2	EA
6	Lumber 2x6x11-1/4' cut from 16' (Crip)	3	EA
7	Lumber 2x6xRL back (cut from 16')	4.9	LF
8	Insulation r19 unf 15x39.2"	188.1	SF
9	Gypsum-vinyl Morroccan sand	231.4	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
11. Mating Walls-Type A		1	EA
1	Lumber, 2x3x106" stud f j wes	36	EA
2	Lumber 1x3xRL back (cut from 14')	56	LF
3	Lumber 2x3xRL back (cut from 14')	56	LF
4	Lumber 2x3x22-1/2 cut (cut from 14') (Splice blk)	8	EA
5	Lumber 1x3xrL (cut from 12')	37.2	LF
6	Lumber 2x3xrL (cut from 14')	17.4	LF
7	Gypsum-vinyl sussex	127.5	SF
8	Gypsum-vinyl Morroccan sand	342.1	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
12. Ceiling Type A		1	EA
1	Dw 28std 21-1/2x158-1/2 ct	47	EA
2	lumber, 2x4xrl(cut from 14')	56	LF
3	lumber, 2x3xrl (cut from 14')	92	LF
4	lumber, 2x6xrl (cut from 16')	92	LF
5	Lumber 2x6x30-1/2' cut from 16' (Header)	88	EA
6	Lumber, 1-1/2x18x24' LVL	2	EA
7	Lumber, 1x3xrl (cut from 14')	96	LF
8	Lumber 2x6x22-1/2' cut from 14'(splice blocks)	8	EA
9	Lumber 2x6x22-1/2' cut from 16'(splice blocks)	8	EA
10	Lumber 2x6x16 btr #2	4	EA
11	Lumber, 2x3x8' stud	12	EA
12	Ceiling board, 1/2", 13'4"	1173	SF
13	Lumber 2x4x22-1/2' cut from 14'(splice blocks)	4	EA
14	Insulation cellulose	28	BG
15	Vapor barrier 275 gal	2.93	GL
16	Insulation r19 unf 15x39.2"	110	SF
17	Tape mesh blue	0.9	RL
18	Mud-MH superset 20 min	2.6	EA
19	Mud g series all props	16	BX
20	Gypsum obsolete-end rafters	5	EA
21	Lumber, 1x3x28 (cut from 14')	13	EA
22	Sheathing, goldguard	40.5	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
13. Exterior Finish Assembly-A		1	EA
1	Sheathing, goldguard, 7/16x96"	1099	SF
2	OSB board 7/16 4x8	64	SF
3	Starter strip, 12'	140	LF
4	Siding, dbl. 4-1/2 dl. Clay	11.6	SQ
5	Outside corner, 8'-6", clay	4	EA
6	J block, light large, white	2	EA
7	J block, recept, white	1	EA
8	Door, rear. Sd, 4x24 slb, 38x79	1	EA
9	Window, metal, white 30x60 ext	5	EA
10	Window, metal, white 30x27 ext	1	EA
11	Window, metal, white 46x60 ext	3	EA
12	Window, metal, white 30x60 white storm	5	EA
13	Window, metal, white 30x27 white storm	1	EA
14	Shutter, 12x56, rsp	2	PR
15	Fascia, white steel	148	LF
16	Soffit receiver, w/steel 10'	140	LF
17	Soffit vented, white	130	SF
18	J channel, 12-6x40 pc/carton	40	LF
19	Finish trim, white	40	LF

Item		Part/Quantity	Unit
14. Exterior Roof Finish Assembly-A		1	EA
1	OSB board 7/16 4x8	1342	SF
2	SGL Underlayment 48'x600'	376	SF
3	SGL Underlayment 96'x300'	1504	SF
4	Roof cement,5 gallon pails	2.1	GA
5	Drip edge, 10' white	150	LF
6	Shingles-royal sovereign	14.5	SQ
7	Roof vent, black	8	EA
8	Flashing, plastic 1 1/2	2	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
15. Trim -A1		1	EA
1	Door, plymouth oak, 2/0 x 6/6	6	EA
2	Door jamb, 1/2x3 1/4x80 7/8"	102	LF
3	Lockset, passage, chrome std	4	EA
4	Lockset, privacy, chrome std	2	EA
5	Flat, 1-1/4"x8' Part A	153	LF
6	Door stop 7'	51	LF
7	Door hinge, interior chrome	9	EA
8	Flat, 1-1/4"x8' Part B	36	LF
9	Cabinet panel, 1/8"-A	5	SF
10	Batten, flat 7/8"-A	17	LF
11	Cabinet panel, 1/8"-B	30.5	SF
12	Batten, flat 7/8"-B	8.5	LF
13	Cabinet panel, 1/8"-B	21.6	SF
14	Batten, flat 7/8"-C	5.1	LF
15	Tub trim 7'-A	13.2	LF
16	Tub trim 7'-B	21.5	LF
17	Tub trim 7'-C	23.5	LF
18	Batten, flat 7/8"-D	37.5	LF
19	Batten, oak 2" flat	248	LF
20	Batten, oak 2" flat	156	LF
21	Cab crown with 8" lip	40	LF
22	Batten, flat 7/8"E	1351	LF
23	Shelving, Wire closet	26.3	LF
24	Brackets, end shelving	10	EA
25	Brackets u-clamp	20	EA
26	Support, shelf, 12"	8	EA
27	Corner brace, shelving	2	EA
28	Lumber, 1x3xrl (cut from 14')	32	LF
29	Lumber, 1x4xrl (cut from 14')	32	LF
30	Gypsum vinyl morroccan sand	26.1	SF
31	Skylite lip moulding 9'	68	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
16. Final Finish-A		1	EA
1	Refer, 16 cf	1	EA
2	Range, gas, std clean pilot	1	EA
3	Range hood	1	EA
4	Pipe, range hood, 5"x60"	1	EA
5	Drapes, springdale	1	EA
6	Rod, curtain, 28-48, 2"cl	2	EA
7	Rod, curtain, 48-24, 2"clr	5	EA
8	Mini blind 29"x33"	1	EA
9	Mini blind 29"x64"	5	EA
10	Mini blind 45"x64"	3	EA
11	Mirror, std 24x36	3	EA
12	Grill, brown, 24x24 return air	2	EA
13	Shower liner, 72x72	1	EA
14	Ring, shower curtain	12	EA
15	Rod, shower, 60"	1	EA
16	Flange, white shower rod, wsrf	2	EA
17	Close up plastic, std, 14'x300,	150	LF
18	Lumber, close up	44	LF
19	OSB, 7/16 4x8	36	SF
20	Gypsum vinyl morroccan sand	22	SF
21	U-channel , 5/16x12' pol wht	34	LF
22	Towel bar, chrome complete	2	EA
23	Paper roller, chrome complete	2	EA
24	Door stop, interior chrome	10	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
17. Cabinet Assembly-A		1	EA
17.1. Base Assembly-6"		1	EA
1	6" base	1	EA
2	Stile 3", wrapped atkins oak	5.3	LF
3	Cabinet panel, 1/8"	11	SF
4	Lumber, 3/4x3/4/10 #3 btr	20.6	LF
17.2 Base Assembly-19"		1	EA
1	Stile 3", wrapped atkins oak	3.8	LF
2	Stile 2", wrapped atkins oak	5	LF
3	Cabinet door, slab 15x21	1	EA
4	Hinge, ovrlly adj	2	EA
5	Knob, chrome, cabinet	2	EA
6	Drawer front, slab 6"x15"	1	EA
7	Drawer side, 5/16x4-1/2 -A	3.7	LF
8	Drawer side, 5/16x4-1/2 -B	2.2	LF
9	Cabinet panel, 1/4", 2 sided	2	SF
10	Drawer guide, 22"	1	PR
11	Backsocket, drw guide	1	PR
12	Cabinet shelf, 1/2x22x97	1.6	LF
13	Cab shelf, atkins oak, 3/8 mdf	2.9	SF
14	Cabinet panel, 1/8"	7	SF
15	Cabinet panel, 1/4"	5.4	SF
16	Lumber, 3/4x3/4/10 #3 btr	27.4	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
17. Cabinet Assembly-A		1	EA
17.3 Base Cabinet Assembly			
1	Stile 3", wrapped atkins oak	6.5	LF
2	Stile 2", wrapped atkins oak	4.6	LF
3	Cabinet door, slab 12"x21"	1	EA
4	Drawer front, slab 6"x24"	1	EA
5	Drawer side, 5/16x4-1/2 -A	3.5	LF
6	Drawer frt&back5/16x3-3/4x58	3.6	LF
7	Backsocket, drw guide	1	PR
8	Drawer guide, 22"	1	PR
9	Hinge, ovrlly adj	4	EA
10	Knob, chrome, cabinet doors	3	EA
11	Cabinet panel, 1/8"	1	SF
12	Cabinet panel, 1/4" two sided	11	SF
13	Cabinet shelf, 1/2x22x97	2.3	LF
14	Lumber, 3/4x3/4/10 #3 btr	32.1	LF
15	Cab panel, seconds, 1/4"	3.2	SF
16	Cab shelf, atkins oak, 3/8 mdf	4.2	SF
17.4. Corner Base Cabinet Assembly-3/4"			
1	Stile 3", wrapped atkins oak	7.1	LF
2	Stile 2", wrapped atkins oak	3.6	LF
3	Cabinet door, slab 12"x21"	1	EA
4	Drawer front, slab 6"x24"	1	EA
5	Drawer side, 5/16x4-1/2 -A	3.5	LF
6	Drawer frt&back5/16x3-3/4x58	2.2	LF
7	Backsocket, drw guide	1	PR
8	Drawer guide, 22"	1	PR
9	Hinge, ovrlly adj	2	EA
10	Knob, chrome, cabinet doors	2	EA
11	Cabinet shelf, 1/2x22x97	3.5	LF
12	Cabinet panel, 1/8"	1.4	SF
13	Cabinet panel, 1/4" two sided	5.5	SF
14	Cab panel, seconds, 1/4"	2.1	SF
15	Lumber, 3/4x3/4/10 #3 btr	41	LF
16	Cab shelf, atkins oak, 3/8 mdf	6.4	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
17. Cabinet Assembly-A		1	EA
17.5. Sink Base Cabinet Assembly		1	EA
1	Stile 3", wrapped atkins oak	2.5	LF
2	Stile 2", wrapped atkins oak	10.1	LF
3	Cabinet door, slab 15"x21"	2	EA
4	Drawer front, slab 6"x30"	1	EA
5	Hinge, ovrlly adj	4	EA
6	Knob, chrome, cabinet doors/drws	2	EA
7	Cabinet panel, 1/8"	1.1	SF
8	Cabinet panel, 1/4" two sided	12.4	SF
9	Lumber, 3/4x3/4/10 #3 btr	42.5	LF
17.6 Bar Base Cabinet Assembly		1	EA
1	Stile 3", wrapped atkins oak	7.5	LF
2	Stile 2", wrapped atkins oak	22.8	LF
3	Cabinet door, slab 12"x21"	3	EA
4	Hinge, ovrlly adj	6	EA
5	Knob, chrome, cabinet doors/drws	5	EA
6	Drawer front, slab 6"x12"	1	EA
7	Drawer front, slab 6"x24"	2	EA
8	Drawer side, 5/16x4-1/2 -A	7.3	LF
9	Drawer side, 5/16x4-1/2 -A	5.3	LF
10	Cabinet panel, 1/4" two sided	4.9	SF
11	Backsocket, drw guide	2	PR
12	Drawer guide, 22"	2	PR
13	Cabinet shelf, 1/2x22x97	5.6	LF
14	Cab shelf, atkins oak, 3/8 mdf	10.2	SF
15	Cabinet panel, 1/8"	37.2	SF
16	Cabinet panel, 1/4" two sided	5.4	SF
17	Lumber, 3/4x3/4/10 #3 btr	67	LF
18	Lumber, 1x2 #3 btr mill room	42.8	LF
19	Counter top, pebble santos	14	SF
20	Self edge 2.5" moss erosiom	14.2	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
17. Cabinet Assembly-A		1	EA
17.7. Bar Overhead Cabinet		1	EA
1	Stile 3", wrapped atkins oak	12.7	LF
2	Stile 2", wrapped atkins oak	24.2	LF
3	Cabinet door slab, 15"x21"	3	EA
4	Hinge, ovrlly adj	14	EA
5	Knob, chrome, cabinet doors/drwr	3	EA
6	Cabinet door, slab china, 15x21	4	EA
7	Glass, china door 11-1/2x17-1/2	4	EA
8	Cabinet shelf, 1/2x22x97	11.2	LF
9	Cabinet panel, 1/8"	13.2	SF
10	Cabinet panel, 1/4" two sided	2	SF
11	Lumber, 3/4x3/4/10 #3 btr	33.7	LF
17.8. 27" Overhead Cabinet		1	EA
1	Stile 2", wrapped atkins oak	15.8	LF
2	Cabinet door slab, 12"x21"	4	EA
3	Hinge, ovrlly adj	8	EA
4	Knob, chrome, cabinet doors/drwr	4	EA
5	Cabinet shelf, 1/2x22x97	9	LF
6	Cabinet panel, 1/8"	17.8	SF
7	Cabinet panel, 1/4" two sided	8	SF
8	Lumber, 3/4x3/4/10 #3 btr	49.2	LF
17.9. Overhead Range Cabinet		1	EA
1	Stile 3", wrapped atkins oak	6.4	LF
2	Stile 2", wrapped atkins oak	7.1	LF
3	Cabinet door slab, 18"x15"	2	EA
4	Hinge, ovrlly adj	4	EA
5	Knob, chrome, cabinet doors/drwr	2	EA
6	Cab shelf, atkins oak, 3/8 mdf	4.4	SF
7	Cabinet panel, 1/8"	10.1	SF
8	Lumber, 3/4x3/4/10 #3 btr	25.4	LF
9	Cabinet panel, 1/4" two sided	4.2	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
17. Cabinet Assembly-A		1	EA
17.10. Corner Overhead Cabinet		1	EA
1	Stile 3", wrapped atkins oak	2	LF
2	Stile 2", wrapped atkins oak	8.7	LF
3	Cabinet door slab, 18"x21"	1	EA
4	Hinge, ovrlly adj	2	EA
5	Knob, chrome, cabinet doors/drwr	1	EA
6	Cabinet shelf, 1/2x22x97	5.8	LF
7	Cabinet panel, 1/8"	13.7	SF
8	Cabinet panel, 1/4" two sided	2	SF
9	Lumber, 3/4x3/4/10 #3 btr	22	LF
17.11. Reference Shelf		1	EA
1	Stile 2", wrapped atkins oak	2.9	LF
2	Cabinet panel, 1/8"	5.7	SF
3	Lumber, 3/4x3/4/10 #3 btr	7.5	LF
17.12. 21" Pantry Shelf		1	EA
1	Stile 3", wrapped atkins oak	5.7	LF
2	Stile 2", wrapped atkins oak	15.1	LF
3	Cabinet door slab, 18"x21"	1	EA
4	Cabinet door slab, 18"x54 3/4	1	EA
5	Hinge, ovrlly adj	5	EA
6	Knob, chrome, cabinet doors/drwr	2	EA
7	Cab shelf, atkins oak, 3/8 mdf	6.4	SF
8	Cabinet panel, 1/8"	19.3	SF
9	Cabinet panel, 1/4" two sided	25.3	SF
10	Lumber, 3/4x3/4/10 #3 btr	54	LF
17.15. Kitchen Counter Tops		1	EA
1	Lumber, 1x2 #3 btr mill room	9	LF
2	Counter top, pebble santos	23.1	SF
3	Self edge 2.5" moss erosion	15.5	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
17. Cabinet Assembly-A		1	EA
17.13. Vanity Cabinet Module-A		1	EA
1	Stile 2", wrapped atkins oak	11.5	LF
2	Drawer front slab 6"x12"	3	EA
3	Drawer side 5/16x4-1/2	8	LF
4	Drawer frt&back5/16x3-3/4x58	4.5	LF
5	Cabinet panel, 1/4" two sided	3.2	SF
6	Knob, chrome, cabinet doors/drws	3	EA
7	Backsocket, drw guide	3	PR
8	Drawer guide, 16"	3	PR
9	Cabinet panel, 1/8"	1	SF
10	Cabinet panel, 1/8"	4.7	SF
11	Lumber, 3/4x3/4/10 #3 btr	13.9	LF
12	Lumber, 1x2 #3 btr mill room	3	LF
13	Counter top, pebble santos	2.2	SF
14	Self edge 2.5" moss erosion	3	LF
17.14. Vanity Cabinet Module-B		1	EA
1	Stile 3", wrapped atkins oak	6	LF
2	Stile 2", wrapped atkins oak	35.1	LF
3	Cabinet door slab, 12"x15"	3	EA
4	Hinge, ovrlly adj	12	EA
5	Knob, chrome, cabinet doors/drws	9	EA
6	Drawer front slab 6"x24"	3	EA
7	Drawer side 5/16x4-1/2	4.8	LF
8	Drawer frt&back5/16x3-3/4x58	10.5	LF
9	Drawer guide, 9/14"	3	PR
10	Backsocket, drw guide	3	PR
11	Cabinet panel, 1/4" two sided	4.2	SF
12	Cab shelf, atkins oak, 3/8 mdf	10.5	SF
13	Cabinet panel, 1/8"	4.5	SF
14	Cabinet panel, 1/4" two sided	14.1	SF
15	Lumber, 3/4x3/4/10 #3 btr	90	LF
16	Lumber, 1x2 #3 btr mill room	12.3	LF
17	Counter top, pebble santos	12.3	SF
18	Self edge 2.5" moss erosion	12.3	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
18. Fuse Panel Doors		1	EA
1	Stile 2", wrapped atkins oak	6.9	LF
2	Hinge, overly,em	2	EA
3	Cabinet door, slab 18"x21"	1	EA

Item		Part/Quantity	Unit
19. Fasteners		44	LF
Refrigerators		1	EA
Washers		1	EA
Fan		1	EA
Dryer		1	EA

Item		Part/Quantity	Unit
1. Frame Assembly B		1	EA
1	Frame s. triple, 10"	2	EA
2	Axle, idler, 99-1/2 recycled	4	EA
3	Axle, brake, 99-1/2 recycled	2	EA
4	Tyre, new 8-14.5/12ply	12	EA
5	Bolt, shackle, 1/2-13x3-1/2	24	EA
6	Lock, nut, 1/2-13, top notched	24	EA
7	Wire, 18-1, sae, primary red	116	LF
8	Wire, 18-1, sae, primary white	116	LF
9	Wire, 18-1, sae, primary black	116	LF
10	Wire brake, 14/2 sae red jacket	64	LF
11	Lug, ground 14-4 cu, 1/4 hole	2	EA
12	Wire, Bare Copper, 8sd	6	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
2. Floor Assembly B1		1	EA
1	Lumber, 2x6x14-1/2-cut, splice block	12	EA
2	Lumber, 2x6x19-1/2-cut, furnace block	2	EA
3	Lumber, 2x6x157-#2 btr	68	EA
4	Lumber, 2x6x29-3/4"	52	EA
5	Lumber, 2x6x12- # 3	15	EA
6	Bottom board, 176, ms1763	1349	SF
7	Insulation, r11, unf, 90"x75'	1012	SF
8	Insulation, r19, unf, 15"x39'2"	515	SF
9	Head Duct Aluminium- 5" x 12"	56	LF
10	Head Duct Aluminium- 5" x 12"	24	LF
11	Ground Strap' 4"x120"	2	EA
12	Insulation, r11, unf, 15"x93	112	SF
13	Strapping Steel, Crossover	4	EA
14	Boot, Register, 4"x10"x6"	6	EA
15	Register, 4x10, white	8	EA
16	Collar, start, 5"	2	EA
17	Flexduct, 5x10", insulated	30	LF
18	Tie Strap, 21" nylon, heat duct	4	EA
19	Boot, 4x10x5, inline	2	EA
20	Lag, 5/16x3, hex, s/l, waxed	328	EA

Item		Part/Quantity	Unit
2.1. Floor Assembly-B2		1	EA
1	Novodeck, 96x168, (trim 160)	1120	SF
2	Novodeck,48x168, (trim 160)	112	SF

2.2. Floor Assembly-B3		1	EA
1	Linoleum, 13'6"	40.5	SY
2	Carpet	61	SY
3	Carpet Pad	61	SY

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
7.1. Electrical Assembly Stage-B1		1	EA
1	Coupling-1 1/2	1	EA
2	Conduit 1 1/2 pvc	5	LF
3	Adapter 1-1/2 sch	1	EA
4	Connector-romex	9	EA
5	Wire 14/2 w/ground	705	LF
6	Wire 12/2 w/ground	235	LF
7	Wire 10/2 w/ground	10	LF
8	Wire 10/3 w/ground	12	LF
9	Wire-bare copper 8sd	10	LF
10	Lug ground 14-4	1	EA
11	Wire-thermostat	30	LF
12	Connector-crossover	3	EA
7.2. Electrical Assembly Stage-B2		1	EA
1	Box-2 gang	4	EA
2	Box-1 gang	14	EA
3	Box-plastic round	15	EA
4	Recept-gfi	3	EA
5	Recept-duplex	25	EA
6	Switch-grd screw	15	EA
7	Plate-1g switch	5	EA
8	Plate-1g recept	19	EA
9	Plate 2g switch	5	EA
7.3. Electrical Assembly Stage-B3		1	EA
1	Fixture ext light	2	EA
2	Jelly jar ext light	2	EA
3	Ceiling lite textured	13	EA
4	Globe-fluted ball	13	EA
5	Breeze bath fan	2	EA
6	Flex duct 3" dia	20	LF
7	Plate nail 1-1/2	33	EA
8	Sleeve wire	40	EA

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
8. Interior Partition B		1	EA
8.1 Interior Partition Type B1		1	EA
1	Lumber 2x3x8' stud	4	EA
2	Lumber 2x3x9' stud fj west	2	EA
3	Lumber 2x3xRL back (cut from 14')	18.6	LF
4	Lumber 1x3xRL back (cut from 12')	16.8	LF
5	Gypsum-vinyl sussex	165.8	SF
6	Gypsum-vinyl Morroccan sand	143.6	SF
8.2 Interior Partition Type B2		1	EA
1	Lumber 2x4x8' stud	5	EA
2	Lumber 2x4x9' stud(cut from 10')	2	EA
3	Lumber 1x4xRL back (cut from 14')	18.6	LF
4	Lumber 1x3xRL (cut from 12')	17.8	LF
5	Gypsum-vinyl sussex	82.9	SF
6	Gypsum-vinyl Morroccan sand	82.9	SF
8.3. Interior Partition Type B3		1	EA
1	Lumber 2x3x9' stud fj west	9	EA
2	Lumber 2x3xRL back (cut from 14')	12.6	LF
3	Lumber 1x3xRL back (cut from 14')	27	LF
4	Lumber 1x3xRL back (cut from 12')	27.1	LF
5	Gypsum-vinyl sussex	54.8	SF
6	Gypsum-vinyl Morroccan sand	118.8	SF
8.4. Interior Partition Type B4		1	EA
1	Lumber 2x3x8' stud	2	EA
2	Lumber 2x3xRL back (cut from 14')	4	LF
3	Lumber 1x3xRL back (cut from 12')	1.8	LF
4	Gypsum-vinyl Morroccan sand	36	SF
8.5. Interior Partition Type B5		1	EA
1	Lumber 2x3x8' stud	2	EA
2	Lumber 2x3x9' stud fj west	2	EA
3	Lumber 2x3xRL back (cut from 14')	4.7	LF
4	Lumber 1x3xRL back (cut from 14')	5.8	LF
5	Gypsum-vinyl Morroccan sand	23	SF
8.6. Interior Partition Type B6		1	EA
1	Lumber 2x4x8' stud	5	EA
2	Lumber 2x4x9' stud(cut from 10')	4	EA
3	Lumber 2x4xRL back (cut from 14')	8.1	LF
4	Lumber 1x4xRL back (cut from 14')	25.4	LF
5	Lumber 1x3xRL (cut from 12')	19.3	LF
6	Gypsum-vinyl Morroccan sand	191.4	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
8. Interior Partition B		1	EA
8.7. Interior Partition Type B7		1	EA
1	Lumber 2x3x8' stud	2	EA
2	Lumber 2x3xRL back (cut from 14')	4	LF
3	Lumber 1x3xRL back (cut from 12')	1.8	LF
4	Gypsum-vinyl Moroccan sand	36	SF
8.8. Interior Partition Type B8		1	EA
1	Lumber 2x3x8' stud	7	EA
2	Lumber 2x3xRL back (cut from 14')	6.1	LF
3	Lumber 1x3xRL back (cut from 14')	20.2	LF
4	Gypsum-vinyl Moroccan sand	110.6	SF

Item		Part/Quantity	Unit
9. Side Walls B		1	EA
1	Lumber 2x6x81-7/8' stud	66	EA
2	Lumber 1x6xRL back (cut from 12')	88	EA
3	Lumber 2x6xRL back (cut from 16')	88	EA
4	Lumber 2x6x14-1/2' cut from 16'(splice blocks)	12	EA
5	Lumber 2x6x30-1/2' cut from 16' (Header)	6	EA
6	Lumber 2x6x46-1/2' cut from 16' (Header)	4	EA
7	Lumber 2x6x7-1/4' cut from 16' (Crip)	19	EA
8	Lumber 2x6x11-1/4' cut from 16' (Crip)	15	EA
9	Lumber 2x6x44-1/4' cut from 16' (Crip)	4	EA
10	Lumber 3/4x3/4/10' #3 btr	104	LF
11	Insulation r19 unf	444.2	SF
12	Gypsum-vinyl sussex	107.3	SF
13	Gypsum-vinyl Moroccan sand	504.7	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
10. End Wall Type-B		1	EA
10.1. End Wall Type-B1		1	EA
1	Lumber 2x6x8 # 3	10	EA
2	Lumber 2x6x10' # 4	11	EA
3	Lumber 2x6xRL back (cut from 16')	51.7	LF
4	Lumber 2x6x14-1/2' cut from 16'(splice blocks)	4	EA
5	Lumber 2x6x30-1/2' cut from 16' (Header)	4	EA
6	Lumber 2x6x46-1/2' cut from 16' (Header)	2	EA
7	Lumber 2x6xRL back (cut from 16')	18.2	LF
8	Lumber 2x6x11-1/4' cut from 16' (Crip)	10	EA
9	Insulation r19 unf 15x39.2"	188.1	SF
10	Gypsum-vinyl Morroccan sand	231.4	SF
10.2. End Wall Type-B2		1	EA
1	Lumber 2x6x8 # 3	11	EA
2	Lumber 2x6x10' # 4	10	EA
3	Lumber 2x6xRL back (cut from 16')	51.7	LF
4	Lumber 2x6x14-1/2' cut from 16'(splice blocks)	4	EA
5	Lumber 2x6x30-1/2' cut from 16' (Header)	2	EA
6	Lumber 2x6x11-1/4' cut from 16' (Crip)	3	EA
7	Lumber 2x6xRL back (cut from 16')	4.9	LF
8	Insulation r19 unf 15x39.2"	188.1	SF
9	Gypsum-vinyl Morroccan sand	231.4	SF

Item		Part/Quantity	Unit
11. Mating Walls-Type B		1	EA
1	Lumber, 2x3x106" stud fj wes	36	EA
2	Lumber 1x3xRL back (cut from 14')	56	LF
3	Lumber 2x3xRL back (cut from 14')	56	LF
4	Lumber 2x3x22-1/2 cut (cut from 14') (Splice blk)	8	EA
5	Lumber 1x3xrL (cut from 12')	37.2	LF
6	Lumber 2x3xrL (cut from 14')	17.4	LF
7	Gypsum-vinyl sussex	127.5	SF
8	Gypsum-vinyl Morroccan sand	342.1	SF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
12. Ceiling Type B		1	EA
1	Dw 28std 21-1/2x158-1/2 ct	47	EA
2	lumber, 2x4xrl(cut from 14')	56	LF
3	lumber, 2x3xrl (cut from 14')	92	LF
4	lumber, 2x6xrl (cut from 16')	92	LF
5	Lumber 2x6x30-1/2' cut from 16' (Header)	88	EA
6	Lumber, 1-1/2x18x24' LVL	2	EA
7	Lumber, 1x3xrl (cut from 14')	96	LF
8	Lumber 2x6x22-1/2' cut from 14'(splice blocks)	8	EA
9	Lumber 2x6x22-1/2' cut from 16'(splice blocks)	8	EA
10	Lumber 2x6x16 btr #2	4	EA
11	Lumber, 2x3x8' stud	12	EA
12	Ceiling board, 1/2", 13'4"	1173	SF
13	Lumber 2x4x22-1/2' cut from 14'(splice blocks)	4	EA
14	Insulation cellulose	28	BG
15	Vapor barrier 275 gal	2.93	GL
16	Insulation r19 unf 15x39.2"	110	SF
17	Tape mesh blue	0.9	RL
18	Mud-MH superset 20 min	2.6	EA
19	Mud g series all props	16	BX
20	Gypsum obsolete-end rafters	5	EA
21	Lumber, 1x3x28 (cut from 14')	13	EA
22	Sheathing, goldguard	40.5	SF
Item		Part/Quantity	Unit
15. Exterior Finish Assembly-B		1	EA
1	Sheathing, goldguard, 7/16x96"	1099	SF
2	OSB board 7/16 4x8	64	SF
3	Starter strip, 12'	140	LF
4	Siding, dbl. 4-1/2 dl. Clay	11.6	SQ
5	Outside corner, 8'-6", clay	4	EA
6	J block, light large, white	2	EA
7	J block, receipt, white	1	EA
8	Door, frt. Sd, 4x24 slb, 38x78	1	EA
9	Window, metal, white 46x60 white storm	3	EA
10	Shutter, 12x56, rsp	2	PR
11	Fascia, white steel	148	LF
12	Soffit receiver, w/steel 10'	140	LF
13	Soffit vented, white	130	SF
14	J channel, 12-6x40 pc/carton	40	LF
15	Finish trim, white	40	LF

Table B1(cont): Product Breakdown Structure

Item		Part/Quantity	Unit
14. Exterior Roof Finish Assembly-B		1	EA
1	OSB board 7/16 4x8	1342	SF
2	SGL Underlayment 48'x600'	376	SF
3	SGL Underlayment 96'x300'	1504	SF
4	Roof cement,5 gallon pails	2.1	GA
5	Drip edge, 10' white	150	LF
6	Shingles-royal sovereign	14.5	SQ
7	Roof vent, black	8	EA
8	Flashing, plastic 1 1/2	2	EA

Item		Part/Quantity	Unit
16. Final Finish-B		1	EA
1	Drapes, springdale	1	EA
2	Rod, curtain, 28-48, 2"cl	2	EA
3	Rod, curtain, 48-24, 2"clr	5	EA
4	Mini blind 29"x33"	1	EA
5	Mini blind 29"x64"	5	EA
6	Mini blind 45"x64"	3	EA
7	Mirror,std 24x36	3	EA
8	Close up plastic, std, 14'x300,	150	LF
9	Lumber, close up	44	LF
10	OSB, 7/16 4x8	36	SF
11	Gypsum vinyl morroccan sand	22	SF
12	U-channel , 5/16x12' pol wht	34	LF
13	Door stop, interior chrome	5	EA

Item		Part/Quantity	Unit
19. Fasteners		44	EA

APPENDIX-C

PRODUCT-TREE STRUCTURE FOR CASE-STUDY FACTORY

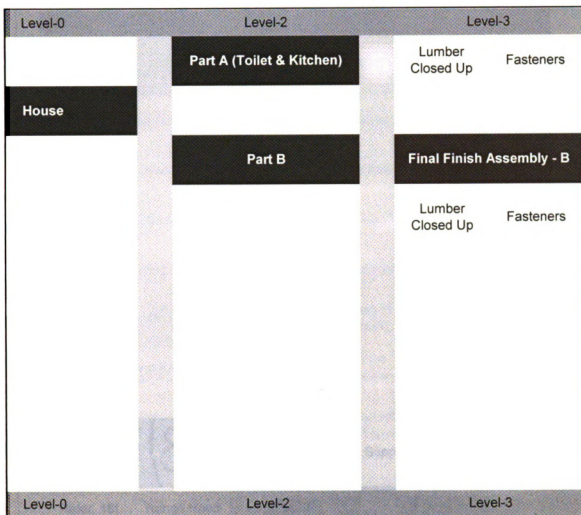


Figure C1: Product Tree Diagram

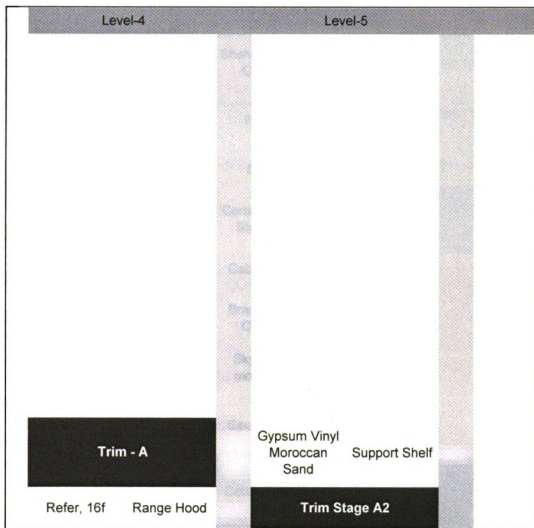


Figure C1(cont): Product Tree Diagram

Level-4		Level-5		Level-6
Electrical Assembly - A3		Shelving-Wire Closet	Flat B	
Range Gas	Mirror Std	Flat A	Lockset	
Pipe-Range Hood	Mini Blind-A	Door	Door Stop	
Drapes	Mini Blind-B	Corner Brace Shelving	Door Jamb	
Curtain Rod-A	Mini Blind-C	Cab Crown	Door Hinge	
Curtain Rod-B	Return Air Grill	Brackets-U Clamp	Brackets-End Shelving	
OSB Board	Shower Rod	Skylite lip moulding	Smoke Detector	
Gypsum Vinyl Morroccan Sand	Flange-Shower Rod	SleeveWire	Exterior Jelly Jar Light	
U-Channel	Closed Plastic Stand	Ceiling Light	Exterior Light Fixture	Trim Stage A1

Trim Stage A1		Exterior Finish Assembly A	
Level-6		Level-7	
Batten 7/8 E	Batten 7/8 D	Cabinet Panel 1/8A	Lumber 1x3xRL (cut from 14)
Batten 7/8 F	Batten-7/8 A	Lumber 1x3xRL (cut from 14)	Lumber 1x4xRL (cut from 14)
Batten 7/8 G		Lumber 1x4xRL (cut from 14)	
Trim Stage B1		Exterior Finish Assembly B	

Figure C1(cont): Product Tree Diagram

Level-4		Level-5		Level-6	
Curtain Rod-A	Door Stop	Globe Fluted Ball	Flexi Duct	Batten 7/8 E	Batten 7/8 D
Curtain Rod-B	Paper Roller	Brackets-End Shelving	Plate-Nail	Batten 7/8 F	Batten-7/8 A
Mini Blind-A	Closed Plastic Stand	Ceiling Light	Exterior Jelly Jar Light	Batten 7/8 G	
Mini Blind-B	Door Stop	Brackets-U Clamp	Lockset	Trim Stage B1	
Mini Blind-C	Drapes	Corner Brace Shelving	Plate-Nail		
Electrical Assembly - B3		Door	Shelving-Wire Closet		
Mirror Std	U-Channel	Support Shelf	Flexi Duct		
Gypsum Vinyl Moroccan Sand	Shower Liner	Door Jamb	Skylite lip moulding		
OSB Board	Shower Curtain Ring	Trim Stage B2			

Level-4	Level-5	
Trim - B	Gypsum Vinyl Moroccan Sand	Globe Fluted Ball
	SleeveWire	Exterior Light Fixture
	Door Hinge	Door Stop
	Fan	

Figure C1(cont): Product Tree Diagram

Electrical Assembly - A2			
Level-8		Level-9	
Exterior Roof Finish A		Ceiling Type A	
Door-Rear SD	Finish Trim	Box plastic Round	Box-2 Gang
Fuse Panel Door Assembly		Box-1 Gang	Switch Plate-C
Fascia White	J Block	Cabinet Door	Drip Edge
J Channel	Window Metal-30x27 white storm	Shingles	Switch Plate-D
OSB Board	Outside Corner	Receptacle-dryer	Hinge
Siding Double	Window Metal-30x60	Stile	Receptacle-GFI
Window Metal-30x60 white storm	Soffit Vented	Switch Ground Screw	
Window Metal-46x60	Window Metal-30x27	Switch Plate-A	Roof Vent
		Ceiling Type A Stage	

Figure C1(cont): Product Tree Diagram

Level-8		Level-9		Level-10
Door-Front SD	Soffit Receiver	Switch Plate-B	Box plastic Round	Ceiling Type B Stage 2
Electrical Assembly - B2		SGL Underlayment	OSB Board 7/16	End Wall B
Siding Double	Soffit Receiver	Flashing Plastic	OSB Board 7/16	
Soffit Vented	OSB Board	Roof Cement	Receptacle-duplex	
J Channel	J Block	Ceiling Type B		
Starter Strip	Sheathing Goldguard	Receptacle-GFI	Switch Ground Screw	
Outside Corner		Flashing Plastic	Switch Plate-C	
Finish Trim		Roof Cement	Switch Plate-B	
Fascia White	Window Metal-46x60	Box-1 Gang	Switch Plate-A	
Level-8		Level-9		Level-10
Exterior Roof Finish B		Roof Vent	SGL Underlayment	
		Drip Edge	Shingles	

Figure C1(cont): Product Tree Diagram

Level-11		Level-12		Level-13	
		Lumber-2x6x11	Lumber-2x6x46		
		Lumber-2x6x11	Lumber-2x6x10		
		Lumber-2x6x22-16	Gypsum Vinyl Moroccan Sand		
Ceiling Type A Stage 1		Lumber-2x6x14	Lumber-2x3xRL		
End Wall Type1		Lumber-2x6x81	Insualtion r19	Side Wall Stage-1	
End Wall Type2		Lumber-2x6x14	Ceiling Board	Electrical Assembly - A1	
Mating Wall A		Lumber-1x3xRL	Lumber-2x6x30	Lumber-2x3x22 (cut from 14)	Lumber-2x3xRL (cut from 14)
Insualtion r19	Insulation Cellulose	Lumber-2x6x10	Lumber-2x4xRL	Lumber-1x3xRL (cut from 12)	Gypsum Vinyl Sussex
Mud	Mud-g	Gypsum Vinyl Moroccan Sand	Gypsum-end rafters	Gypsum Vinyl Moroccan Sand	Lumber-2x3x106 stud f/west

Figure C1(cont): Product Tree Diagram

Level-11		Level-12		Level-13	
Sheathing-Goldguard	Insulation Cellulose	Lumber 1x3x28	Lumber 2x3x8 stud	Lumber 2x3x106 stud f/west	Gypsum Vinyl Moroccan Sand Lumber 1x3xRL (cut from 14)
Tape Mesh	Sheathing-Goldguard	Lumber 2x6x22-14	Lumber 2x3xRL	Interior Partition B	
Mud-g	Insulation r19	Insulation r19	Gypsum Vinyl Moroccan Sand		
Vapor Barrier	Tape Mesh	Lumber 2x6x22-16	Lumber 2x4x22-splice block	Lumber 1x3xRL (cut from 12)	Lumber 2x3xRL (cut from 14)
Mud	Vapor Barrier	Lumber 2x6x30	Gypsum-end rafters	Lumber 2x3x22 (cut from 14)	Gypsum Vinyl Sussex
Ceiling Type B Stage 1		Lumber 1x3xRL	Lumber 2x4xRL	Electrical Assembly - B1	
End Wall Type1		Lumber 2x6x81	Insulation r19	Side Wall Stage-1	
End Wall Type2		Dw 28std	Lumber 2x6x10		
		Lumber-2x6x14	Lumber LVL		
Level-11		Level-12		Level-13	

Figure C1(cont): Product Tree Diagram

Level-14		Level-15	
Wire-D	Lumber-2x6x44	Lumber 1x3xRL back (cut from 12')	Gypsum-vinyl sussex
Lumber-2x6x30	Lumber-2x6x81	Lumber 2x3xRL (cut from 14')	Gypsum-vinyl Morroccan sand
Wire-E	Lumber-2x6x7	Lumber 2x4x8' stud	Lumber 1x3xRL (cut from 14')
Lumber-2x6x46	Conduit	Lumber 2x4x9' stud(cut from 10')	Gypsum-vinyl sussex
Connector-Crossover	Connector Romex	Lumber 2x3x8' stud	Lumber 1x3xRL back (cut from 12')
Lumber-2x6x30	Lumber-2x6x44	Lumber 2x3x9' stud fj west	Gypsum-vinyl sussex
Floor Assembly B3		Lumber 2x3xRL back (cut from 14')	Gypsum-vinyl Morroccan sand
Interior Partition-B3		Lumber 1x3xRL (cut from 14')	Lumber-2x3x9 stud fj west
Interior Partition-B5		Bowl Toilet	Bowl Tank

Figure C1(cont): Product Tree Diagram

Level-16			Level-17	
Knob, chrome, cabinet doors	Drawer front, slab 6"x24"	Lumber, 1x2 #3 btr mill room	Valve	Crimp Ring-B
Cabinet shelf, 1/2x22x97	Drawer side, 5/16x4-1/2 -A Drawer	Counter top, pebble santos	Furnace	Adapter-A
Cabinet panel, 1/8"	frt&back5/16x3 3/4x58	Backsocket, drw guide	Adapter-E	Elbow-B
Cabinet panel, 1/4" two sided	Knob, chrome, cabinet doors/drws	Drawer guide, 22"	Adapter-C	
Cab panel, seconds, 1/4"	Cab shelf, atkins oak, 3/8 mdf	Stile 3", wrapped atkins oak		
Lumber, 3/4x3/4/10 #3 btr	Cabinet panel, 1/8"	Stile 2", wrapped atkins oak	Frame Assembly B	
Cab shelf, atkins oak, 3/8 mdf	Cabinet panel, 1/4" two sided	Cabinet door slab, 18"x21"	Furnace	Lumber - 2x6x12
Stile 2", wrapped atkins oak	Lumber, 3/4x3/4/10 #3 btr	Cabinet door slab, 18"x54 3/4	Boot Registrar	Lumber - 2x6x14
Cabinet door slab, 18"x21"	Self edge 2.5" moss erosion	Hinge, ovrlly adj	Ground Strap	Bottom Board
			Collar Start	Lumber - 2x6x157

Figure C1(cont): Product Tree Diagram

Level-17		17	
Flexduct-Insulated	Insulation r11		
Insualtion r19	Ventilaire		
Boot Registrar	Lumber - 2x6x12		
Heat Duct Aluminium	Connector		
Lag	Lumber - 2x6x157		
Drain Water Vent Assembly			
Adapter	Vermin Proofer A	Axle Brake	Wire Copper
Plenum	Vermin Proofer B	Bolt Shackle	Wire-Black
Crimp Ring-A	Adapter-B	Lug Ground	Frames-Triple,10"
Register	Vermin Proofer C	Lock Nut	Wire-Red

Figure C1(cont): Product Tree Diagram

APPENDIX-D

**MATERIAL HANDLING DEVICES IN CASE-STUDY
FACTORY**

Table D1: List of the Material Handling Equipments used in Case-study Factory

Name	Type	Quantity	Costs		Available Time (in min)	Template		Utilization
			Fixed	F/P/M		Load	Unload	
<i>Electric Hoist A</i>	Special	18	3000	5	115200	Hoist Load-A	Hoist Unload-A	85%
<i>Electric Hoist B</i>	Special	6	3000	5	115200	Hoist Load-B	Hoist Unload-B	85%
<i>Electric Hoist C</i>	Special	3	4500	10	115200	Hoist Load-C	Hoist Unload-C	85%
<i>Fork Lift Caterpillar</i>	Lift truck	4	26000	5	115200	Fork Load-1	Fork Unload-1	85%
<i>Fork Lift Caterpillar Large</i>	Lift truck	3	36000	5	115200	Fork Load-2	Fork Unload-2	85%
<i>Fork Lift Ingersollrand</i>	Lift truck	4	34000	5	115200	Fork Load-3	Fork Unload-3	85%
<i>Fork Lift Mitsubishi</i>	Lift truck	3	23500	5	115200	Fork Load-4	Fork Unload-4	85%
<i>Fork Lift Toyota</i>	Lift truck	2	24000	5	115200	Fork Load-5	Fork Unload-5	85%
<i>Hand Trolley</i>	Hand truck	20	100	0	115200	Load-1	Unload-1	85%
<i>Human</i>	Human	20	0	0	115200	Load-2	Unload-2	85%

APPENDIX-E

**DISTANCE-COST REPORT FOR CASE-STUDY FACTORY
& PART-ROUTING INFORMATION**

Table E1: Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
27" Overhead Assembly					
Adapter	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.08
Adapter Cleanout	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Adapter-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.39
Adapter-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-D	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-E	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Adapter-Swivel Trap	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Axle Brake	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
Axle Idler	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
	Receiving Dock-1	Storage 1	Fork Lift Toyota	507.42	\$0.00
	Storage 1	Station 1A	Fork Lift Toyota	208.95	\$0.00
Backsocket	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Hand Unit	Distance Travelled	Cost/Day
Base Cabinet Assy	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Bar Cabinet Assy	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Base	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.06
	Storage 4B	Station 4B	Human	41.94	\$0.05
Base Assembly 19"	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Base Assembly 6"	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Base Cabinet Assembly	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Batten 7/8 B	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$0.01
	Storage 21	Station 26	Human	263.44	\$0.24
Batten 7/8 C	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$0.01
	Storage 21	Station 26	Human	263.44	\$0.15
Batten 7/8 D	Receiving Dock-9	Storage 21	Fork Lift Caterpillar	470.87	\$0.11
	Storage 21	Station 26	Human	263.44	\$0.97
Batten 7/8 E	Receiving Dock-9	Storage 21	Fork Lift Caterpillar	470.87	\$0.71
	Storage 21	Station 26	Human	263.44	\$6.27
Batten 7/8 F	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$0.16
	Storage 21	Station 26	Human	263.44	\$3.96
Batten 7/8 G	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$1.42
	Storage 21	Station 26	Hand Trolley	263.44	\$34.14
Batten-7/8 A	Receiving Dock-9	Storage 21	Fork Lift Caterpillar	470.87	\$0.02
	Storage 21	Station 26	Human	263.44	\$0.24
Bolt Closet	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.11
	Storage 4A	Station 4A	Human	47	\$0.12
Bolt Shake	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.03
	Storage 1	Station 1A	Fork Lift Mitsubishi	208.95	\$0.03

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Traveled	Cost/Day
Boot Registrar	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.16
	Storage 2D	Station 2B	Human	305.69	\$0.18
	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.16
	Storage 2D	Station 2B	Human	305.69	\$0.18
Bottom Board	Receiving Dock-2	Storage 2C	Fork Lift Toyota	98.18	\$0.88
	Storage 2C	Station 2B	Fork Lift Toyota	246.33	\$0.88
	Receiving Dock-2	Storage 2C	Fork Lift Toyota	98.18	\$0.88
	Storage 2C	Station 2B	Fork Lift Toyota	246.33	\$0.88
Bowl Tank	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.07
	Storage 4A	Station 4A	Human	47	\$0.07
Bowl Toilet	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
	Storage 4A	Station 4A	Human	47	\$0.05
Box plastic Round	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.38
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.40
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.38
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.40
Box White Plumbing	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A	Human	47	\$0.07
Box-1 Gang	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.71
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.73
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.71
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.73
Box-2 Gang	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.20
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.22
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.20
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.22
Brackets-End Shelving	Receiving Dock-9	Storage 28	Fork Lift Mitsubishi	608.08	\$0.01
	Storage 28	Station 30	Hand Trolley	499.79	\$0.28
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.03
	Storage 28	Station 29	Hand Trolley	475.65	\$0.28

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Brackets-U Clamp	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.06
	Storage 28	Station 30	Hand Trolley	499.79	\$0.57
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.06
	Storage 28	Station 29	Hand Trolley	475.65	\$0.56
Breaker-A	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
Breaker-B	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
Breaker-C	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
Breaker-D	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
Breaker-E	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
Bushing-A	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.01
Bushing-B	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.11
	Storage 28	Station 30	Hand Trolley	499.79	\$1.04
Cabinet Assembly	Station 4	Station 5	Fork Lift Ingersollrand	102.23	\$0.01

Table E1(cont'd): Distance Cost Report

<i>Part Description</i>	<i>From</i>	<i>To</i>	<i>Material Handling Unit</i>	<i>Distance Travelled</i>	<i>Cost/Day</i>
Cabinet Door	Receiving Dock-5	Storage 15	Fork Lift Mitsubishi	853.77	\$0.00
	Storage 15	Station 6A1	Hand Trolley	108.7	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.12
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
Cabinet Panel 1/4"	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07

Table E1 (contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Cabinet Panel 1/4" 2 sided	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.11
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.22
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.13
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.33
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
Cabinet Panel 1/8 B	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.30
Cabinet Panel 1/8 C	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.00
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.03
Cabinet Panel 1/8 C	Receiving Dock-6	Station 17	Hand Trolley	721.65	\$0.81
	Storage 18B	Station 18B	Fork Lift Mitsubishi	965.9	\$0.02
	Storage 18B	Station 17	Hand Trolley	721.65	\$0.58

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Cabinet Panel 1/8"					
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.47
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.13
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.37
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.27
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.20
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.51
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.06
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.35
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.04
	Storage 4B	Station 4B	Human	41.94	\$0.96
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.30
Cabinet Panel 1/8A	Receiving Dock-6	Storage 18B	Fork Lift Mitsubishi	965.9	\$0.01
	Storage 18B	Station 17	Hand Trolley	721.65	\$0.16

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Cabinet Shelf	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.11
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.30
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.08
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.06
Cabinet Shelf mdf	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.25
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.17
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.28
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.13
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.18
Cabinet Shelf-mdf	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.28
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.09
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.13
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$1.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.12

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Carpet	Receiving Dock-1	Storage 3	Fork Lift Caterpillar	504.7	\$0.18
	Storage 3	Station 3	Electric Hoist A	134.47	\$16.85
	Receiving Dock-1	Storage 3	Fork Lift Caterpillar	504.7	\$0.18
Carpet Pad	Storage 3	Station 3	Electric Hoist A	134.47	\$16.85
	Receiving Dock-1	Storage 3	Fork Lift Caterpillar	504.7	\$0.18
	Storage 3	Station 3	Electric Hoist A	134.47	\$16.85
Ceiling Board	Receiving Dock-1	Storage 9A	Fork Lift Mitsubishi	543.33	\$1.23
	Storage 9A	Station 8A	Hand Trolley	92.47	\$29.64
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$3.34
Ceiling Light	Storage 9B	Station 9A	Hand Trolley	100.43	\$29.64
	Receiving Dock-9	Storage 22	Fork Lift Caterpillar	616.94	\$0.02
	Storage 22	Station 32	Human	592.28	\$0.46
Ceiling Type A	Receiving Dock-9	Storage 22	Fork Lift Ingersollrand	616.94	\$0.03
	Storage 22	Station 31	Human	567.28	\$0.46
	Station 8	Station 10	Fork Lift Ingersollrand	36.17	\$0.01
Ceiling Type A Stage 1	Station 8A	Station 8B	Electric Hoist B	129.02	\$0.58
Ceiling Type A Stage 2	Station 8B	Station 8	Electric Hoist C	249.94	\$6.29
Ceiling Type B	Station 9	Station 11	Fork Lift Ingersollrand	36.88	\$0.01
Ceiling Type B Stage 1	Station 9A	Station 9B	Electric Hoist B	118.76	\$0.56
Ceiling Type B Stage 2	Station 9B	Station 9	Electric Hoist C	254.52	\$6.29
Clamp Ground	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.08
Closed Plastic Stand	Receiving Dock-9	Storage 24	Fork Lift Caterpillar	692.38	\$0.43
	Storage 24	Station 32	Fork Lift Mitsubishi	667.72	\$0.16
	Receiving Dock-9	Storage 24	Fork Lift Caterpillar	692.38	\$0.43
	Storage 24	Station 31	Fork Lift Mitsubishi	642.72	\$0.16

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Collar Start	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.05
	Storage 2D	Station 2B	Human	305.69	\$0.08
	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.05
	Storage 2D	Station 2B	Human	305.69	\$0.08
Conduit	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.13
	Storage 15	Station 6A1	Human	108.7	\$0.15
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.13
	Storage 15	Station 6A1	Human	108.7	\$0.15
Connector	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.05
Connector Gas - 1/2x18"	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Connector Gas - 1/2x36"	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Connector Romex	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.23
	Storage 15	Station 6A1	Human	108.7	\$0.25
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.23
	Storage 15	Station 6A1	Human	108.7	\$0.25
Connector-Crossover	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.08
	Storage 15	Station 6A1	Human	108.7	\$0.10
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.08
	Storage 15	Station 6A1	Human	108.7	\$0.10
Corner Base Cabinet Assem	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Corner Brace Shelving	Receiving Dock-9	Storage 28	Fork Lift Mitsubishi	608.08	\$0.00
	Storage 28	Station 30	Human	499.79	\$0.08
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.01
	Storage 28	Station 29	Human	475.65	\$0.08

Table E1(contd): Distance Cost Report

<i>Part Description</i>	<i>From</i>	<i>To</i>	<i>Material Handling Unit</i>	<i>Distance Travelled</i>	<i>Cost/Day</i>
Corner Overhead Cabinet A	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Counter Top	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.03
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.37
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.60
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.37
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.33
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.37
Coupling	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Human	108.7	\$0.05
	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.05
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Human	108.7	\$0.05
Coupling-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.32
Coupling-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.11
Cover Waterproof Receptacl	Receiving Dock-9	Storage 22	Fork Lift Caterpillar	616.94	\$0.01
	Storage 22	Station 32	Human	592.28	\$0.08
Crimp Ring-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$3.04
Crimp Ring-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$1.26
Curtain Rod-A	Receiving Dock-9	Storage 27	Fork Lift Ingersollrand	618.61	\$0.01
	Storage 27	Station 32	Human	593.96	\$0.08
	Receiving Dock-9	Storage 27	Fork Lift Caterpillar	618.61	\$0.01
	Storage 27	Station 31	Human	568.96	\$0.08

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Curtain Rod-B	Receiving Dock-9	Storage 27	Fork Lift Ingersollrand	618.61	\$0.02
	Storage 27	Station 32	Human	593.96	\$0.16
	Receiving Dock-9	Storage 27	Fork Lift Caterpillar	618.61	\$0.01
Diverter	Storage 27	Station 31	Human	568.96	\$0.16
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A	Human	47	\$0.07
Door	Receiving Dock-9	Storage 28	Fork Lift Mitsubishi	608.08	\$0.01
	Storage 28	Station 30	Human	499.79	\$0.33
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.02
Door Hinge	Storage 28	Station 29	Human	475.65	\$0.33
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.03
	Storage 28	Station 30	Human	499.79	\$0.26
Door Jamb	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.03
	Storage 28	Station 29	Human	475.65	\$0.26
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.29
Door Stop	Storage 28	Station 30	Hand Trolley	499.79	\$2.61
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.29
	Storage 28	Station 29	Hand Trolley	475.65	\$2.61
Door Stop	Receiving Dock-9	Storage 27	Fork Lift Ingersollrand	618.61	\$0.03
	Storage 27	Station 32	Human	593.96	\$0.27
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.15
Door-Front SD	Storage 28	Station 30	Hand Trolley	499.79	\$1.32
	Receiving Dock-9	Storage 27	Fork Lift Caterpillar	618.61	\$0.03
	Storage 27	Station 31	Human	568.96	\$0.27
Door-Rear SD	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.15
	Storage 28	Station 29	Hand Trolley	475.65	\$1.32
	Receiving Dock-2	Storage 11A	Fork Lift Caterpillar	308.91	\$0.00
Door-Rear SD	Storage 11A	Station 13	Hand Trolley	266.69	\$0.05
	Receiving Dock-2	Storage 11A	Fork Lift Mitsubishi	308.91	\$0.00
	Storage 11A	Station 12	Hand Trolley	282.69	\$0.05

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Drain Water Vent Assembly					
Drapes	Station 2E	Station 2B	Fork Lift Ingersollrand	275.66	\$0.01
	Receiving Dock-9	Storage 25	Fork Lift Ingersollrand	677.87	\$0.00
	Storage 25	Station 32	Human	653.21	\$0.06
	Receiving Dock-9	Storage 25	Fork Lift Caterpillar	677.87	\$0.00
	Storage 25	Station 31	Human	628.21	\$0.06
Drawe Guide 22"	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.08
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.08
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.03
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.03
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.03
	Storage 4B	Station 4B	Human	41.94	\$0.05
Drawer Front	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.11
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Drawer Front&Back	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.08
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.13
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.28
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.08
Drawer Side	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.17
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.11
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.22
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.22
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.11
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.34
Drip Edge	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.43
	Storage 16	Station 10	Human	519.4	\$3.81
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.50
	Storage 16	Station 11	Human	536.11	\$3.81
Dust Cap	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Dw 28std	Receiving Dock-1	Storage 9A	Fork Lift Mitsubishi	543.33	\$0.06
	Storage 9A	Station 8A	Hand Trolley	92.47	\$1.21
	Receiving Dock-1	Storage 9A	Fork Lift Mitsubishi	543.33	\$0.06
	Storage 9A	Station 9A	Hand Trolley	96.12	\$1.21

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
E-Gasket	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A		47	\$0.07
Elbow	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.01
Elbow-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.50
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Elbow-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.16
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Elbow-C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Elbow-D	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Elbow-E	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.01
Elbow-F	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.01
Elbow-G	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.05
Electrical Assembly - A1	Station 6A1	Station 6	Human	378.14	\$0.05
Electrical Assembly - A2	Station 6A1	Station 12	Hand Trolley	483.36	\$0.06
Electrical Assembly - A3	Station 32	Station 32	Human	0	\$0.04
Electrical Assembly - B1	Station 6A1	Station 6	Human	378.14	\$0.05
Electrical Assembly - B2	Station 6A1	Station 13	Hand Trolley	498.36	\$0.06
Electrical Assembly - B3	Station 31	Station 31	Human	0	\$0.04

Table E1 (contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
End Wall A	Station 7	Station 8	Fork Lift Ingersollrand	20.88	\$0.01
End Wall B	Station 7	Station 9	Fork Lift Ingersollrand	36.88	\$0.01
End Wall Type1	Station 7A	Station 7	Electric Hoist A	317.13	\$0.50
	Station 7A	Station 7	Electric Hoist A	317.13	\$0.50
End Wall Type2	Station 7A	Station 7	Electric Hoist A	317.13	\$0.50
	Station 7A	Station 7	Electric Hoist A	317.13	\$0.50
Exterior Finish Assembly A	Station 12	Station 14	Fork Lift Ingersollrand	36.88	\$0.01
	Station 14	Station 16	Fork Lift Caterpillar	36.88	\$0.01
	Station 16	Station 17	Fork Lift Caterpillar	20.88	\$0.01
Exterior Finish Assembly B	Station 13	Station 15	Fork Lift Ingersollrand	36.88	\$0.01
	Station 15	Station 17	Fork Lift Caterpillar	39.88	\$0.01
	Station 17	Station 18	Fork Lift Caterpillar	20.14	\$0.01
Exterior Jelly Jar Light	Receiving Dock-9	Storage 22	Fork Lift Caterpillar	616.94	\$0.00
	Storage 22	Station 32	Human	592.28	\$0.06
	Receiving Dock-9	Storage 22	Fork Lift Ingersollrand	616.94	\$0.00
	Storage 22	Station 31	Human	567.28	\$0.06
Exterior Light Fixture	Storage 22	Station 32	Human	592.28	\$0.06
	Receiving Dock-9	Storage 22	Fork Lift Caterpillar	616.94	\$0.00
	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.00
	Storage 22	Station 31	Human	567.28	\$0.06
Exterior Roof Finish A	Station 10	Station 12	Fork Lift Ingersollrand	36.91	\$0.01
Exterior Roof Finish B	Station 11	Station 13	Fork Lift Ingersollrand	36.88	\$0.01
Fan	Receiving Dock-9	Storage 22	Fork Lift Caterpillar	616.94	\$0.01
	Storage 22	Station 32	Human	592.28	\$0.08
	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.00
	Storage 22	Station 31	Human	567.28	\$0.08

Table E1 (contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Fascia White	Receiving Dock-5	Storage 16	Fork Lift Mitsubishi	979.36	\$0.16
	Storage 16	Station 12	Hand Trolley	555.11	\$3.77
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.42
Fasteners	Storage 16	Station 13	Hand Trolley	571.11	\$3.77
	Receiving Dock-9	Storage 26	Fork Lift Mitsubishi	126.24	\$0.00
	Storage 26	Station 34	Human	74.38	\$0.03
Faucet	Receiving Dock-9	Storage 26	Fork Lift Caterpillar	126.24	\$0.00
	Storage 26	Station 33	Human	220.7	\$0.03
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
Faucet-Lav	Storage 4A	Station 4A	Human	47	\$0.05
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.08
	Storage 4A	Station 4A	Human	47	\$0.10
Filler Garden tub	Receiving Dock-3	Storage 4A	Fork Lift Caterpillar	525.21	\$0.01
	Storage 4A	Station 4A	Human	47	\$0.05
	Station 32	Station 34	Fork Lift Ingersollrand	76.91	\$0.01
Finish Trim	Station 31	Station 33	Fork Lift Ingersollrand	76.96	\$0.01
	Receiving Dock-5	Storage 16	Fork Lift Mitsubishi	979.36	\$0.04
	Storage 16	Station 12	Hand Trolley	555.11	\$1.04
Flange	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.13
	Storage 16	Station 13	Hand Trolley	571.11	\$1.04
	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Flange-Shower Rod	Receiving Dock-9	Storage 27	Fork Lift Mitsubishi	618.61	\$0.00
	Storage 27	Station 32	Human	593.96	\$0.08
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.01
Flashing Plastic	Storage 16	Station 10	Human	519.4	\$0.08
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.01
	Storage 16	Station 11	Human	536.11	\$0.08

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Flat A	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.44
	Storage 28	Station 30	Hand Trolley	498.79	\$3.89
Flat B	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.11
	Storage 28	Station 30	Hand Trolley	498.79	\$0.94
Flexduct-Insulated	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.76
	Storage 2D	Station 2B	Human	305.69	\$0.78
	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.76
	Storage 2D	Station 2B	Human	305.69	\$0.78
Flexi Duct	Receiving Dock-9	Storage 22	Fork Lift Caterpillar	616.94	\$0.06
	Storage 22	Station 32	Hand Trolley	592.28	\$0.54
	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.02
	Storage 22	Station 31	Hand Trolley	567.28	\$0.54
Floor Assembly A1	Station 2B	Station 2A	Fork Lift Ingersollrand	61.97	\$0.01
	Station 2A	Station 2C	Fork Lift Ingersollrand	51.75	\$0.01
	Station 2C	Station 2D	Fork Lift Ingersollrand	90.3	\$0.01
Floor Assembly A2	Station 2D	Station 3	Fork Lift Ingersollrand	109.33	\$0.01
Floor Assembly A3	Station 3	Station 4	Fork Lift Ingersollrand	86.49	\$0.01
	Station 4	Station 5	Fork Lift Ingersollrand	102.23	\$0.01
Floor Assembly B1	Station 2B	Station 2A	Fork Lift Ingersollrand	61.97	\$0.01
	Station 2A	Station 2C	Fork Lift Ingersollrand	51.75	\$0.01
	Station 2C	Station 2D	Fork Lift Ingersollrand	90.3	\$0.01
Floor Assembly B2	Station 2D	Station 3	Fork Lift Ingersollrand	109.33	\$0.01
Floor Assembly B3	Station 3	Station 4	Fork Lift Ingersollrand	86.49	\$0.01
	Station 4	Station 5	Fork Lift Ingersollrand	102.23	\$0.01
F-Moulding	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
	Storage 4A	Station 4A	Human	47	\$0.05
Frame Assembly A	Station 1A	Station 1B	Fork Lift Ingersollrand	69.15	\$0.01
	Station 1B	Station 2A	Fork Lift Ingersollrand	180.36	\$0.01
	Station 2A	Station 2B	Fork Lift Ingersollrand	61.97	\$0.01

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Frame Assembly B	Station 1A	Station 1B	Fork Lift Ingersollrand	69.15	\$0.01
	Station 1B	Station 2A	Fork Lift Ingersollrand	180.36	\$0.01
	Station 2A	Station 2B	Fork Lift Ingersollrand	61.97	\$0.01
Frames-Triple,10"	Receiving Dock-1	Storage 1	Fork Lift Ingersollrand	507.42	\$0.01
	Storage 1	Station 1B	Fork Lift Ingersollrand	148.01	\$0.01
	Station 1B	Station 1A	Fork Lift Ingersollrand	69.15	\$0.01
	Receiving Dock-1	Storage 1	Fork Lift Ingersollrand	507.42	\$0.01
	Storage 1	Station 1B	Fork Lift Ingersollrand	148.01	\$0.01
	Station 1B	Station 1A	Fork Lift Ingersollrand	69.15	\$0.01
Furnace	Receiving Dock-2	Storage 2D	Fork Lift Caterpillar	66.09	\$0.01
	Storage 2D	Station 2B	Human	305.69	\$0.05
	Station 2B	Storage 2D	Fork Lift Ingersollrand	66.09	\$0.01
Fuse Panel Door Assembly	Storage 2D	Station 2B	Human	305.69	\$0.05
	Station 6A1	Station 12	Human	483.36	\$0.06
	Station 2E	Station 2B	Fork Lift Ingersollrand	275.66	\$0.01
Gas Assembly	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.12
	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.01
Globe Fluted Ball	Storage 22	Station 32	Human	592.28	\$0.33
	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.01
	Storage 22	Station 31	Human	567.28	\$0.33
Ground Strap	Receiving Dock-3	Storage 2D	Fork Lift Caterpillar	454.54	\$0.01
	Storage 2D	Station 2B	Human	305.69	\$0.08
	Receiving Dock-3	Storage 2D	Fork Lift Ingersollrand	454.54	\$0.01
	Storage 2D	Station 2B	Human	305.69	\$0.08

Table E1 (contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Gypsum Vinyl					
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.66
	Storage 28	Station 30	Human	499.79	\$5.85
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.24
	Storage 7A	Station 7A	Hand Trolley	105.2	\$5.85
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.24
	Storage 7A	Station 7A	Hand Trolley	105.2	\$5.85
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.36
	Storage 7A	Station 6B	Hand Trolley	107.39	\$8.66
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.33
	Storage 6	Station 6A	Hand Trolley	109.24	\$12.77
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.10
	Storage 5	Station 5A	Hand Trolley	135.1	\$2.52
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.15
	Storage 5	Station 5A	Hand Trolley	135.1	\$3.66
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.07
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.70
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.03
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.83
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.11
	Storage 5	Station 5A	Hand Trolley	135.1	\$2.57
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.04
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.08

Table E1(contd): Distance Cost Report

<i>Part Description</i>	<i>From</i>	<i>To</i>	<i>Material Handling Unit</i>	<i>Distance Travelled</i>	<i>Cost/Day</i>
<i>Gypsum Vinyl</i>	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.66
	Storage 7A	Station 6B	Hand Trolley	107.39	\$3.66
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.15
	Storage 5	Station 5A	Hand Trolley	135.1	\$3.66
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.04
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.93
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.08
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.60
	Receiving Dock-4	Storage 5	Fork Lift Caterpillar	686.81	\$0.24
	Storage 5	Station 5A	Hand Trolley	135.1	\$2.12
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.40
	Storage 5	Station 5A	Hand Trolley	135.1	\$3.07
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.17
	Storage 5	Station 5A	Hand Trolley	135.1	\$4.26
	Receiving Dock-4	Storage 5	Fork Lift Caterpillar	686.81	\$0.10
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.93
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.64
	Storage 5	Station 5A	Hand Trolley	135.1	\$4.84
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.12
	Storage 5	Station 5A	Hand Trolley	135.1	\$2.83

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Gypsum Vinyl Moroccan Sa	Receiving Dock-9	Storage 27	Fork Lift Mitsubishi	618.61	\$0.02
	Storage 27	Station 32	Hand Trolley	593.96	\$0.59
	Receiving Dock-9	Storage 27	Fork Lift Caterpillar	618.61	\$0.06
	Storage 27	Station 31	Hand Trolley	568.96	\$0.59
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.13
Gypsum Vinyl Sussex	Storage 7A	Station 6B	Hand Trolley	107.39	\$0.25
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.07
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.72
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.03
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.83
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.30
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.06
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.44
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.06
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.37
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.06
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.39
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.07
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.70
Gypsum-end rafters	Receiving Dock-4	Storage 7A	Fork Lift Caterpillar	811.61	\$0.36
	Storage 7A	Station 6B	Hand Trolley	107.39	\$3.25
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.07
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.72
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.11
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.82
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.18
	Storage 5	Station 5A	Hand Trolley	135.1	\$1.41
	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.01
	Storage 8	Station 8A	Hand Trolley	112.76	\$0.15

Table E1 (contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
House Insulation r19	Station 35	Station 36	Fork Lift Caterpillar La	423.7	\$0.68
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.31
	Storage 9B	Station 8B	Human	71.87	\$2.79
	Receiving Dock-2	Storage 7A	Fork Lift Mitsubishi	485.93	\$0.20
	Storage 7A	Station 7A	Human	105.2	\$4.76
	Receiving Dock-2	Storage 7A	Fork Lift Mitsubishi	485.93	\$0.20
	Storage 7A	Station 7A	Human	105.2	\$4.76
	Receiving Dock-2	Storage 6	Fork Lift Toyota	472.71	\$0.29
	Storage 6	Station 6A	Human	109.24	\$11.21
	Receiving Dock-2	Storage 2D	Human	66.09	\$12.99
	Storage 2D	Station 2B	Human	305.69	\$13.00
	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.12
	Storage 9B	Station 9B	Human	59.37	\$2.79
	Receiving Dock-2	Storage 7A	Fork Lift Caterpillar	485.93	\$0.54
Insulation Cellulose	Storage 7A	Station 7A	Human	105.2	\$4.76
	Receiving Dock-2	Storage 7A	Fork Lift Ingersollrand	485.93	\$0.63
	Storage 7A	Station 7A	Human	105.2	\$4.76
	Receiving Dock-2	Storage 6	Fork Lift Toyota	472.71	\$0.29
	Storage 6	Station 6A	Human	109.24	\$11.21
	Receiving Dock-2	Storage 2D	Human	66.09	\$12.99
	Storage 2D	Station 2B	Human	305.69	\$13.00
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.08
	Storage 9B	Station 8B	Electric Hoist B	71.87	\$9.37
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.08
	Storage 9B	Station 9B	Electric Hoist B	59.37	\$9.37
	Receiving Dock-2	Storage 2D	Human	66.09	\$25.52
	Storage 2D	Station 2B	Human	305.69	\$25.53
	Storage 2D	Station 2B	Human	305.69	\$25.53

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Knob-Chrome Cabinet	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.10
	Storage 4B	Station 4B	Human	41.94	\$0.12
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.08
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.13
	Storage 4B	Station 4B	Human	41.94	\$0.15
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.03
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.08
	Storage 4B	Station 4B	Human	41.94	\$0.05
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.23
	Storage 4B	Station 4B	Human	41.94	\$0.25
Lag	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.08
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.08
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-3	Storage 2D	Fork Lift Mitsubishi	454.54	\$0.34
	Storage 2D	Station 2B	Human	305.69	\$17.00
	Receiving Dock-3	Storage 2D	Fork Lift Caterpillar	454.54	\$0.94
	Storage 2D	Station 2B	Human	305.69	\$8.29

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lav	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.08
	Storage 4A	Station 4A	Human	47	\$0.10
Linoleum	Receiving Dock-1	Storage 3	Fork Lift Caterpillar	504.7	\$0.12
	Storage 3	Station 3	Electric Hoist A	134.47	\$11.26
	Receiving Dock-1	Storage 3	Fork Lift Caterpillar	504.7	\$0.12
	Storage 3	Station 3	Electric Hoist A	134.47	\$11.26
Load Center-100amp	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Human	108.7	\$0.05
Lock Nut	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.03
	Storage 1	Station 1A	Human	208.95	\$0.61
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.03
	Storage 1	Station 1A	Human	208.95	\$0.61
Lockset	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.02
	Storage 28	Station 30	Human	499.79	\$0.15
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.02
	Storage 28	Station 29	Human	475.65	\$0.15
Lug	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Human	108.7	\$0.05
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.00
	Storage 1	Station 1A	Human	208.95	\$0.07
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1	Human	108.7	\$0.05
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.00
	Storage 1	Station 1A	Human	208.95	\$0.07
Lug Ground	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Lumber - 2x6x12	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.01
	Storage 2C	Station 2B	Fork Lift Mitsubishi	246.33	\$0.02
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.01
	Storage 2C	Station 2B	Fork Lift Mitsubishi	246.33	\$0.02

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber - 2x6x14	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.01
	Storage 2C	Station 2B	Fork Lift Mitsubishi	246.33	\$0.01
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.01
Lumber - 2x6x157	Storage 2C	Station 2B	Fork Lift Mitsubishi	246.33	\$0.01
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.05
	Storage 2C	Station 2B	Fork Lift Mitsubishi	246.33	\$0.07
Lumber - 2x6x19	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.06
	Storage 2C	Station 2B	Fork Lift Caterpillar	246.33	\$0.20
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.00
Lumber - 2x6x29	Storage 2C	Station 2B	Human	246.33	\$0.08
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.00
	Storage 2C	Station 2B	Human	246.33	\$0.08
Lumber 1x3x28	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.03
	Storage 2C	Station 2B	Fork Lift Mitsubishi	246.33	\$0.06
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.03
Lumber 1x3x28	Storage 2C	Station 2B	Fork Lift Caterpillar	246.33	\$0.15
	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.01
	Storage 8	Station 8A	Hand Trolley	112.76	\$0.35
Lumber 1x3xRL	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.01
	Storage 9B	Station 9A	Hand Trolley	100.43	\$0.35
	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.10
	Storage 8	Station 8A	Hand Trolley	112.76	\$2.45
	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.10
	Storage 9B	Station 9A	Hand Trolley	100.43	\$2.45

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber 1x3xRL (cut from 12)	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.04
	Storage 7A	Station 6B	Hand Trolley	107.39	\$0.96
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.04
Lumber 1x3xRL (cut from 14)	Storage 7A	Station 6B	Hand Trolley	107.39	\$0.96
	Receiving Dock-6	Storage 18B	Fork Lift Caterpillar	965.9	\$0.09
	Storage 18B	Station 17	Hand Trolley	721.65	\$0.84
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.06
	Storage 7A	Station 6B	Hand Trolley	107.39	\$1.44
Lumber 1x4xRL (cut from 14)	Receiving Dock-6	Storage 18B	Fork Lift Caterpillar	965.9	\$0.09
	Storage 18B	Station 18	Hand Trolley	738.29	\$0.84
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.06
	Storage 7A	Station 6B	Hand Trolley	107.39	\$1.44
	Receiving Dock-6	Storage 18B	Fork Lift Mitsubishi	965.9	\$0.03
	Storage 18B	Station 17	Hand Trolley	721.65	\$0.84
Lumber 2x3x106 stud fj west	Receiving Dock-6	Storage 18B	Fork Lift Caterpillar	965.9	\$0.09
	Storage 18B	Station 18	Hand Trolley	738.29	\$0.84
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.04
	Storage 7A	Station 6B	Hand Trolley	107.39	\$0.93
Lumber 2x3x22 (cut from 14)	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.04
	Storage 7A	Station 6B	Hand Trolley	107.39	\$0.93
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.06
	Storage 7A	Station 6B	Hand Trolley	107.39	\$1.44
	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.06

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber 2x6x22-16	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.01
	Storage 8	Station 8A	Hand Trolley	112.76	\$0.22
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.02
	Storage 9B	Station 9A	Hand Trolley	100.43	\$0.22
Lumber 2x6x30	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.09
	Storage 8	Station 8A	Hand Trolley	112.76	\$2.24
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.25
	Storage 9B	Station 9A	Hand Trolley	100.43	\$2.24
Lumber 2x6x81	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.07
	Storage 7A	Station 7A	Hand Trolley	105.2	\$1.69
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.07
	Storage 7A	Station 7A	Hand Trolley	105.2	\$1.69
Lumber 2x6xRL	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.10
	Storage 8	Station 8A	Hand Trolley	112.76	\$2.34
	Receiving Dock-1	Storage 9C	Fork Lift Mitsubishi	398.36	\$0.10
	Storage 9C	Station 9A	Hand Trolley	207.51	\$2.35
Lumber 2x6xRL (cut from 16)	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.05
	Storage 7A	Station 7A	Hand Trolley	105.2	\$1.33
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.05
	Storage 7A	Station 7A	Hand Trolley	105.2	\$1.33
	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.15
	Storage 7A	Station 7A	Hand Trolley	105.2	\$1.33
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.05
	Storage 7A	Station 7A	Hand Trolley	105.2	\$1.33

Table E1 (contd). Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber Closed Up	Receiving Dock-9	Storage 26	Fork Lift Caterpillar	126.24	\$0.13
	Storage 26	Station 34	Human	74.38	\$1.13
	Receiving Dock-9	Storage 26	Fork Lift Caterpillar	126.24	\$0.13
Lumber LVL	Storage 26	Station 33	Human	220.7	\$1.13
	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.00
	Storage 8	Station 8A	Hand Trolley	112.76	\$0.07
Lumber, 3/4 #3btr	Receiving Dock-1	Storage 9A	Fork Lift Ingersollrand	543.33	\$0.01
	Storage 9A	Station 9A	Hand Trolley	96.12	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.09
Lumber, 3/4 #3btr	Storage 4B	Station 4B	Human	41.94	\$2.29
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.04
	Storage 4B	Station 4B	Human	41.94	\$1.05
Lumber, 3/4 #3btr	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.57
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.04
Lumber, 3/4 #3btr	Storage 4B	Station 4B	Human	41.94	\$1.09
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.05
	Storage 4B	Station 4B	Human	41.94	\$1.26
Lumber, 3/4 #3btr	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.06
	Storage 4B	Station 4B	Human	41.94	\$1.38
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.03
Lumber, 3/4 #3btr	Storage 4B	Station 4B	Human	41.94	\$0.66
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.54
Lumber, 3/4 #3btr	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.37
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber 2x3xRL	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.10
	Storage 8	Station 8A	Hand Trolley	112.76	\$2.34
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.26
	Storage 9B	Station 9A	Hand Trolley	100.43	\$2.34
Lumber 2x3xRL (cut from 14	Receiving Dock-4	Storage 7A	Fork Lift Mitsubishi	811.61	\$0.08
	Storage 7A	Station 6B	Hand Trolley	107.39	\$1.92
	Receiving Dock-4	Storage 7A	Fork Lift Caterpillar	811.61	\$0.21
	Storage 7A	Station 6B	Hand Trolley	107.39	\$1.92
Lumber 2x4x22-splice block	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.00
	Storage 8	Station 8A	Hand Trolley	112.76	\$0.12
	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.00
	Storage 9B	Station 9A	Hand Trolley	100.43	\$0.12
Lumber 2x4xRL	Receiving Dock-1	Storage 8	Fork Lift Mitsubishi	551.8	\$0.06
	Storage 8	Station 8A	Hand Trolley	112.76	\$1.44
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.16
	Storage 9B	Station 9A	Hand Trolley	100.43	\$1.44
Lumber 2x6x10	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.01
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.30
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.01
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.30
	Receiving Dock-5	Storage 7A	Fork Lift Ingersollrand	920.76	\$0.04
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.30
	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.03
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.30

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber, mill room	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.25
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.04
	Storage 4B	Station 4B	Human	41.94	\$1.10
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.33
Lumber-1x3xRL (cut from 14	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.24
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.03
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.66
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.22
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.46
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.34
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.48
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.49
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.17
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Caterpillar	686.81	\$0.02

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber-1x3xRL back	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.08
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.17
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.22
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.46
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.59
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.06
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.47
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.45
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.09
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.71
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.07
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.07
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.06
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.49
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.02
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.51
	Receiving Dock-4	Storage 5	Fork Lift Caterpillar	686.81	\$0.06
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.53

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber-1x3xRL back	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.03
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.66
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.25
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.03
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.66
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.09
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.70
Lumber-1x4xRL (cut from 14	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.17
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.03
	Storage 5	Station 5A	Hand Trolley	135.1	\$0.23
Lumber-1x6xRL	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.06
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.24
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.06
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.24
Lumber-2x3x8 stud	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.01
	Storage 5	Station 5A	Human	135.1	\$0.20
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.19
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.07
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.12

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber-2x3x9 stud if west	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.19
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.07
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.03
	Storage 5	Station 5A	Human	135.1	\$0.25
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.01
	Storage 5	Station 5A	Human	135.1	\$0.07
Lumber-2x3x9 (cut from 14	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.02
	Storage 5	Station 5A	Human	135.1	\$0.14
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.04
Lumber-2x4x8 stud	Storage 5	Station 5A	Hand Trolley	135.1	\$0.34
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.05
	Receiving Dock-4	Storage 5	Fork Lift Ingersollrand	686.81	\$0.02
	Storage 5	Station 5A	Human	135.1	\$0.15
Lumber-2x4x9 stud	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.07
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
Lumber-2x4x9 stud if west	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.12
	Receiving Dock-4	Storage 5	Fork Lift Mitsubishi	686.81	\$0.00
	Storage 5	Station 5A	Human	135.1	\$0.07

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber-2x6x11	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.01
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.27
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.01
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.27
	Receiving Dock-4	Storage 5	Fork Lift Toyota	686.81	\$0.01
	Storage 5	Station 6A	Hand Trolley	130.49	\$0.40
	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.03
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.27
	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.03
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.27
	Receiving Dock-4	Storage 5	Fork Lift Toyota	686.81	\$0.01
	Storage 5	Station 6A	Hand Trolley	130.49	\$0.40
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Human	105.2	\$0.12
Lumber-2x6x14	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Human	105.2	\$0.12
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.01
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.32
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.01
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.32
	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.01
	Storage 7A	Station 7A	Human	105.2	\$0.12
	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.01
	Storage 7A	Station 7A	Human	105.2	\$0.12
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.12
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.12
Lumber-2x6x30	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.12
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.12
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.00
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.16

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber-2x6x44	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.00
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.12
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.00
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.12
Lumber-2x6x46	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.05
	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.00
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.05
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.00
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.12
	Receiving Dock-5	Storage 7A	Fork Lift Ingersollrand	920.76	\$0.01
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.05
Lumber-2x6x7	Receiving Dock-5	Storage 7A	Fork Lift Caterpillar	920.76	\$0.01
	Storage 7A	Station 7A	Hand Trolley	105.2	\$0.05
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.00
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.12
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.01
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.50
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.04
	Storage 6	Station 6A	Hand Trolley	109.24	\$1.69
Lumber-2x6x81	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.04
	Storage 6	Station 6A	Hand Trolley	109.24	\$0.04
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$1.69
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.24
Lumber-2x6xRL	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.06
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.24
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.06
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.24
Lumber-2x6xRL back	Receiving Dock-5	Storage 7A	Fork Lift Mitsubishi	920.76	\$0.02

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Lumber-3/4"	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.07
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.85
	Receiving Dock-4	Storage 6	Fork Lift Toyota	710.61	\$0.07
	Storage 6	Station 6A	Hand Trolley	109.24	\$2.85
Mating Wall A	Station 7	Station 7	Fork Lift Ingersollrand	0	\$0.01
Mating Wall B	Station 7	Station 7	Fork Lift Ingersollrand	0	\$0.01
Mating Wall Stage A1	Station 6B	Station 7	Electric Hoist A	319.31	\$0.50
Mating Wall Stage B1	Station 6B	Station 7	Electric Hoist A	319.31	\$0.50
Mini Blind-A	Receiving Dock-9	Storage 24	Fork Lift Mitsubishi	692.38	\$0.00
	Storage 24	Station 32	Human	667.72	\$0.06
	Receiving Dock-9	Storage 24	Fork Lift Caterpillar	692.38	\$0.00
	Storage 24	Station 31	Human	642.72	\$0.06
Mini Blind-B	Receiving Dock-9	Storage 24	Fork Lift Mitsubishi	692.38	\$0.01
	Storage 24	Station 32	Human	667.72	\$0.16
	Receiving Dock-9	Storage 24	Fork Lift Caterpillar	692.38	\$0.02
	Storage 24	Station 31	Human	642.72	\$0.16
Mini Blind-C	Receiving Dock-9	Storage 24	Fork Lift Caterpillar	692.38	\$0.01
	Storage 24	Station 32	Human	667.72	\$0.11
	Receiving Dock-9	Storage 24	Fork Lift Caterpillar	692.38	\$0.01
	Storage 24	Station 31	Human	642.72	\$0.11
Mirror Std	Receiving Dock-9	Storage 27	Fork Lift Mitsubishi	618.61	\$0.00
	Storage 27	Station 32	Human	593.96	\$0.17
	Receiving Dock-9	Storage 27	Fork Lift Caterpillar	618.61	\$0.01
	Storage 27	Station 31	Human	568.96	\$0.17
Mud	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.00
	Storage 9B	Station 8B	Human	71.67	\$0.09
	Storage 9B	Station 9B	Human	59.37	\$0.09
	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.00

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Novodeck-48x168	Storage 9B	Station 9B	Hand Trolley	59.37	\$0.42
	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.07
	Storage 2C	Station 2D	Fork Lift Toyota	162.03	\$0.07
	Receiving Dock-1	Storage 2C	Fork Lift Ingersollrand	448.08	\$0.38
	Storage 2C	Station 2D	Fork Lift Toyota	162.03	\$0.07
Novodeck-96x168	Receiving Dock-1	Storage 2C	Fork Lift Toyota	448.08	\$0.74
	Storage 2C	Station 2D	Fork Lift Toyota	162.03	\$0.74
	Receiving Dock-1	Storage 2C	Fork Lift Ingersollrand	448.08	\$3.78
	Storage 2C	Station 2D	Fork Lift Toyota	162.03	\$0.74
	Receiving Dock-1	Storage 2C	Fork Lift Ingersollrand	448.08	\$3.78
Nut	Storage 2C	Station 2D	Fork Lift Toyota	162.03	\$0.74
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.10
	Storage 4A	Station 4A	Human	47	\$0.10
Nut-Ballock OSB Board	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.05
	Receiving Dock-9	Storage 23	Fork Lift Caterpillar	688.97	\$0.10
	Storage 23	Station 32	Hand Trolley	674.32	\$0.94
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.18
	Storage 16	Station 12	Hand Trolley	555.11	\$1.65
	Receiving Dock-9	Storage 23	Fork Lift Caterpillar	688.97	\$0.10
	Storage 23	Station 31	Hand Trolley	649.32	\$0.94
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.21
	Storage 16	Station 13	Hand Trolley	571.11	\$1.65
	Receiving Dock-5	Storage 9C	Fork Lift Caterpillar	361.51	\$3.83
OSB Board 7/16	Storage 9C	Station 10	Fork Lift Mitsubishi	424.24	\$1.41
	Receiving Dock-5	Storage 9C	Fork Lift Ingersollrand	361.51	\$4.50
	Storage 9C	Station 11	Fork Lift Mitsubishi	440.94	\$1.41
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.01
	Storage 16	Station 12	Human	555.11	\$0.13
Outside Corner	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.01
	Storage 16	Station 13	Human	571.11	\$0.13

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Part A (Tollet & Kitchen)	Station 34	Station 35	Fork Lift Caterpillar La	77.49	\$0.66
Part B	Station 33	Station 35	Fork Lift Caterpillar La	78.48	\$0.66
Pipe A	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.06
Pipe B	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.01
Pipe C	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.03
Pipe-1"	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Pipe-1/2"	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.02
Pipe-3/4"	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
Pipe-Range Hood	Receiving Dock-9	Station 26	Fork Lift Caterpillar	126.24	\$0.01
	Storage 26	Station 32	Human	49.92	\$0.05
Plate-Nail	Receiving Dock-9	Station 22	Fork Lift Mitsubishi	616.94	\$0.03
	Storage 22	Station 32	Human	592.28	\$0.86
	Receiving Dock-9	Station 22	Fork Lift Mitsubishi	616.94	\$0.03
	Storage 22	Station 31	Human	567.28	\$0.86
Plenum	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.03
	Storage 2D	Station 2B	Human	305.69	\$0.05
	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.03
	Storage 2D	Station 2B	Human	305.69	\$0.05
Plug Cap	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Plug Cleanout	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.08
	Storage 4A	Station 4A	Human	47	\$0.10
	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.11
Plug Lift	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A	Human	47	\$0.07
Plumbing Assembly	Station 4A	Station 4	Fork Lift Ingersollrand	86.66	\$0.01
	Station 4	Station 5	Fork Lift Ingersollrand	102.23	\$0.01
P-Trap-A	Receiving Dock-3	Station 2E	Human	424.51	\$0.16
P-Trap-B	Receiving Dock-3	Station 2E	Human	424.51	\$0.16
P-Trap-C	Receiving Dock-3	Station 2E	Human	424.51	\$0.22

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Range Hood	Receiving Dock-9	Storage 26	Fork Lift Mitsubishi	126.24	\$0.00
	Storage 26	Station 32		49.92	\$0.05
Receptacle-dryer	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.03
	Storage 15	Station 6A1		108.7	\$0.05
Receptacle-duplex	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.63
	Storage 15	Station 6A1	Human	108.7	\$0.65
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.63
	Storage 15	Station 6A1	Human	108.7	\$0.65
Receptacle-GFI	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.08
	Storage 15	Station 6A1	Human	108.7	\$0.10
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.08
	Storage 15	Station 6A1	Human	108.7	\$0.10
Refer. 16f	Receiving Dock-9	Storage 26	Fork Lift Mitsubishi	126.24	\$0.00
	Storage 26	Station 32		49.92	\$0.05
Reference Shelf	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Refrigerators	Receiving Dock-9	Storage 26	Fork Lift Mitsubishi	126.24	\$0.00
	Storage 26	Station 32	Human	49.92	\$0.05
Register	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.21
	Storage 2D	Station 2B	Hand Trolley	305.69	\$0.23
	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.21
	Storage 2D	Station 2B	Hand Trolley	305.69	\$0.23
Return Air Grill	Receiving Dock-9	Storage 26	Fork Lift Caterpillar	126.24	\$0.01
	Storage 26	Station 32		49.92	\$0.09
Ring Wax	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.05
	Storage 4A	Station 4A	Human	47	\$0.07
Roof Cement	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.01
	Storage 16	Station 10	Human	519.4	\$0.08
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.01

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Roof Vent	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.02
	Storage 16	Station 10	Human	519.4	\$0.33
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.03
Seat Toilet	Storage 16	Station 11	Human	536.11	\$0.33
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A	Human	47	\$0.09
Self Edge	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.38
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.33
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.08
SGL Underlayment	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.10
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$5.36
	Storage 16	Station 10	Human	519.4	\$47.67
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$6.30
	Storage 16	Station 11	Human	536.11	\$7.67
Sheathing Goldguard	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$3.13
	Storage 16	Station 12	Hand Trolley	555.11	\$27.77
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$3.13
Sheathing-Goldguard	Storage 16	Station 13	Hand Trolley	571.11	\$28
	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.04
	Storage 9B	Station 8B	Hand Trolley	71.67	\$1.04
Shelving-Wire Closet	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.12
	Storage 9B	Station 9B	Hand Trolley	59.37	\$1.04
	Receiving Dock-9	Storage 28	Fork Lift Mitsubishi	608.08	\$0.03
	Storage 28	Station 30	Human	499.79	\$0.67
	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.07
	Storage 28	Station 29	Human	475.65	\$0.67

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Shingles	Receiving Dock-5	Storage 16	Fork Lift Mitsubishi	979.36	\$0.02
	Storage 16	Station 10	Human	519.4	\$0.81
	Receiving Dock-5	Storage 16	Fork Lift Ingersollrand	979.36	\$0.05
Shower Curtain Ring	Storage 16	Station 11	Human	536.11	\$0.82
	Receiving Dock-9	Storage 27	Fork Lift Mitsubishi	618.61	\$0.01
	Storage 27	Station 32	Human	593.96	\$0.33
Shower Door	Receiving Dock-3	Storage 4A	Fork Lift Toyota	525.21	\$0.00
	Storage 4A	Station 4A	Human	47	\$0.05
Shower Fiberglass	Receiving Dock-3	Storage 4A	Fork Lift Mitsubishi	525.21	\$0.00
	Storage 4A	Station 4A	Human	47	\$0.05
Shower Head	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A	Human	47	\$0.05
Shower Head-Kit Chrome	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
	Storage 4A	Station 4A	Human	47	\$0.05
Shower Liner	Receiving Dock-9	Storage 27	Fork Lift Mitsubishi	618.61	\$0.00
	Storage 27	Station 32	Human	593.96	\$0.06
Shower Rod	Receiving Dock-9	Storage 27	Fork Lift Caterpillar	618.61	\$0.00
	Storage 27	Station 32	Human	593.96	\$0.06
Side Wall A	Station 6	Station 7	Fork Lift Ingersollrand	18.41	\$0.01
Side Wall B	Station 6	Station 7	Fork Lift Ingersollrand	18.41	\$0.01
Side Wall Stage-1	Station 6A	Station 6	Electric Hoist A	280.13	\$0.49
	Station 6A	Station 6	Electric Hoist A	280.13	\$0.49
Siding Double	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.03
	Storage 16	Station 12	Hand Trolley	555.11	\$0.32

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
SleeveWire	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.04
	Storage 22	Station 32	Human	592.28	\$1.04
	Receiving Dock-9	Storage 22	Fork Lift Mitsubishi	616.94	\$0.04
Smoke Detector	Storage 22	Station 31	Human	567.28	\$1.04
	Receiving Dock-9	Storage 23	Fork Lift Caterpillar	698.97	\$0.00
	Storage 23	Station 32	Hand Trolley	674.32	\$0.06
Soffit Receiver	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.40
	Storage 16	Station 12	Hand Trolley	555.11	\$3.57
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.40
Soffit Vented	Storage 16	Station 13	Hand Trolley	571.11	\$3.57
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.37
	Storage 16	Station 12	Hand Trolley	555.11	\$3.31
Sprinkler Head Starter Strip	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.37
	Storage 16	Station 13	Hand Trolley	571.11	\$3.31
	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.03
Stifle	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.40
	Storage 16	Station 12	Hand Trolley	555.11	\$3.57
	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.40
Stifle	Storage 16	Station 13	Hand Trolley	571.11	\$3.57
	Receiving Dock-5	Storage 15	Fork Lift Mitsubishi	853.77	\$0.01
	Storage 15	Station 6A1	Human	108.7	\$0.20

Table E1(cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
<i>Stile 2"</i>					
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.31
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.14
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.03
	Storage 4B	Station 4B	Human	41.94	\$0.63
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.04
	Storage 4B	Station 4B	Human	41.94	\$0.90
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.15
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.24
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.20
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.40
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.59
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.11
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.27
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.02
	Storage 4B	Station 4B	Human	41.94	\$0.42
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.09

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Stile 3"	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.07
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.20
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.18
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.34
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.16
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.12
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.00
	Storage 4B	Station 4B	Human	41.94	\$0.08
	Receiving Dock-4	Storage 4B	Human	41.94	\$0.17
Strainer Basket	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.15
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.18
	Receiving Dock-4	Storage 4B	Fork Lift Mitsubishi	518.43	\$0.01
	Storage 4B	Station 4B	Human	41.94	\$0.21
Strainer Shower	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.06
	Storage 4A	Station 4A	Human	47	\$0.09
Strapping steel	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
	Storage 4A	Station 4A	Human	47	\$0.05
	Receiving Dock-2	Storage 2D	Fork Lift Mitsubishi	66.09	\$0.00
	Storage 2D	Station 2B	Hand Trolley	305.69	\$0.11
	Receiving Dock-2	Storage 2D	Fork Lift Mitsubishi	66.09	\$0.00
	Storage 2D	Station 2B	Hand Trolley	305.69	\$0.11

Table E1(contd). Distance Cost Report

<i>Part Description</i>	<i>From</i>	<i>To</i>	<i>Material Handling Unit</i>	<i>Distance Travelled</i>	<i>Cost/Day</i>
Support Shelf	Receiving Dock-9	Storage 28	Fork Lift Caterpillar	608.08	\$0.02
	Storage 28	Station 30	Hand Trolley	499.79	\$0.22
	Receiving Dock-9	Storage 28	Fork Lift Mitsubishi	608.08	\$0.01
Switch Ground Screw	Storage 28	Station 29	Hand Trolley	475.65	\$0.22
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.38
	Storage 15	Station 6A1	Human	108.7	\$0.40
Switch Plate-A	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.38
	Storage 15	Station 6A1	Human	108.7	\$0.40
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.13
Switch Plate-B	Storage 15	Station 6A1	Human	108.7	\$0.15
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.49
	Storage 15	Station 6A1	Human	108.7	\$0.50
Switch Plate-C	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.13
	Storage 15	Station 6A1	Human	108.7	\$0.15
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.13
Switch Plate-D	Storage 15	Station 6A1	Human	108.7	\$0.15
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.13
	Storage 15	Station 6A1	Human	108.7	\$0.15
Tank Toilet	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.08
	Storage 15	Station 6A1	Human	108.7	\$0.10
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.11
Tape Mesh	Storage 4A	Station 4A	Human	47	\$0.09
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	483.5	\$0.00
	Storage 9B	Station 8B	Human	71.67	\$0.04
	Receiving Dock-1	Storage 9B	Fork Lift Ingersollrand	483.5	\$0.00
	Storage 9B	Station 9B	Human	59.37	\$0.04

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Hand Unit	Distance Travelled	Cost/Day
Base Cabinet Assy	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Bar Cabinet Assy	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Base	Receiving Dock-4	Storage 4B	Hand Trolley	518.43	\$0.06
	Storage 4B	Station 4B	Human	41.94	\$0.05
Base Assembly 19"	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Base Assembly 6"	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Base Cabinet Assembly	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Batten 7/8 B	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$0.01
	Storage 21	Station 26	Human	263.44	\$0.24
Batten 7/8 C	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$0.01
	Storage 21	Station 26	Human	263.44	\$0.15
Batten 7/8 D	Receiving Dock-9	Storage 21	Fork Lift Caterpillar	470.87	\$0.11
	Storage 21	Station 26	Human	263.44	\$0.97
Batten 7/8 E	Receiving Dock-9	Storage 21	Fork Lift Caterpillar	470.87	\$0.71
	Storage 21	Station 26	Human	263.44	\$6.27
Batten 7/8 F	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$0.16
	Storage 21	Station 26	Human	263.44	\$3.96
Batten 7/8 G	Receiving Dock-9	Storage 21	Fork Lift Mitsubishi	470.87	\$1.42
	Storage 21	Station 26	Hand Trolley	263.44	\$34.14
Batten-7/8 A	Receiving Dock-9	Storage 21	Fork Lift Caterpillar	470.87	\$0.02
	Storage 21	Station 26	Human	263.44	\$0.24
Bolt Closet	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.11
	Storage 4A	Station 4A	Human	47	\$0.12
Bolt Shackle	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.03
	Storage 1	Station 1A	Fork Lift Mitsubishi	208.95	\$0.03

Table E1(continued): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Trim Stage B1	Station 18	Station 19A	Fork Lift Caterpillar	105.69	\$0.01
	Station 19A	Station 20A	Fork Lift Caterpillar	99.97	\$0.01
	Station 20A	Station 21A	Fork Lift Caterpillar	99.97	\$0.01
	Station 21A	Station 22A	Fork Lift Caterpillar	67.64	\$0.01
	Station 22A	Station 23	Fork Lift Caterpillar La	1,106.77	\$0.72
Trim Stage A2	Station 23	Station 25	Fork Lift Caterpillar La	57.82	\$0.66
	Station 26	Station 28	Fork Lift Caterpillar La	54.79	\$0.66
	Station 28	Station 30	Fork Lift Caterpillar La	53.93	\$0.66
Trim Stage B2	Station 25	Station 27	Fork Lift Caterpillar La	54.79	\$0.66
	Station 27	Station 29	Fork Lift Caterpillar La	54.51	\$0.66
Tub corner	Receiving Dock-3	Storage 4A	Fork Lift Mitsubishi	525.21	\$0.00
Tub Fibreglass	Storage 4A	Station 4A	Human	47	\$0.05
	Receiving Dock-3	Storage 4A	Fork Lift Mitsubishi	525.21	\$0.00
Tub	Storage 4A	Station 4A	Human	47	\$0.05
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
Tubing-A	Storage 4A	Station 4A	Human	47	\$0.05
Tubing-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$1.95
Tubing-C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$2.12
Tubing-D	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$1.47
Tyre	Receiving Dock-1	Storage 1	Hand Trolley	424.51	\$0.73
U-Channel	Storage 1	Station 1A	Fork Lift Toyota	507.42	\$0.01
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	208.95	\$0.01
	Storage 1	Station 1A	Fork Lift Toyota	507.42	\$0.01
U-Channel	Receiving Dock-9	Storage 27	Fork Lift Mitsubishi	208.95	\$0.01
	Storage 27	Station 32	Fork Lift Mitsubishi	618.61	\$0.04
	Receiving Dock-9	Storage 27	Human	593.96	\$0.89
	Storage 27	Station 31	Fork Lift Caterpillar	618.61	\$0.10
			Human	568.96	\$0.89

Table E1 (cont'd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Valve					
	Receiving Dock-3	Storage 4A	Hand Trolley	525.21	\$0.03
	Storage 4A	Station 4A	Human	47	\$0.05
	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.05
Valve-Gas Ball	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.05
Vanity Cabinet Module-A	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Vanity Cabinet Module-B	Station 4B	Station 4	Electric Hoist A	113.84	\$0.49
Vapor Barrier					
	Receiving Dock-1	Storage 9B	Fork Lift Mitsubishi	493.5	\$0.00
	Storage 9B	Station 8B	Hand Trolley	71.67	\$0.09
	Receiving Dock-1	Storage 9B	Fork Lift Caterpillar	493.5	\$0.01
	Storage 9B	Station 9B	Hand Trolley	59.37	\$0.09
Vent	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.01
Ventilaire	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.05
	Storage 2D	Station 2B	Human	305.69	\$0.05
	Receiving Dock-2	Storage 2D	Hand Trolley	66.09	\$0.05
	Storage 2D	Station 2B	Human	305.69	\$0.05
Vermin Proofer	Receiving Dock-3	Storage 4A	Fork Lift Mitsubishi	525.21	\$0.00
	Storage 4A	Station 4A	Human	47	\$0.07
	Receiving Dock-3	Station 2E	Human	424.51	\$0.11
Vermin Proofer-A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.26
Vermin Proofer-B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.08
Vermin Proofer-C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.11
Washer	Receiving Dock-3	Storage 2D	Fork Lift Mitsubishi	454.54	\$0.30
	Storage 2D	Station 2B	Fork Lift Mitsubishi	305.69	\$0.30
	Receiving Dock-3	Storage 2D	Fork Lift Ingersollrand	454.54	\$0.95
	Storage 2D	Station 2B	Fork Lift Ingersollrand	305.69	\$0.95
Waste Cont	Receiving Dock-3	Storage 4A	Fork Lift Mitsubishi	525.21	\$0.00

Table E1(contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Window Metal-30x27 white s	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.00
	Storage 16	Station 12	Hand Trolley	555.11	\$0.06
Window Metal-30x60	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.02
	Storage 16	Station 12	Hand Trolley	555.11	\$0.16
Window Metal-30x60 white s	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.02
	Storage 16	Station 12	Hand Trolley	555.11	\$0.16
Window Metal-46x60	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.01
	Storage 16	Station 12	Hand Trolley	555.11	\$0.11
Wire Copper	Receiving Dock-5	Storage 16	Fork Lift Caterpillar	979.36	\$0.01
	Storage 16	Station 13	Hand Trolley	571.11	\$0.11
Wire-A	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.01
	Storage 1	Station 1A	Human	208.95	\$0.18
Wire-B	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.01
	Storage 1	Station 1A	Human	208.95	\$0.18
Wire-Black	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$21.00
	Storage 15	Station 6A1	Human	108.7	\$17.79
Wire-C	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$17.92
	Storage 15	Station 6A1	Human	108.7	\$17.79
Wire-Black	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$21.00
	Storage 15	Station 6A1	Human	108.7	\$5.94
Wire-Black	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$5.94
	Storage 15	Station 6A1	Human	108.7	\$5.94
Wire-Black	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$2.12
	Storage 1	Station 1A	Human	208.95	\$2.95
Wire-C	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.12
	Storage 1	Station 1A	Human	208.95	\$2.95
Wire-C	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.25
	Storage 15	Station 6A1	Human	108.7	\$0.27
Wire-C	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.25
	Storage 15	Station 6A1	Human	108.7	\$0.27

Table E1 (contd): Distance Cost Report

Part Description	From	To	Material Handling Unit	Distance Travelled	Cost/Day
Wire-Copper	Receiving Dock-3	Station 2E	Fork Lift Mitsubishi	424.51	\$0.00
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.30
	Storage 15	Station 6A1	Human	108.7	\$0.32
Wire-E	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.30
	Storage 15	Station 6A1	Human	108.7	\$0.32
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.25
	Storage 15	Station 6A1	Human	108.7	\$0.27
	Receiving Dock-5	Storage 15	Hand Trolley	853.77	\$0.25
Wire-Red	Storage 15	Station 6A1	Human	108.7	\$0.27
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.12
	Storage 1	Station 1A	Human	208.95	\$2.95
Wire-White	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.12
	Storage 1	Station 1A	Human	208.95	\$2.95
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.12
	Storage 1	Station 1A	Human	208.95	\$2.95
	Receiving Dock-1	Storage 1	Fork Lift Mitsubishi	507.42	\$0.12
Wye A	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.11
Wye B	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.08
Wye C	Receiving Dock-3	Station 2E	Hand Trolley	424.51	\$0.08
Grand Total:				589,319.93	\$1,235.71

APPENDIX-F
REVIEW FROM PROFESSIONAL PRACTITIONERS

"All at Cohen Brothers Homes were quite impressed by the scope and content of your MH facility layout analysis process, which was presented to us this week. In reviewing the presentation summary package I would offer the following comments.

- As a tool for use by a profit-oriented entity, any analysis process must present some kind of conclusion to decision makers. The conclusion can be based on a range of results, but there should be some recommended course of action that comes out of the analysis process. Whatever the relative strength of any analytical technique might be, analysis is only useful if it enables enlightenment. That said, an analysis assessment/conclusion methodology is necessary to provide a user of your process with a way to realize its benefits. This wasn't clear to us in the materials although we did end up discussing this quite a bit at the presentation.*
- I have no significant concerns with the overall methodology or how it has been constructed. In fact, I believe--given your problem definition—that the process is very comprehensive and addresses the problem in the most rational sequence.*
- In the absence of an available plan (e.g. An existing facility) I'm not clear how one begins to make choices relative to facility layout, other than intuition borne of experience. For new facilities, it seems that one would produce a baseline layout without any quantitative assessment and then simply refine that through the modeling process. Adequate product definition is essential, clearly, to being able to maximize the usefulness of your process.*

- *I mentioned in the presentation that being able to integrate the modeling process with product information that is maintained in a database would be very helpful to the on-going implementation of this technique.*
- *From a presentation standpoint, being able to see how outputs (e.g. printed reports) tie to the defined steps on the flowchart would be very helpful. This would help integrate a user's understanding of the information--where it "fits" in the overall analysis. Adding labels that reference which process / sub-process / step that an output exhibit belongs to would be a logical way to handle this. This probably means that you would need to establish a process outline numbering system.*
- *Integrating this element of the facility design process into a comprehensive facility design process, where labor cost and quality processes are taken into account, would seem to be the next logical phase of research. We have been incorporating Lean-flow manufacturing techniques into our facility design work and would expect that any modern manufacturer want to blend that discipline into the overall process.*
- *Based on what we've seen, we are very interested in using the methodology to further refine our whole-house building plant design."*

○ *Lee Dehmlow*

Manager of Operations

Cohen Brothers Homes

REFERENCES

- (Abu Hammad 2003) Hammad A.A. A., (2003) A Decision Support System For Manufactured Housing Production Process Planning And Facility Design, Ph.D Dissertation, Department of Civil and Environmental Engineering, University of Cincinnati, Ohio.
- (Abdulghani 1996) Abdulghani B, (1996), Material Flow And Volume Distance Relationships In Line Layout Manufacturing Systems, Rensselaer Polytechnic Institute
- (Albern 1997) William F. Albern.,(1997) M. D. Morris.,(1997), "Factory-Constructed Housing Developments" C R C Press LLC
- (Agarwal 1995) Agarwal A, (1995), Analysis Of Cellular And Functional Manufacturing Systems (Conversion), PhD Dissertation, The University Of Texas At Arlington
- (Ananth 2002) Ananth K, (2002), Analytical Performance Models For Material Control Strategies in Manufacturing Systems, PhD Dissertation, The University of Wisconsin-Madison
- (Apple 1963) James M. Apple (1963), "Plant Layout and Material Handling", The Ronald Press Company New York
- (Apple 1977) Apple, J.M., 1977, Plant Layout and Material Handling, 3rd edition, John Wiley & Sons, New York
- (AutoB 2002) Automated Builder, January 2002
- (Martinez 1998) Martinez, J (1998), Introduction to EZSTROBE – Tutorial, Department Of Civil Engineering, University of Michigan, Ann Arbor
- (Barriga 2003) Barriga Edgar (2003), Material Supply Management System for Manufactured Housing Industry., MS Thesis, Construction Management Program , Purdue University
- (Barshan 2003) Barshan, A, (2003), Methodology For Evaluating And Ranking Manufactured Houses Based On Construction Value, MS Thesis, Construction Management Program, Michigan State University
- (Barshan et.al 2003). Barshan, A., Willenbrock, J., Abdelhamid, T., Syal, M. (2003). "Manufactured Housing Construction Quality Guidelines". Michigan State University, USA

- (Bernhardt 1980) Aurthur D. Bernhardt (1980), "Building Tomorrow: The mobile/manufactured Housing Industry" Massachusetts Institute Of Technology, The MIT Press, Massachusetts, Cambridge, and London, England
- (Bhat 1989) Bhat R.J., (1989) Knowledge Based System for Facilities Design and Material Handling System (FADAMATES), The University of Texas at El Paso
- (Budiman 1999) Budiman S, (1999), Design And Implementation Of A Decision Support Framework For Evaluating Manufacturing Alternatives, Oregon State University
- (Chandra 2002) Chandra M T (2002),Efficient Approach To Optimization Under Uncertainty With Application To Large Scale Engineering Systems, Carnegie Mellon University
- (Chen 1995) Chen J. (1995) Cellular Manufacturing System Design: Optimal Solution of Large Scale Real World Problems, Industrial Engineering, Rensselaer Polytechnic Institute
- (Chitla 2002) Chitla V (2002), Performance Assessment Of Planning Processes During Manufactured Housing Production Operations Using Lean Production Principles, MS Thesis, Construction Management Program, Michigan State University
- (Chittratanawat 2001) Chittratanawat S. (2001) Operations based facilities design, University of Missouri, Columbia
- (Churirat 2002) Churirat B, (2002), Analysis Of Operations Research Models Using Activity Based Costing, Pennsylvania State University
- (Chung 1989) Chung E K, (1989), A Survey Of Process Modeling Tools, Technical Report No 7, Computer Integrated Construction Research Program, The Pennsylvania State University
- (Cigdem 2002) Cigdem Z, (2002), Performance Analysis And Capacity Planning Of Multi-Stage, Multi-Product, Decentralized and Market Driven Manufacturing Systems, Rutgers State University Of New Jersey-New Brunswick
- (CohenBrothers 2003) CohenBrothers Homes
<http://www.cohenbrothershomes.com> (viewed May 2003)

- (Census 2002) U.S. Census Bureau, U.S. Commerce Department.
<http://www.census.gov/pub/const/mhs/mhstabplcmnt.pdf> (viewed May 2002)
- (CMTC 2000) California Manufacturing Technology Center,
<http://www.cmtc.com/services/plantlayout.asp> (viewed May 2002)
- (Deneba 2002) <http://www.deneba.com/community/howto/flowcharts/default.html>
(viewed May 2002)
- (Dogan 1995) Dogan E, (1995), Performance Analysis And Design Issues in Transfer Line (Manufacturing), Rutgers the State University Of New Jersey, New Brunswick
- (Donaghey 2000) MHAND, BLOCPLAN 2000, Donaghey and Pire, Industrial Engineering Department, University of Huston
- (EAI 1999) Engineering Animation, Inc., FactoryPLAN, Factory 1999
- (EDS 2002) EDS (2002), "FactoryFLOW Class Guide", FactoryFLOW Training Manual v.1.2
- (GATECH 2003) www.gatech.edu (viewed on September, 2003)
- (Gau 1998) Gau K Y (1998), Facility Layout With An Iterative Algorithm, Auburn University
- (Hammad 2001) Hammad A.A. A., (2001) "Simulation Modeling for Manufactured Processes in Construction", Masters Thesis, Department of Civil and Environmental Engineering, University of Cincinnati, Ohio
- (Hsieh 1994) Hsieh J C, (1994) Measurement Of Cellular Manufacturing: Evaluation Of The Efficiency Of Clustering Algorithms And The Performance Of Alternative Layouts, The University Of Texas Arlington
- (Heragu 1997) Heragu S. S., (1997) "*Facilities Design*", PWS Publishing Company, Boston
- (Huang 1999) Huang C. (1999) Autonomy and Viability in Agent-based Manufacturing Systems, Industrial Engineering, Purdue University
- (Huang 1992) Huang J. (1992), Load Volume Considerations in the Collision Free Route Planning of Material Handling Devices in FMS (Flexible Manufacturing Systems), Industrial Engineering, University of Illinois at Urbana-Champaign

- (Houten 1998) Houten M, (1998), Function Approximation Concepts For Multidisciplinary Design Optimization, Technische Universiteit Eindhoven (Netherlands)
- (HUDMHCSS 1999) Chapter XX--Office Of Assistant Secretary For Housing—Federal Housing Commissioner, Department Of Housing And Urban Development Part 3280--Manufactured Home Construction And Safety Standards
- (Ioannou 1995) Ioannou G. (1995) Integrated Manufacturing Facility Design (Routing, Shop Layout), Industrial Engineering, University of Maryland, College Park
- (Ireson 1954) William Grant Ireson (1954), "Factory Planning and Layout" Prentice-Hall, Inc. New York
- (Joseph 1998) Joseph T C, (1998) A Design Algorithm For Continuous Melt-Phase Polyester Manufacturing Processes; Optimal Design, Product Sensitivity, And Process Flexibility, Ohio University
- (Kim 2002) Kim B.I.(2002) Intelligent Agent Based Planning, Scheduling, and Control: Warehouse Management Application, Industrial Engineering, Rensselaer Polytechnic Institute
- (Kochhar 1997) Kochhar J.S.(1997) Design of a Dynamic Facility: A Genetic Algorithm Based Approach, Industrial Engineering, Rensselaer Polytechnic Institute
- (Koo 1996) Koo P.(1996) Flow Planning and Control of Single-stage Multimachine Systems, Industrial Engineering, Purdue University
- (Lara 1999) Lara Gracia, Marco Anonio (1999) Conflict Resolution in Collaborative Facility Design, Industrial Engineering, Purdue University
- (Lars Peter 2002) Lars Pter F, (2002) A Framework For Analyzing The Performance of Sequential Module Flows, PhD Dissertation, Chalmers Tekniska Hogskola, Sweden
- (Lee and Englin 1989) Lee, A. and Englin, J. (1989). "Using a Model and Empirical Data to Analyze Manufactured Home Conversation Retrofit". Energy and Buildings
- (Li 1994) Li Ming, The Simulation Of Material Flow And Productivity In a Manufacturing Facility, University Of Lowell

- (Litchfield 1995) Litchfield J.A.,(1995) Improving Job Shop Performance through Utilization of System Information in Process Queue Management under Transfer Batching, Business Administration, Michigan State Univeristy, East Lansing, Michigan
- (Luke 2002) Luke C M, Quantitative Methodology And Applications In Measuring Supply Chain Complexity, MS Thesis, Florida Atlantic University
- (Mehrotra 2002) Mehrotra N; (2002), "Manufactured Housing Production Plant: Layout Design Process", Masters thesis, Construction Management Program, Michigan State University, East Lansing, Michigan
- (Mehrotra 2003) Mehrotra N; (2003), "Manufactured Housing Production Plant: Layout", Construction Management Congress, Hawaii 2003
- (Meng 2002) Meng G.(2002) Open Queuing Network Performance Analyzer for Reconfigurable Manufacturing Systems, Industrial Engineering, Rensselaer Polytechnic Institute
- (MHI-1) Manufactured Housing Institute,
http://www.mfghome.org/fast_facts.html (viewed May 2002)
- (MHI-2) Manufactured Housing Institute,
http://manufacturedhousing.org/quick_facts/industry_overview.html (viewed May 2002)
- (MHI-3) Manufactured Housing Institute,
<http://www.mfghome.org/statistics/costs.html> (viewed May 2002)
- (MHI 2000) http://www.mfghome.org/MC_industry_statistics.html (viewed May 2002)
- (MHRA 2000) Plants That Shine, Newsletter at The Manufactured Housing Research Alliance, Volume-2, Issue-1, Winter 2000
- (MHRP 1996) Burkhardt, T. H., Mireley. S. L., Syal. M., (1996) Manufactured Housing Research Project, Michigan State University, East Lansing, Michigan
- (MHRP 1993) Warner, Kate., and Johnson, Robert., (1993), Manufactured Housing Research, Project Michigan State University, College of Architecture and Urban Planning, Ann Arbor, Michigan
- (Montreuil 1982) Montreuil, B,(1982), "Interactive Optimization Based Facility Layout", Ph.D Dissertation, Georgia Institute of Technology

- (Mrozowski & Sambhare 2002). Tim Mrozowski, Reshma Sambhare (2002)
 “Manufactured Housing in Michigan (Volume-2)- An Assessment
 of Site Regulatory Requirements Impacting the Use of
 Manufactured Housing”
- (Mullens 2002) Mullens M, UCF Housing Constructability Lab, 2002 Annual
 Report Prepared for The National Consortium of Housing
 Research Centers, Department of Industrial Engineering &
 Management Systems, University of Central Florida
- (Muther 1973) Muther R., (1973), “*Systematic Layout Planning*”, 2nd edition,
 Cahners Books, Boston
- (NAHB 1998) Factory And Site-Built Housing A Comparison For The 21st
 Century, October 1998, NAHB Research Center Inc., Upper
 Marlboro, MD
- (Noble 1991) Noble J.S., (1991) A Framework for the Design Justification of
 Material Handling Systems, Industrial Engineering, Purdue
 University
- (OWEN 2002) Facility Layout and Relayout Tool (FLRT), Engineering
 Animation Incorporated (EAI)
<http://www.owensiec.com/download/flrt.doc> (viewed May 2002)
- (Pandit 1990) Pandit R. (1990) Job Shop Scheduling to Minimize Makespan with
 Explicit Material Handling Considerations (Flexible
 Manufacturing), Industrial Engineering, University of Illinois at
 Urbana-Champaign
- (Patrick 2002) Patrick, S, (2002), A Design Methodology For Scalable Machine
 Systems, Thesis, University Of Michigan College Of Engineering
 Grad. Prof. Progs
- (Palekar 1998) Palekar. U. S., (1998) Lecture Notes, Plant Layout, IE 261:
 Facilities Planning and Design, Mechanical and Industrial
 Engineering, University of Illinois at Urbana-Champaign
- (Ragsdale 2002) C. T. Ragsdale, (2001). Spreadsheet Modeling and Decision
 Analysis, 3rd Edition, South-Western, Ohio
- (Rajagopalan 1999) Rajagopalan S. (1999) Flowpath Design and Analysis of AGV-
 based Material Handling Systems, Industrial Engineering,
 Rensselaer Polytechnic Institute

- (Ramu 1996) Ramu N V, (1996), Design Methodology for Modeling Warehouse Internal Layout Integrated With Operating Policies, Clemson University
- (Reed 1967) Reed R. Jr., "*Plant Layout: Factors, Principles, and Techniques*", Richard. D. Irwin
- (Rembold 1992) Rembold B.F.,(1992) An Integrated Framework for the Design of Material Flow Systems, Industrial Engineering, Purdue University
- (Rongliang 2001) Rongliang W, (2001), A System For Facility Layout Design, The University of Brunswick, Canada
- (Sam 1996) Sam V S, (1996), Strategic Planning Of Flexible Assembly Systems For Electronic Industry, Texas A&M University
- (Savas 2000) Savas S. (2000) A Spatial Modeling Perspective to Problems in Facilities Design, Operations Research, State University of New York at Buffalo
- (Senghore 2001) Senghore Omar., (2001)"The Production and Material Flow Process Model for Manufactured Housing", MS Thesis, Construction Management Program, Michigan State University, East Lansing, MI
- (Sheikhzadeh 1997) Sheikhzadeh M, (1997), Issues In Design, Planning And Control Of Multi-Product Manufacturing Systems, University Of Minnesota
- (Shubin & Madeheim 1951). Shubin J. A. & H. Madeheim (1951) "*Plant Layout*" Eaglewood Cliffs, New Jersey, Prentice Hall
- (Sule 1988) D.R. Sule (1988)"Manufacturing Facilities - Location, Planning, and Design", PWS-KENT Publishing Company, Boston
- (Syal & Hastak 2002) Syal M., Hastak M., (2002) "Manufactured Housing Production Process Analysis and Facility Layout", A Proposal for National Science Foundation (NSF)
- (Syal & Mehrotra 2001) Syal M., Mehrotra N., "Manufactured Housing Trends and Regulations in Michigan" Construction Management Program, Michigan State University, East Lansing, Michigan
- (Taghaboni 1989) Taghaboni F.,(1989) Scheduling and Control of Manufacturing Systems with Critical Material Handling, Industrial Engineering, Purdue University

- (Taho 1996) Taho Y, (1996), Facility Layout And Material Handling System Design Integration In Manufacturing Systems, Texas A&M University
- (Tompkins G 1995) Tompkins G H, (1995), Optimization Of Qualitative Variables In Discrete Event Simulation Models (Manufacturing, Genetic Algorithm), Kansas State University
- (Tompkins et al., 1996) Tompkins J. A., White J. A., Bozer Y. A., Frazelle E. H., Tanchoco J. M.A., Trevino J., (1996) "Facilities Planning", John Wiley & Sons, Inc
- (Venkatadri 1995) Venkatadri U, (1995), Fractal Layout For Job Shops (Workstations), Purdue University
- (Waraporn 2002) Waraporn I, (2002) A Method For Simulation Optimization With Applications In Robust Process Design And Locating Supply Chain Operations, PhD Dissertation, Ohio State University
- (Willenbrock 1998) Jack H. Willenbrock (1998), "Residential Design and Construction", Prentice Hall, New Jersey
- (Witzerman 1995) Witzerman J.P. (1995) A Facility Description Language for Distributed Design Integration, Industrial Engineering, Purdue University
- (Yang 1999) Yang S. (1999) Décision Support System for Machine Re-layout Planning, Industrial Engineering, Purdue University
- (Yaen 1996) Yaen C, (1996), New Strategies For Device Dispatching In Trip Based Material Handling Systems, The University Of Michigan