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A DECISION SUPPORT SYSTEM FOR MANUFACTURED HOUSING PRODUCTION PROCESS PLANNING AND FACILITY LAYOUT

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ABSTRACT

Productivity improvement of manufactured housing (MH) production systems has been a great concern to manufacturers and production managers. The evaluation of the production system efficiency in the factory is essential for meeting the growing demand of customers with respect to design and size of the manufactured housing product (MH).

The purpose of this research is to resolve some of the problems of the MH production system. The problems of the existing system are identified in the master’s thesis, Abu Hammad 2001, as follows: i) process bottlenecks hindering productivity, ii) unbalanced processes, and iii) layout limitations to the production capacity. Moreover, a lack of technology is observed in the existing MH operations. Existing production systems employing the traditional production line have low throughput and are inefficient. This dissertation research explores alternative layout designs that are proven via simulation to be more efficient and productive. Additionally, an advanced MH production system employing recent theories in technology and manufacturing is addressed in this research.

The major contribution of this dissertation is to develop a decision support system (DSS), which provides the MH industry with an efficient tool to streamline the performance of existing MH facilities. This dissertation investigates the interrelation impact of multiple factors on the productivity of four modules: (i) market, (ii) factory, (iii) manufactured housing processes, and (iv) production system layout. The following objectives have been achieved in support of the stated goal:

1. Develop a streamlined MH process;
2. Develop optimization models to streamline the activities and predict relevant parameters;
3. Develop advanced layout designs employing recent theories in manufacturing (i.e., lean
production theory).

The DSS provides assistance in the following decisions: (i) selecting an efficient system layout matching user requirements, (ii) streamlining activities and operations of the overall production system, and (iii) predicting the productivity and product sizes based on the organizational requirements. Finally, a feedback from the manufacturers has indicated that the DSS meets a crucial need for streamlining the system operations. The proposed DSS is a practical, simple, and accurate tool for scheduling and planning the operations, resources, and material requirements of the production system.
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Ayman Abdallah Abu Hammad
To the soul of my father, to my mother,

wife: Souma,

and

sons: Mahmoud and Omar
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A manufactured house (MH) is the housing unit, mostly constructed in a factory, and then transported to the site on its permanent chassis and wheels. It can be single-bay or multi-section. The MH has a price advantage over conventional on-site construction housing units. The lower first cost rate makes the MH economically attractive to low income households, young families, the elderly, and retired persons (Lee 1989). Since the implementation of the Housing and Community Development Act in 1976, the manufactured homes (termed mobile homes before the issuance of the 1976 HCDA) had become the first form of permanent housing built to meet the national standard of construction and safety. Moreover, MH became an ultimate housing solution with respect to (i) construction quality, (ii) design, (iii) cost, and (iv) safety (MHI 2003).

1) Quality: high quality of building materials with advantages of economy of scale in volume purchasing. In addition, all of the construction operations are managed inside a controlled factory environment. Thus, the weather doesn’t interfere with construction and cause delays. All technicians, craftsmen and assemblers work as a team and are professionally supervised, and products are continually inspected. Inventory is better controlled and materials are protected from waste and weather-related damage (MHI 2003).

2) Design: The building materials in today’s manufactured home are the same as those used in a site-built home. Thus, manufactured homes are compatible with almost any neighborhood due to variety in exterior designs and building materials. In addition, MH offer a wide variety of floor plans and interior finishes with vaulted ceilings, bay windows, fully-equipped kitchens and
bathrooms, and walk-in closets. A variety of exterior siding is offered including metallic, vinyl, wood, or hardboard. Most homes have pitched roofs with shingles and gabled ends. In many cases, the home can be customized to meet the needs of the consumer (MHI 2003).

3) Cost: economy of scale in volume purchasing of building materials and appliances. In addition, this type of housing does not include the cost of interim construction financing.

4) Safety: manufactured homes are engineered for wind safety and energy efficiency based on the geographic region where they are sold. Manufactured homes conform to federal laws requiring smoke detectors, escape windows, and limited combustible materials around furnaces, water heaters and kitchen ranges. Properly installed homes can withstand 120-130 mph 3-second gust winds in areas prone to hurricanes (MHI 2003).

1.1.2 Overview

The manufactured housing industry is a major provider of housing units in the United States. The MH market-share was 350 thousand units in the year 1999. The total housing production at the same year was 1,275,000 units. Manufactured house (MH) is a housing unit that is entirely manufactured in a controlled factory setting. MH cost advantage over the site built house (SBH) is due to economies of scale and mass production offered by the factory production line. This type of housing was realized after the issuance of HUD code in 1976, a code that regulates the quality and durability of the MH (HUD 2002). Since 1976, the MH sales have been increasing substantially until 1998 with MH sales of 372,843 (Census 2002). A gradual drop in MH sales was observed after 1998 to 193,300 units in the year 2001. Although MH is still competitive compared to site built housing its prices have not improved from an affordability point of view. Instead, they were observed to increase annually in such a way that efficiency gained through industrialization and mass production were no longer sufficient to attract low-
income households to buy MH as underlined by the decrease in MH placements after 1998 and the drop in total retail sales (Census 2002).

There has been a rising interest in analyzing the current MH production system to determine ways that lead to improve the process and increase the productivity.

1.1.3 Manufactured Housing Trends

MHI shipped 350,000 housing units in the year 1999, whereas the annual housing supply was estimated to be 1.5 Million units during the 1990’s for an annual need that exceeds 2 Million units (Syal and Hastak 2000). Manufactured housing is rapidly becoming an integral part of the nation’s housing. Manufactured homes represented 20.7% of all new single-family housing starts in 1999, according to the U.S. Census Bureau and the Housing and Urban Development Code (HUD) (MHI 2001). In 1999, 21.4 million Americans (about 7.6 percent of the U.S. population) lived in 8.9 million manufactured homes across the United States. These homes represent almost 1/6th of the new single-family housing starts in 2000. From the housing trailers built in the 1950’s to today’s multi-section manufactured homes with up to 2000 SF, this industry has made substantial impact on fulfillment of housing needs (Syal and Hastak 2000). The trend related to unit size also indicates the growth of larger multi-section manufactured housing as compared to single section home of the 1970’s. Table 1.1 shows cost and size comparisons for new manufactured homes and new single family site-built homes for the years 1993-1999.

In 1999, multi-section homes represented 64.7% of all industry shipments, compared to single-section homes at 35.3%. In 1999, the average price of a manufactured home was $43,600, compared to the average cost of a site-built home at $153,425, excluding land price, Where MH accounted for approximately 1/4th of the SBH price.
Table 1.1 Cost and Size Comparisons

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</thead>
<tbody>
<tr>
<td><strong>New Manufactured Homes (Including Typical Installation Costs)</strong></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td><strong>(All Homes)</strong></td>
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<td></td>
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</tr>
<tr>
<td>Average Sales Price</td>
<td>$30,500</td>
<td>$32,900</td>
<td>$35,400</td>
<td>$37,400</td>
<td>$40,400</td>
<td>$41,900</td>
<td>$43,600</td>
<td>$46,300</td>
<td>$48,800</td>
</tr>
<tr>
<td>Average Square Footage</td>
<td>1,295</td>
<td>1,335</td>
<td>1,360</td>
<td>1,385</td>
<td>1,420</td>
<td>1,455</td>
<td>1,480</td>
<td>1,505</td>
<td>1,540</td>
</tr>
<tr>
<td>Cost per Square Foot</td>
<td>$23.55</td>
<td>$24.64</td>
<td>$26.03</td>
<td>$27.00</td>
<td>$28.17</td>
<td>$28.80</td>
<td>$29.46</td>
<td>$30,500</td>
<td>$31,69</td>
</tr>
<tr>
<td><strong>Single-Section</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Average Sales Price</td>
<td>$21,900</td>
<td>$23,900</td>
<td>$26,200</td>
<td>$27,900</td>
<td>$29,400</td>
<td>$31,000</td>
<td>$31,800</td>
<td>$30,500</td>
<td>$30,700</td>
</tr>
<tr>
<td>Average Square Footage</td>
<td>1,065</td>
<td>1,105</td>
<td>1,135</td>
<td>1,165</td>
<td>1,200</td>
<td>1,240</td>
<td>1,245</td>
<td>1,140</td>
<td>1,102</td>
</tr>
<tr>
<td>Cost per Square Foot</td>
<td>$20.56</td>
<td>$21.63</td>
<td>$23.08</td>
<td>$23.94</td>
<td>$25.00</td>
<td>$25.54</td>
<td>$26,75</td>
<td>$27,41</td>
<td></td>
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<tr>
<td><strong>Multi-section</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Average Sales Price</td>
<td>$39,600</td>
<td>$41,800</td>
<td>$44,300</td>
<td>$45,700</td>
<td>$47,300</td>
<td>$48,700</td>
<td>$50,200</td>
<td>$53,600</td>
<td>$55,100</td>
</tr>
<tr>
<td>Average Square Footage</td>
<td>1,525</td>
<td>1,555</td>
<td>1,575</td>
<td>1,580</td>
<td>1,580</td>
<td>1,605</td>
<td>1,655</td>
<td>1,675</td>
<td></td>
</tr>
<tr>
<td>Cost per Square Foot</td>
<td>$25.97</td>
<td>$26.88</td>
<td>$28.13</td>
<td>$28.92</td>
<td>$30,03</td>
<td>$31,28</td>
<td>$32,00</td>
<td>$32,51</td>
<td></td>
</tr>
<tr>
<td><strong>New Single-Family Site-Built Homes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Average Sales Price</td>
<td>$147,700</td>
<td>$154,100</td>
<td>$158,700- $166,400</td>
<td>$176,200</td>
<td>$181,900</td>
<td>$195,800</td>
<td>$207,000</td>
<td>$212,300</td>
<td></td>
</tr>
<tr>
<td>Price of Structure</td>
<td>$110,775</td>
<td>$115,575</td>
<td>$124,125</td>
<td>$131,150</td>
<td>$138,450</td>
<td>$142,125</td>
<td>$161,288</td>
<td>$164,217</td>
<td></td>
</tr>
<tr>
<td>Average Square Footage</td>
<td>2,095</td>
<td>2,115</td>
<td>2,050</td>
<td>2,090</td>
<td>2,140</td>
<td>2,170</td>
<td>2,230</td>
<td>2,266</td>
<td>2,324</td>
</tr>
<tr>
<td>Cost Per Square Foot</td>
<td>$52.88</td>
<td>$54.65</td>
<td>$60.55</td>
<td>$62.75</td>
<td>$64.70</td>
<td>$65.50</td>
<td>$62.80</td>
<td>$71.18</td>
<td>$70.66</td>
</tr>
</tbody>
</table>

Source: U.S. Department of Commerce, Bureau of the Census


Multi-section shipments in 2000 have exceeded single-section shipments, commanding 70.1% of total shipments. In 1999, multi-section shipments were 64.7% of the total production. Figure 1.1 shows the relative percentages for both types for the years 1993-1999. This indicates an increasing demand on the luxurious sizes of MH unit’s since 1996. In 2000, the industry shipped 250,550 homes from 280 manufacturing facilities. Table 1.2 shows the respective shipments of Single vs. Multi-section units for the years 1993-2001. The top 25 firms have produced (91%) of total industry shipments, compared to (95%) in 1999. The top 10 companies have produced 78.8% of the homes shipped in 2000 (MHI 2001).
Figure 1.1 Growth of Multi-section Home Shipments

Source: National Conference of States on Building Codes and Standards, 1995-2001


Table 1.2 New Manufactured Home Placements (1993-1999)

<table>
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<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total Placements</td>
<td>254,276</td>
<td>303,932</td>
<td>339,601</td>
<td>363,411</td>
<td>353,377</td>
<td>372,843</td>
<td>348,671</td>
<td>250,550</td>
<td>193,300</td>
</tr>
<tr>
<td>Single Sections</td>
<td>134,440</td>
<td>156,171</td>
<td>173,735</td>
<td>173,674</td>
<td>148,809</td>
<td>144,328</td>
<td>122,926</td>
<td>74,919</td>
<td>48,924</td>
</tr>
<tr>
<td>Average Sales Price</td>
<td>20,500</td>
<td>23,500</td>
<td>25,800</td>
<td>27,000</td>
<td>27,900</td>
<td>28,800</td>
<td>29,300</td>
<td>30,400</td>
<td>30,700</td>
</tr>
<tr>
<td>Multi Sections</td>
<td>119,836</td>
<td>147,761</td>
<td>165,816</td>
<td>189,737</td>
<td>204,568</td>
<td>228,515</td>
<td>225,745</td>
<td>175,500</td>
<td>144,916</td>
</tr>
<tr>
<td>Average Sales Price</td>
<td>40,200</td>
<td>42,000</td>
<td>44,600</td>
<td>46,200</td>
<td>48,100</td>
<td>49,800</td>
<td>51,000</td>
<td>53,900</td>
<td>55,200</td>
</tr>
</tbody>
</table>

Source: U.S. Department of Commerce, Bureau of the Census

(http://www.manufacturedhousing.org/media_center/quick_facts2003/cost_size.html)

The following are observed from Table 1.2:

1) Escalating prices of MH units. The annual increase is $1,000-$2,000. The total increase in one
decade is $10,000 on the price of the single-bay units (50% increase) and $15,000 on the price of the double-bay units (38% increase).

2) Substantial decrease in MH placements after the peak of 1998 (with 372,843 units) to 193,300 units in 2001. The decrease in MH placements has affected the total retail sales, which dropped to 9.4 billion from a high 16.3 billion in the year 1998. Although MH is still competitive with SBH, this fact does not mean that MH prices are improving from an affordability point of view. Instead, they are observed to increase annually in such a way that efficiency gained through industrialization and mass production would no longer attract low-income households to buy MH. The decrease in MH placements after 1998 and the drop in the total retail sales underline this fact.

1.2 NEEDS OF THE MH INDUSTRY

In general, the MHI needs can be categorized under three themes, economic, manufacturing, and innovation needs.

1. Economic Needs:

A) National level: all U.S. industries are targeting cost effective operations to sustain slow down in the economy characterized mainly by declined sales;

B) MH industry level: need to keep the competitive advantage of MH against other housing types as main provider of affordable houses. Emerging need of factory management to reduce manufacturing costs associated to the production system;

C) Company level: Most of MH firms produce their products in more than one facility, reduction of number of facilities and resources will definitely reduce costs and offer affordable prices of housing units. Cost reduction could be achieved by reducing inventory levels, lead times and integrating the supply chain. Moreover, it would be achieved through eliminating waste and all
scrap forms in products, (scrap) is the major loss in factory resources and materials (Black 1998);
D) Customer level: to keep the MH unit as an attractive solution for low and middle-income classes.

2. Manufacturing Needs

The industrialization of housing has accomplished high production levels and substantial cost reductions due to mass production and economies of scale. However, reverse impacts are observed in terms of the design flexibility aspect.
A) Reengineering: emerging market needs of innovative housing solutions (architectural wise) and increasing demand on double bay housing (size wise) that requires a flexible manufacturing system that could be easily reconfigured or redesigned to adapt to emerging customer needs with minimal lead times of supply from factory to customer (NSF-PATH Roadmapping 2002);
B) Efficient production system that eliminates the effects of mixed model manufacturing (i.e., process bottlenecks). There is a need for a practical method to streamline the activities and operations of existing MH production systems.
C) Incorporate technology in assembly line configuration and station equipments and machines (NSF-PATH Roadmapping 2002);
D) Improve the material handling system and apply good house keeping practices (Syal and Hastak 2000);
E) Shop floor design specific to MH processes, with respect to space and production requirements;
F) Level of Automation and integrating computerization in all manufacturing stages (NSF-PATH Roadmapping);
G) Utilization of new building Materials (NSF-PATH Roadmapping), such as steel, composites,
plastic boards, and study the impact of the building material used on the factory layout design and requirements;

![Diagram](image)

**Figure 1.2** Research Needs

H) Integrate Urban Design theories in housing to improve MH image and provide customers with a wide variety of housing shapes and functionality. Row housing and clustered MH housing shown in Figure 1.3 have better urban image. Additionally, they result in substantial savings in material cost and energy;

I) Future extension procedure reduces the initial cost of the MH to the customer. And provides the family with additional space as the family grows in size;

J) Consider two story housing unit designs for MH. Vertical extention is efficient in reducing land costs compared to the double bay housing unit.
The uniqueness of the construction process of a manufactured house in a factory emphasizes a greater need for investigating innovative production and material flow processes for the manufactured housing industry. This need has taken on a greater importance with the growing trend towards multi-section manufactured homes as compared to single section homes of the 1970’s and 1980’s. The process modeling of the assembly process along with the material inventory, storage, in-plant delivery, and utilization process promises the possibility of improving the production efficiency, cost effectiveness, and quality.

Research conducted through the NSF-PATH Project (Syal and Hastak 2000) has identified several process bottlenecks through simulation that could be removed to achieve improvements in productivity. However, the extent of possible modifications is constrained due to the limitations of the existing facility layout design. The following needs can be defined from the above discussion.

1) There is a need to eliminate the bottlenecks in the production process and material flow;
2) Alternative facility design and layout should be investigated to facilitate better production
process and supply chain management;

3) Innovative changes to the conceptual planning of the production system should be investigated to bring the manufactured housing industry at par with some of the other manufacturing industries in terms of technology and process planning.

1.3 PROBLEM STATEMENT

Manufactured housing (MH) production processes do not benefit greatly from advancements in technology or manufacturing theories. Despite the critical role of MH in meeting the U.S. housing needs, most of the assembly line processes are labor-driven. Additionally, the assembly line stations are equipped with manual tools. Productivity improvement of the production system is the main challenge for the MH industry.

The master’s thesis, Abu Hammad (2001), endeavors to improve the productivity of existing systems within their current boundaries without changing the layout. It identifies process bottlenecks by using simulation. However, bottlenecks are eliminated by increasing the capacity of the bottleneck stations in the simulation model. A practical procedure for transferring improvements from the simulation model to the actual factory setting is not achieved. Research work started in Abu Hammad (2001) culminates in part of the Ph.D. dissertation results. This dissertation proposes optimization and simulation models to adjust station time and balance the overall system. Extensive modeling provides production managers with a practical tool for improving productivity. Moreover, this research proposes advanced system designs proven by simulation to have higher throughput. Productivity of MH systems is increased up to four times the productivity of existing systems. The NSF-PATH project on MH production and material utilization, Syal and Hastak (2000), provided a good opportunity to assess technologies and industry practices used in the manufacturing and construction of the manufactured house.
Lessons learned and experience gained throughout the project, partially documented in Abu Hammad (2001), shows these major drawbacks in the existing MH production systems:

1. MH systems employ mixed model manufacturing, *i.e.*, producing different housing unit sizes in the same production line. The mixed model manufacturing system is difficult to balance. This imbalance causes process bottlenecks, hindering overall system productivity.

2. Productivity of existing MH systems is limited by the layout flow pattern. Efficiency of new layout designs is investigated in this research under fixed conditions to evaluate the increased performance of the new layout design;

3. The MH industry suffers from primitive production processes, characterized by minimal use of technology and computerization and major dependence on labor force in handling materials and running processes. The material handling systems are not efficient; the manual pushing of the floors through the assembly line underlines the need for advanced material handling system.

MH industry has a crucial need to benefit from technological advancements in construction and manufacturing theories, like any other type of industries. The production system should be redesigned to integrate technological advancements, modern theories, and industry practices in a more efficient shop floor layout.

### 1.4 RESEARCH HYPOTHESIS

The above problems adversely affect the performance of the existing MH systems and their productivity. Generally, existing MH systems cannot produce at desired levels. To address this problem, the following hypotheses are proposed:

1) Productivity improvement of existing MH systems is achieved by eliminating potential bottlenecks in the production process and material flow.

2) New layout designs, using (i) different material flow patterns, (ii) advanced material
handling systems, and (iii) more efficient machines and equipment, achieve higher productivity and improved performance.

3) MH production systems are balanced by using simulation models in tandem with optimization models. A balanced station cycle time is identified via simulation. Then the cycle time is applied within the station by rescheduling the station’s activities via the optimization model. An efficient production planning is achieved by using the simulation models.

1.5 RESEARCH OBJECTIVES

The main objective of this dissertation is to develop a decision support system (DSS) to facilitate the design and development of efficient production systems specific to user requirements. Production efficiency is achieved if: (i) production process bottlenecks are identified, (ii) corrective procedures are developed to eliminate the deficiencies, and (iii) efficient plant layouts are implemented (Hastak et al 1993, Abu Hammad et al 2002a, Abu Hammad et al 2002b). To achieve the stated objectives, the research methodology has been divided into seven steps as described below. An extensive literature review has been conducted for techniques relevant to this research. The following steps support the above stated objective:

1.6 RESEARCH METHODOLOGY

Step 1: Explore available techniques in other industries and their adoption in MH:

This step covers theories used in manufacturing that could be adopted in manufactured housing [e.g., lean production theory (LPT) and the application of an efficient just-in-time (JIT) system having an advanced material flow control system (Kanban) and integrated supply chain management]. Rapid change industries have adopted lean production versus mass production as a growth paradigm (Sanchez 2001). This approach investigates the applicability of LPT to MH systems. LPT employed in auto-industry and other manufacturing systems has proven its cost
effective and improved planning control (Monden 1983). Additionally, LPT has proven substantial impacts on waste reduction, system flexibility and lead-time reduction (Herague 1997, Gerald 1999, Kulkarni 1995, and Larso 1998). This new technique is analyzed and integrated with available criteria observed in the MH factories to develop the new layout designs. This research implements the LPT to develop efficient and flexible system having high quality housing units, high productivity, and minimum lead times. System efficiency is no longer measured by its productivity. It is rather measured by the flexibility of the system to meet the market need, in short lead time, under fluctuations in the market demand and supply chain (Barad 1988). The firm competitive advantage was dependent on the price efficiency accrued by economies of scale and mass production during the 30’s. Quality had merged as an important component of competitive advantage in the late 1950s, followed by flexibility in the 1980s and lead time in the 1990s (see Table 1.3).

**Table 1.3 Competitive Advantage Trend**

<table>
<thead>
<tr>
<th>Decade</th>
<th>1930’s</th>
<th>1950’s</th>
<th>1980’s</th>
<th>1990’s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Competitive Advantage</strong></td>
<td>Productivity</td>
<td>Quality</td>
<td>Flexibility</td>
<td>Lead Time</td>
</tr>
</tbody>
</table>

**Step 2: Develop a streamlined manufactured housing process (efficient production process):**

1) Conduct a comparative analysis of existing MH systems;

   A comparative study of existing production systems is conducted to analyze the system limitations relative to the physical setting and available resources. Advantages and disadvantages of each system are pinpointed. Efficiencies and deficiencies within the process are then identified. The comparative study is based on full understanding of activity interrelationships and
the specific nature of the processes. Additionally, the study analyzes limitations due to the layout
design. Finally, efficiencies are combined to develop a streamlined production process for MH.

2) Develop simulation models for two case study systems;

   A simulation model was developed by the author (Abu Hammad 2001) for the two case
   studies. The models are used to capture the logic of the physical setting. In addition, simulation
   models are then developed by using the same procedure to measure the performance of virtual
   (nonexistent) layout-design alternatives.

3) Generate a composite generic system from the two case study systems;

4) Define generic building blocks of a streamlined MH system.

**Step 3: Develop optimization models for MH production systems:**

The optimization model provides a practical tool to control the station processing time by
reconfiguring the activity sequence. Therefore, the cycle time and number of resources for each
building block is manipulated by using the optimization model. Controlling the station cycle time
is very important to line-balance the system by using the generic building blocks.

**Step 4: Develop alternative layout designs, i.e., efficient production system layouts:**

Tremendous cost saving can be achieved by developing “near optimal” facility design
model and planning paradigm. In this step, alternative factory layouts using the generic building
blocks are developed based on the sequence of the assembly stations. Each layout alternative has
a unique configuration of the generic building blocks. Additionally, each layout has different
station cycle time and different number of resources associated with the activities at each station.
Proximity requirements are satisfied for each layout with respect to other assembly stations,
subassembly stations, and material stacks. These alternatives are analyzed for their effectiveness
in the following step. Four efficient layout design alternatives are developed. Each design
alternative is simulated to: i) measure its performance and ii) balance the stations times by using the optimization model developed in step 3.

**Step 5: Develop simulation models for each design alternative:**

Methodology:

1) Develop a U-shape flow using the generic building blocks;
2) Simulate the new U-shape layout;
3) Compare the performance of the new system to the performance of the original systems;
4) Develop a lean spinal flow using the generic building blocks in a cellular manufacturing system;
5) Simulate the spine layout design;
6) Use the simulation model and the optimization model for balancing the system;
7) Develop the J-shape design, simulate the layout; and measure the performance;
8) Develop the Central design; simulate the layout; and measure the performance;
9) Compare the performance measures of the four systems.

**Step 6: Develop design guidelines for manufactured housing production process and plant layout design.**

The design guidelines include all systematic approaches followed in developing virtual layout design alternatives. It is important to develop generic guidelines for manufactured housing production process and plant layout such that it could be used by the industry to evaluate various alternatives for their specific factory and production needs. Such a process is developed from the results obtained from Steps 1-5. From the previous work, the process details of manufactured housing production system is compiled, and based on these process requirements, design guidelines are developed.
Methodology:

1) Develop design guidelines to improve the performance of existing MH systems;

2) Develop design guidelines for constructing a lean production system;

3) Define the design procedure used in developing the U-shape, spine, J-shape, and central layouts;

Step 7: Employ the results from steps 1-6 in developing a decision support system for streamlining and selecting an efficient production system matching user requirement:

The results of the previous steps are computerized to provide the MH production managers with a valuable tool for evaluating their systems. The computerized decision support system (DSS) leads the user through series of steps that would recommend the efficient layout design based on the organization needs (i.e., level of production, facility area, and housing unit size and type). The DSS facilitates the balancing process of the selected layout by using the optimization model.

Methodology:

1) Develop the model framework that addresses steps 1-4;

2) Develop the decision model architecture;

3) Design the user interface;

4) Incorporate spreadsheet programs to support various components of the decision model;

5) Validate the user interface, the model logic, and the model results.

The proposed decision tool is intended to assists the user in two specific situations:

1) Existing Facilities: The DSS leads the user in analyzing the performance of existing MH facilities, and to determine possible ways for modifying the production system to improve the overall performance. The main problems of existing MH facilities are the process bottlenecks
resulted from the mixed model manufacturing. These problems affect, directly or indirectly, the overall system efficiency. Thus the first issue in improving existing systems is to solve the process bottlenecks. Changes to production system configuration are needed in case the performance is below the desired levels (after solving the process bottlenecks). These changes include changing: the product mobility and material handling system, the assembly line flow pattern, the labor assignments on the different activities, the sequence of assembly stations and the sequence of the activities at each station. Thus, the evaluation of the existing factory layout is based on:

A) Maximum level of production achieved;
B) Types and sizes of the products;
C) Product cycle time;
D) Area of the production shop floor;
E) Shape of the assembly line;
F) Sequence of the operations;
G) Scheduling of activities within stations;
H) Size of the work force and the labor assignments to activities.

The production manager utilizes the simulation model in locating the process bottlenecks by inputting the activity times in the tables of the optimization model. The objective function of the model is to minimize the time of the congested station (i.e., the station with the highest queue time). If the performance of the existing system is below the required level, the production manager can enter his requirements and compare his existing system with the system recommended by the DSS. Thus, the decision maker can apply a set of modifications with respect to the recommended system in order to improve the performance.
New facilities: The decision support system provides a framework for recommending optimum layout designs for new MH facilities. As mentioned above, the existing MH facilities and production processes do not employ technology and still use classical facility designs previously used to produce the mobile homes. Advanced facility layouts are recommended by the DSS based on:

A) Required production level;

B) Housing unit types intended for production (single, double, and triple bay sections, a single or double story MH unit, etc.);

C) Housing unit size.

Step 8: Validate the DSS:

Finally, manufacturers, production managers, and other industry personnel are interviewed to validate the DSS system logic, user interface, and results. A feedback is received from manufacturers underlining the usefulness of the DSS in meeting their needs.

1.7 SCOPE OF THE DISSERTATION

The dissertation scope covers analysis, methods, and steps identifying the framework of the decision model. The model framework includes the relationships of different factors on the system productivity, planning, and design. The above stated objective, steps, and methodology define the scope for improving MH systems performance to match the user requirements. Moreover, the decision model assists the user by providing a practical tool for streamlining the operations, predicting the most profitable product mix, and recommending an efficient system capable to produce the required outputs. Figure 1.4 depicts the different sequential tasks covered in the dissertation scope.
1.8 SIGNIFICANCE OF THE RESEARCH

Improvement of the current production systems is on the forefront of the industry needs. There is a lack of research in the area of housing in general, in which little production related research is done to improve the productivity. This dissertation research is the first to solve some of the MH production-related problems. This dissertation employs overall system thinking and innovation to advance the manufactured housing industry in the United States.
1.9 DISSECTATION ORGANIZATION

This dissertation is broken down into 7 chapters. The first chapter discusses the research background, problem, objectives and methodology.

Chapter 2 covers relevant literature topics such as production lines, facilities design, lean production theory, line balancing and sequencing, and production planning theory.

Chapter 3 covers the modeling and analysis of the two case study factories. This chapter includes a brief description of existing MH production systems. Moreover, Chapter 3 presents possible ways for improving existing systems having rigid layouts (inflexible). System alteration involved manipulating the station processing time using a simulation model specifically developed for each factory configuration.

Chapter 4 includes three sections: (i) a comparative analysis of the two existing case study factories discussed in Chapter 3, (ii) the generic building blocks based on the results of the comparative analysis, (iii) the optimization model of the production system using the critical path method. The optimization model is a management tool for balancing the system by controlling the activity sequence, activity resources, consequently, the station cycle time.

Chapter 5 introduces four advanced layout designs of the production system, respective simulation models, and discussion of the run results of each model. Chapter 6 presents framework, architecture, and components of the decision support system. Chapter 6 has incorporated all the research results obtained in the previous chapters.

Chapter 7 includes a summary of the dissertation work, results, and recommendations for future work.
1.10 CHAPTER REFERENCES


(http://www.nwlean.net/)


MHI- Manufactured Housing Institute (2003),

http://www.manufacturedhousing.org/DR_understanding/index.html and


CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

Literature covered in this section includes main techniques and theories used in industrial manufacturing relating to production systems efficiency and design. The first section presents the production-line concept, used by the MH industry. Part 2 discusses facility layout design; this section presents the concept of the flow pattern and different types of layouts used in manufacturing. Part 3 presents types of material handling systems for different layout configurations. Sections 4 and 5 discuss line-balancing techniques and line-sequencing, respectively. Section 6 presents lean production theory, JIT manufacturing, and Kanban control system. Lean production theory has an important role in productivity improvement and operational cost efficiency. The last section presents the production planning systems, the roles of: aggregate planning, master production schedule, material requirement planning, and capacity planning.

2.1.1 Background and Uniqueness of the Research

This research aims at improving MH production systems and is a part of an ongoing project sponsored by the National Science Foundation (NSF) through the Partnership for Advancing Technology in Housing Program (PATH) (Syal and Hastak 2000, Hastak and Syal 2002). Developmental research work achieved in this area can be found in Senghore 2001, Abu Hammad 2001, Abu Hammad et. al. 2002a-b, Abu Hammad 2003, Mehrotra 2002, and Senghore et. al. 2003.

The masters-level thesis (Abu Hammad 2001), entitled “Simulation Modeling for Manufactured Housing Processes,” identifies ways to improve the productivity of an existing
This thesis models the complete production process by including all the stations of the assembly line. Another masters-level thesis (Senghore 2001), entitled “The Production and Material Flow Process Model for Manufactured Housing,” documents the production process and material flow in the manufactured housing factory and concludes with developing a simulation model for one station of the production line.

A third masters-level thesis (Mehrotra 2002) investigates quantitative (distance-based) and qualitative (departmental relationship-based) approaches to evaluate an efficient layout. Mehrotra uses existing commercial software, BlockPlan, to prepare the interrelationships data for two MH case studies and to obtain the final proximity scores for different flow patterns.

Nevertheless, distances and departmental relationships are only two factors relating to the production efficiency. The targeted model in this dissertation is a productivity-based model for evaluating facility layout efficiency. Furthermore, an efficient layout is not necessarily the layout that only has the “least sum of the products of the distances between each pair of departments and the corresponding relationship score” (Mehrotra 2002). Additionally, an efficient layout is not necessarily the layout that has the “least-computed material travel costs and distances”. A trade-off might exist among travel distances, material handling costs, and system productivity, in order to achieve optimal throughput of the facility. The trade-off might include the level of technology used in the manufacturing cells with higher costs relative to the manual procedures currently used. Using an effective material handling system can delineate long material distances; in case of an excessive material travel distant costs of an optimally designed layout (productivity wise). Hence, tools used for evaluating layout efficiency are still lacking a comprehensive approach that includes other factors that contribute to the system optimality. Relative to the previous research done so far, the author concludes that productivity factors are
the main criteria for evaluating MH production processes. Tradeoff between productivity and proximity is expected if the most efficient system is pursued.

This research will develop customized techniques, theories, systems and practices to improve the MH industry through:

1) Mass production by efficient system designs;
2) Zero waste by conforming to lean production theory;
3) High quality, due to improved systems that use recent advancements in technology;
4) Increased sales by providing affordable MH.

Research findings would lead to increased value of manufactured housing by emphasizing that it is the only housing product conforming to a national quality and durability code in the U.S. The following section reflects the findings of the third roadmap, published by the Partnership for the Advancement of Technology in Housing (PATH).

2.1.2 (PATH) Third Technology Roadmap

The author proposes the following strategies concerning the PATH’s third Technology Roadmap: “Whole House and Building Process Redesign”.

Strategy 1: Enhance the affordability and value of MH: The industrialization and mass production of MH results in a 30% reduction in labor costs of a comparable SBH. This reduction comes from employment of semi-skilled workers. Improvements in the current systems are essential for producing more affordable housing solutions. Cost, not price, is the major determinant of affordability. Costs are reduced by integrating lean production concepts in the production process. The major benefits of lean production theory are: reduced production costs, waste elimination, and efficient labor utilization. Initial costs can be reduced substantially by producing designs for future expansion, as shown in Figure 2.1. The future expansion designs
have the following benefits:

- Gradual space expansion according to family size growth;
- Affordable initial cost for low-income families;
- Small-size modules for easier transportation from the factory to the site;
- Flexible assembly design for one or two level houses as shown in Figure 2.1.

![Figure 2.1 Future Expansion](image)

![Figure 2.2 Double-Bay House and Two-Story House](image)
Strategy 2: Consider new building materials resulting in cost effectiveness of resources. Moreover, consider two story MH units with advantages in land area and cost, Figure 2.2.

Strategy 3: Develop an efficient system model and perform analyses and re-engineering that will make manufactured houses (easier, quicker, cheaper) to construct, reduce labor content, reduce production and material costs, and improve quality and durability of MH. The optimum model is used in evaluating existing facilities and is used as an approach for designing new MH production systems. Hammer and Champy (1993) define reengineering as the fundamental rethinking and radical redesign of business processes to achieve improvements in critical and contemporary measures of performance such as cost, quality, service, and speed. Process reengineering has become a popular philosophy and a well-known management concept (Chang and Fan 1999).

2.2 DECISION SUPPORT SYSTEMS (DSS)

2.2.1 Definition of a DSS

The decision making is defined by Turban (2001) as a process of choosing among alternative solutions of a problem to accomplish a goal or multiple goals. Boose (1993) has considered the decision to be a consequence of dynamic interaction between three overlapping circles of information, preferences, and alternative solutions, as shown in Figure 2.3.

A system is a collection of objects (people, resources, concepts and procedures) performing a specific function and serving a specific goal. Systems are divided into inputs, processes, and outputs. The effectiveness of a system is measured by the degree to which goals are achieved, while system efficiency measures the utilization of inputs to achieve outputs (Turban 2001).
A DSS is an interactive computer-based system intended to help managers make decisions (Power 1997). The DSS objective is to insure that the chosen criteria are relevant to the recommended decision taken by the decision maker (Keen 1978). Little (1970) has defined DSS as a set of procedures in a model format. These procedures are intended to process data and judgments in assisting managers in their decisions. In order for a DSS to be successful, the system must be simple, robust, controllable, adaptive, and complete (Little 1970). Bronzik et al 1980 defines a DSS as a computerized system consisting of three interactive components: language system, knowledge system, and a problem-processing system linking the first two systems.

Radermacher (1994) and Wang (1997) have defined the DSS as a computer-mediated tool assisting managerial decision making by presenting information and interpretations for various alternatives. DSS helps decision makers to make more effective and efficient decisions.
Parker et al defines the DSS as a computerized system capable of supporting and assisting decision-making in a specific application (Parker et al 1995).

The previous formal definitions of a DSS have evolved from the functionality of a DSS. However, they do not provide a consistent focus of the term. Turban 2001 describes a DSS as an approach used for supporting decision-making. It provides an interactive, flexible, and adaptable environment; this environment provides a user interface and uses data. A DSS can be used by a single user or multiple users for web-based applications (Turban 2001).

DSS exploits a set of technologies and theories: databases, graphical interface, expert systems, neural networks, fuzzy logic, genetic algorithms, client servers, and the object-oriented modeling approach (Keen 1978). For the DSS to be more reliable in achieving its objective, it should have the ability to frame problems, generate alternatives which involve tradeoffs in preferences and in handling uncertainty. The previous tasks involve human mental activities of reasoning, learning and idea generation using human judgmental inputs (Fazlollahi et al 1997).

Current World Wide Web technologies have provided the appropriate means for large-scale implementation and continued development of the DSS for the architectural, engineering, and construction community (Molenaar and Songer 2001).

### 2.2.2 Characteristics of a DSS

1) Support, but not replace, the decision maker in semi-structured and unstructured cases.

2) Support all decision phases: intelligence, design, choice, and implementation.

3) Adapt to changes over time. Be flexible by adding, deleting, and rearranging basic elements.

4) Improve effectiveness of decisions.

5) Utilize models for analyzing and experimenting decision-situations, with different strategies under different configurations (Turban 2001).
A specific decision model supports operational decision-making (productivity), as shown in Figure 2.4. The DSS also supports more strategic and long-term decision-making and problem-solving. For example, the DSS supports the organization in performing in the way that best meets its sales or profit targets. Finally, the design and capabilities of a DSS influence the real business decisions (Alter 1980). One of the serious pitfalls of a DSS is that managers tend to develop unrealistic expectations of the DSS outputs. Moreover, the misapplication of models and tools can lead to unrealistic and misleading outputs. Comprehensiveness and complexity do not necessarily lead to increased accuracy and reliability of DSS results (Loucks 1987, Westmacott 2001). In addition, Boose et al (1993) have underlined a tradeoff that might exist between the cost and benefit of developing a more complex model.

![Figure 2.4 Characteristics of the Organizational Decision Making Process](image)

Source: James 2002
2.2.3 DSS Components

Turban (2001) has identified the DSS components as follows: a data base system, knowledge system, model base system, and a user interface system.

1) Data base system: The data base system includes information and data obtained internally or externally;
2) Quantitative model or system: a model (e.g., mathematical) that processes the data and performs certain functions;
3) Knowledge system: provides intelligence;
4) User interface system: query DSS components.

Figure 2.5 superimpose the details of a case study on the general structure of a DSS (Zopounidis 2000).

![Diagram of DSS Components]

**Figure 2.5** DSS Components (Zopounidis 2000)
2.2.4 DSS Architecture

Enterprise DSS is linked to large data warehouses and serves multiple managers in a company, unlike the single user DSS, which is a small system residing in an individual manager’s PC. The DSS architecture of a group DSS defines the macro interrelationship between a single user and multiple users. One-way or multiple-way bridging defines the DSS architecture: what data is stored, where, how it will be analyzed, and how it will be displayed. Client-server architecture can create bridges that move data back and forth from the client desktop and associated DSS tools to server-storage and server-based DSS tools. In some organizations analysts prepare a financial analysis using desktop tools; then they publish the results to the company intranet. DSS and data can be anywhere and everywhere in an enterprise (http://dssresources.com/papers/whatisadss/).

A single desktop-user DSS may use spreadsheet programs like Excel or Lotus for analysis. A data-base DSS in an executive’s PC can be implemented in Microsoft Access. Simulation software packages, as well as optimization software packages and a DSS built with them, are commonly implemented as single desktop packages. However, in certain settings, a specific DSS optimization model may use live or “real time” data received over a local or wide area network in its calculations. Moreover, commercial software packages can be used to develop specific DSS applications for individual managers. Specialized DSS packages can be used for a PC or for a server (http://dssresources.com/papers/whatisadss/).

2.3 PRODUCTION LINES

Production line (PL) is one of the most important inventions in modern manufacturing, giving rise to significantly increased productivity and mass production. The reason behind this success is the simplification, standardization, specialization, reduced in-process inventories, and
A production line is a multiple work area (station) arrangement, in which related operations are adjacent to each other, Figure 2.6. The materials move continuously, or step-by-step, through a series of operations, and the overall workflow follows a directed path, or flow pattern (Encyclopedia of Industrial Engineering 2001). This type of production setting is completely different than a job shop. The job shop consists of a variety of different types of machines and different types of jobs at the machines in different sequences. Job shops are appropriate for low volume, high variety products, while production lines are designed for medium to high volume, but low variety products. This fact motivates the researcher to investigate types other than the PL, because the MH operation is considered to produce low volume and high variety products. The large size of the housing modules, coupled with low production volume and high variety, requires a system other than the PL.

![Figure 2.6 Typical Production Line](image)

A typical assembly plant for MH products has lines setup for main assemblies and subassemblies for the various components. Finished products are produced from subassemblies; subassemblies are produced from components, etc. Outputs from the upstream lines feed the downstream lines. The final assembly line is used to assemble the final product. This schema is illustrated in Figure 2.7 (Encyclopedia of Industrial Engineering 2002). The employment of production lines in MH production processes is not an efficient procedure. Integration between the mass production aspect of PL and the uniqueness provided by construction operations is
needed to produce unique products at a high throughput. Independent final assembly is recommended to follow a regular construction operation. The advantage is to free the assembly operations from the constraints of mixed model manufacturing, which create process bottlenecks. Additionally, the construction operation permits the production of unique housing units (underlined by the third PATH Roadmapping: Whole House and Production Process Redesign). The standard components at the subassemblies are similar and need to be produced in large quantities by using production lines.

![Diagram of final assembly preceded by subassemblies]

**Figure 2.7 Final Assembly, Preceded by Subassemblies**

It is concluded from the above discussion that PL have limited flexibility. However, layouts of other types can be considered for having more flexibility to handle the model mix manufacturing associated with MH systems. The following section is a brief elaboration on the overall systems flexibility.

### 2.4 FLEXIBLE MANUFACTURING SYSTEMS

The assembly lines are designed “flexibly” to handle mixes of models so that demand for all the components pulled into the final product is leveled or smoothed (Monden 1983, Chang 1999). This is another reason why the conventional PL fails to serve in more efficient MH facility designs. The MH industry produces a wide variety of model mixes (approximately 150 design variation for the double bay houses and more than 50 variations for the single bay...
houses). However, market trends are drifting towards MH housing units that are constructed on two stories. It is essential to have a flexibility margin within the facility layout to allow producing new product designs to satisfy the market trends. Changing trends in customer demand implies concurrent changes to the product designs. New product designs require simultaneous changes to the production system.

A flexible manufacturing system is defined as “the adaptability to cope with a wide range of possible environments that it may encounter” (Buzacotte 1985). System efficiency is not measured by its productivity alone. However, it is measured by the flexibility of the system to meet the market need, in short lead time, under fluctuations in the market demand and supply chain.

As shown in Table 2.1, the firm competitive advantage is dependent on the price efficiency accrued by economies of scale and mass production during the 1930’s. Quality has emerged as an important competitive factor in the late 1950’s. Quality is followed by flexibility in the 1980’s, and finally lead time is considered a major factor of the company competitive advantage in the 1990’s.

### Table 2.1 Competitive Advantage Trend

<table>
<thead>
<tr>
<th>Decade</th>
<th>1930’s</th>
<th>1950’s</th>
<th>1980’s</th>
<th>1990’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competitive Advantage</td>
<td>Productivity</td>
<td>Quality</td>
<td>Flexibility</td>
<td>Lead Time</td>
</tr>
</tbody>
</table>

The production theory based on cost efficiency (i.e., idle cost, queue cost, setup cost, and inventory cost) does not enable the system to cope with changes in market demand. However, equipment flexibility, system flexibility, product flexibility, and volume flexibility are very important features of an efficient system. A possible trade-off exists between time and cost, e.g., the transition to automation and computerization is costly, and however, it cuts down time
substantially. A compromised solution of the two factors is needed (Barad 1988).

Productivity improvement efforts increase manufacturing flexibility by increasing the available manufacturing capacity. This research is part of an NSF funded project (Syal and Hastak 2000), the project aimed at developing a simulation model for the MH system, in order to allocate and solve the process bottlenecks that hinder the productivity, consequently, improve the overall system performance and productivity. Versatility and variety are essential aspects of a flexible manufacturing system. Laroso (1998) has introduced a measure of capacity-related flexibility, called the capacity flexibility index that measures the available capacity to handle any changes in demand, and also defines a measure called the potential of continuous improvement (to improve the flexibility). The commonly accepted flexibility types (Browne et al 1984, Sethi 1990) include:

**Machine flexibility**: refers to the various types of operations that machine can perform without requiring a prohibitive effort in switching from one operation to another. Machine flexibility is defined by Vakharia et al (1999) as the universe of operations that a machine is capable of performing with respect to the universe of operations that the system can perform (Vakharia et al. 1999).

**Material handling flexibility**: is the ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves.

**Operation flexibility of a part**: refers to its ability to be produced in different ways, commonly by changing the sequence of operations.

**Process flexibility**: relates to the set of component types that the system can produce without major setups.

**Product flexibility**: is the ease with which new part types can be added or substituted for
existing part types. Part volume flexibility is defined as the ability of the system to deal with volume changes in the current product mix, whereas, the part mix flexibility defines the ability of the cellular system to handle different product mixes with minimum disruptions (Vakharia et al 1999).

Routing flexibility of a manufacturing system is the ability to produce a part by alternate routes through the system.

**Volume flexibility:** describes the ability of a manufacturing system to be operated profitably at different overall output levels.

**Expansion flexibility:** describes the ability of a system to increase its capacity and capability when needed.

**Program flexibility:** is the ability of the automated system to run virtually unattended for a long period.

**Production flexibility:** is the universe of product types that the manufacturing system can produce without adding major capital equipment.

**Market flexibility:** is the ease with which the manufacturing system can adapt to a changing market environment.

### 2.5 FACILITIES LAYOUT DESIGN

As mentioned in the previous section, current MH systems need to be redesigned for efficient layout designs. Herague (1997) has listed the following objectives for developing layout designs:

1) Design new facilities;
2) Expand an existing facility for growth needs;
3) Modify or improve the performance of an existing facility;
4) Consolidate existing systems in mergers.

The facilities layout is modified every two to three years for the above reasons (Nicole and Hollier 1983). Modifications are implied by either the product mix (for the mixed model assembly systems) or changes in the customer demand for new style and functionality. The layout redesign will result in producing different layout design alternatives. Each layout alternative will have a certain level of productivity associated with an efficient organization (flow pattern) and material handling systems. Facility design and factory layout should be in tune with the production levels targeted by the company (Herague 1997). Therefore, the organizational long and short term strategies for growth and market expansion should determine the productivity level of the facility. Finally, the productivity level implies the cell equipment and machining and advanced material handling systems.

![Figure 2.8 Activity Assignments to Stations](image-url)
The size, shape, and design of the product define the specific set of elemental tasks as shown in Figure 2.8. Multiple sets of elemental tasks define the required sequence of work stations and station machining necessary to do the job efficiently. A certain sequence of stations includes a specific flow of materials in series or in parallel. Work and materials flow define the flow pattern of a layout. Finally, different scenarios of flow-pattern variations create layout alternatives.

2.5.1 Flow Patterns

The first step in the layout design is to determine the general flow pattern in the system for materials, parts, and work-in-process (WIP).

The flow pattern refers to the pattern in which the product flows in its transformation from raw materials (receiving stage), to the semi-finished product (fabrication stage), to the finished product (assembly stage). The flow pattern describes the precedence of operations and the organization of assembly and subassembly stations in the factory. Although the flow pattern is elastic and can change easily, it is the basis for the layout design. Figure 2.6 shows different PL flow patterns: (i) linear, (ii) U-shape, and (iii) S-shape. The rectangular boxes in Figure 2.9 indicate workstations. The lines between each of them represent the flow direction of materials. The dendrite and spine patterns (Askin and Standridge 1993) are suitable for assembly operations. Each vertical line is a subassembly line, and the horizontal line is the main assembly line serving as the primary aisle for final assembly movement. As mentioned above, the flow pattern variations produce different layout shape. Each layout alternative has a distinct layout shape, referring to the flow pattern. Additionally, a specific layout alternative may follow a specific layout type. Types of layouts are described in the following section.
2.5.2 Types of Layouts

The design process of the layout starts by defining the flow pattern. The second step determines the layout type. Figure 2.10 shows three layout types. There are five layout types
used by most manufacturing facilities (Bazargan 1999):

1) Product (line) layout: This type is also called production line layout or assembly line layout. In this type, the machines and workstations are arranged along the product route in a sequence corresponding to the sequence of operations the product undergoes. The benefits of this layout are: (i) reduced material handling time, (ii) reduced processing time, (iii) simplicity in planning, and (iv) ease of control. However, product layout lacks flexibility. Flexibility of manufacturing systems is illustrated in the following section (Bazargan 1999).

2) Process layout: Machines and stations are grouped on the basis of the performed process.

3) Group technology (GT) layout: This method is used in the JIT system to develop a cellular manufacturing system. In this method, the major system is divided into smaller independent subsystems. Traffic congestion, material handling costs, work-in-process inventory, and waste are significantly reduced in a GT layout, because similar parts are processed almost entirely in their respective cells (Bazargan 1999).

4) Hybrid layout: the utilization of mixed layout types in one facility.

5) Fixed position layout: The product does not move. Instead, the processes and equipments are brought to the product, e.g., plane manufacturing, building construction, shipbuilding (Bazargan 1999).
Figure 2.10 Types of Layouts

Source: Based on (Bazargan 1999)
**Planning Chart:** The planning chart is a graphical illustration of the various steps a product undergoes from receiving to shipping. It is a tabulation of operations, event symbol, cycle time of each operation, number of pieces, type and number of material handling systems required. It also includes the workforce size, department of operation, type and amount of required equipment. The planning chart helps the planners find ways of improving the process efficiency. The significant process improvements can be documented in a new flow chart to measure the improvement, compared with the old plans (Reed 1993).

**Flow Diagram:** The flow diagram shows the operation symbols and sequence in a proposed or existing layout, as shown in Figure 2.11. The layout efficiency may be determined by using subjective criteria (systematic layout planning) or objective measures.

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**Figure 2.11 Relationship Chart**
Muther (1973) uses a systematic qualitative approach to solve the facility layout problem by defining the adjacency or closeness of each pair of operations. After assigning a scoring system for each criterion, software such as BLOCKPLAN or Factory Plan can generate alternative layouts and the respective sum of departmental scores for each layout (Mehrotra 2002).

2.6 MATERIAL HANDLING SYSTEM

The material handling system is defined by the Material Handling Institute as “the system embracing all basic operations involved in moving bulk and packaged or individual products by machinery within the limits of the place of business” (Sule 1994). The material handling system accounts for 20-50% of the total operating cost. The efficient arrangement of the facility reduces the product cost significantly. Efficient arrangement means that there is no other arrangement can be better with regard to the chosen criteria. Thus, other arrangements can be equally good, but none of them is better. In this case there are multiple efficient (optimal) arrangements (Heragu 1997).

Facilities, (i.e., machines, workstations, inspection, offices, lounges...etc.) are the physical arrangement of functioning spaces, organized on the shop floor. The good organization based on proximity requirements of the functioning spaces minimizes the movement of workers and materials, consequently decreases material handling costs, increases the system’s efficiency and productivity. Efficient material handling system includes: the following factors, the factors are related to a high output system and low product variety (Heragu 1997):

1) Minimizing the cost of transporting raw materials, parts, components, tools, work-in-process, and finished products;
2) Reducing congestion to permit the smooth flow of people and materials;
3) Utilizing the available space effectively and efficiently;

4) Facilitate communication and supervision, with providing a safe and pleasant environment for personnel (Heragu 1997). Benjaafar (1999) has identified three types of material handling systems shown in Figure 2.12. The three types are:

A) Unidirectional linear layout: conveyer belts, forklifts or cranes serving linear system

B) Loop layout: serve a rectangular area in the layout.

C) Star layout: serve a central area.

Figure 2.12 Material Handling System Configurations, Based on Benjaafar (1999)

2.7 LINE-BALANCING TECHNIQUE

This term is relevant to manufacturing systems that uses a production line. In which all workstations are arranged in series, with the different products (mixed model manufacturing) moving from one station to the next in succession. The concept of line balancing is very closely linked with cycle time, and the level of balance impacts on the effective utilization of the
resources. A line represents a process where either fabrication operations are carried out on some product or group of products. A Line also refers to an assembly facility, where various components are assembled together to form the final product. The overall work of fabrication or assembly is usually divided into a number of elemental tasks, where a task is defined as the smallest undividable work that can be distinguished. These tasks are then grouped into task modules such that similar tasks fall within the same module. Line balancing basically entails grouping these tasks, for some prescribed cycle time, such that the number of workstations and the idle time at each of these workstations are minimized. Synchronization at all workstations, which is indicative of perfect balance, results in zero idle time at the workstations. This assures smooth flow of work and maximum utilization of labor and equipment. Perfect balance is however difficult to achieve for the following reasons:

(1) Tasks cannot be grouped together for incompatibility reason (painting and sanding cannot be grouped together because of contamination problem);

(2) Differences in elemental task lengths;

(3) Technological precedence ordering for the tasks: even when two tasks are compatible, they cannot be grouped together if there is an unassigned task that comes between them.

Modularization and mass production of MH facilities are undermined by the unique nature of the house product. Therefore, production managers should apply new innovative techniques to identify system bottlenecks and to maintain a balance between efficiency and the implications of product design variations.

Optimization models provide an efficient tool to balance the work loads, and to compare the work allocated to each resource within the available time frame. Static evaluation models (e.g., optimization models) assume a deterministic environment (i.e., predictable schedules, no
breakdowns, and part availability). These models do not include dynamic interactions in the system. However, they provide a rough estimate of the system performance. Deterministic outputs of the optimization model can be used later as inputs to the simulation models. Therefore, the production manager can obtain an evaluation of dynamic interactions of the system (Mahmoodi 1999).

2.7.1 Line Balancing Objectives

Scholl (1999) has classified Line balancing objectives related to capacity (capacity wise) by the following (Scholl 1999):

1. Minimize the number of stations for a given cycle time;
2. Minimize the cycle time for a given number of stations;
3. Minimize the weighted sum of the cycle time and the number of stations;
4. Minimize the flow time (throughput time: time interval between launching the chassis down the line and removing a finished housing unit from the line);
5. Equalizing levels of capacity utilization of the stations;
6. Minimize the average queue time over all stations;
7. Minimize the queue time of floor between the stations (station bottlenecks).

Cost wise: Minimize long-term investment cost and short-term operating costs, costs of production lines are affected by the cycle time and number of stations

1. Cost of machinery;
2. Labor costs;
3. Material costs;
4. Idle time costs;
5. Set-up costs;
6. Inventory costs: dates by which materials are required have to be known exactly, and then delivered JIT (Monden 1998).

Having a fixed output volume and a fixed price, production rate (i.e., cycle time) and prices would be the decision variables, and both are determined by the market demand. Scholl has stated in his conclusions that the solving procedures (using optimization theory) are too restrictive to represent industrial problems completely. “The equalization of work load variations in mixed-model balancing solutions with respect to possible consequences on the short term sequencing, are very important” (Scholl 1999). However, (Taichi 1982) underlines the role of line balancing technique in reducing the production costs throughout reducing waste in all its forms. Taichi has classified waste into 7 categories namely:

1) Overproduction;
2) Waiting;
3) Transition;
4) Processing time;
5) Excessive inventory;
6) Unnecessary motion or activities;
7) Defective products and rework.

Waste in its all forms (scrap and time) is a loss in the capital investment. Efficient layout coupled with better logistics and less material handling, improves quality and eliminates waste.

2.7.2 Line Balancing Methodology

Soman (2000) suggested combining activities and/or combining stations as a main procedure for line balancing the system (Soman 2000).

Scholl (1999) identified the following sequential steps for line balancing process:
(1) Define the elemental tasks;
(2) Identify precedence requirements;
(3) Calculate the minimum number of workstations required;
(4) Apply a suitable procedure for specifying the work content at each workstation;
(5) Compute the efficiency of the line;
(6) Seek further improvements, if possible.

2.7.3 Procedures for Tasks Allocation at Workstations

Line balancing is essentially an optimization problem, with the goal to maximize the effective utilization of resources, by reducing idle time. Optimization procedures based on dynamic programming and integer programming methodology has been proposed. A number of heuristic (rule-of-thumb) procedures have also been proposed. Some of the rules used are as follows (Soman 2000):

(A) **Largest candidate rule**: achieved by assigning tasks in order of decreasing task times, starting with the task whose time requirement is greatest. The steps are as follows:

1. Sort all tasks in descending order of task times;
2. Based on the above order, (Starting with the first task) assign as many tasks as possible to a given workstation. That is, tasks for which: (i) the precedence requirements are not violated, (ii) for which the time requirement does not exceed the cycle time;
3. Repeat (2) continuously until all tasks are assigned.

(B) **Kilbridge and Westers rule**: that is to assign tasks according to precedence ordering, without exceeding the cycle time limit of the station.

1. Arrange tasks in columns according to precedence relationship (Nodes representing work elements of identical precedence are placed in the same column.)
(2) List tasks in order of their columns, indicating the column as well as the task time for each (All columns should be indicated for tasks that can occupy multiple columns.)

(3) Assign tasks to stations in order of the columns (starting with the first column) such that cycle time is not exceeded.

(4) Repeat (3) continuously until all tasks are assigned.

The line-balancing problem discussed above applies to systems where the line is straight and task allocations are performed in a linear manner. A new type of balancing problem has recently been proposed for systems involving U-shape lines, and where flexibility of the workforce makes it possible to assign tasks across sections of the line. In particular, this scenario applies to fabrication or assembly operations in a JIT manufacturing environment. Further improvement in productivity is achieved from adopting U-shape lines over traditional straight lines. There is however an added complexity in the balancing for such lines, in view of the fact that tasks can be assigned in any order and in any direction. Various formulations and methodologies for tackling this problem is an area that is actively being investigated (Soman 2000).

2.7.4 Sequencing of Operations

Sequencing (scheduling) is the allocation of resources to activities. Scheduling is basically concerned with how best to allocate resources over time. Sequencing is primarily a decision at the operational level of a business, and it concerns the determination of the processing order of jobs or operations, on resources or machines. In Chapter 4, the author proposes an optimization model for scheduling and sequencing MH operations. Additionally, the optimization model and the simulation models, facilitates balancing the station processing times to eliminate potential process bottlenecks. In addition to the objective of maximizing resource
utilization, other pertinent goal of sequencing is to minimize work-in-progress (inventory within the process). The process planning for a system involves the determination of appropriate types of processing operations and required sequence. Number of steps per operation determines the planning complexity of the control system; the sequence has an impact on queues and influence the average throughput times of orders. Machining conditions and machining times, especially at bottleneck operations, determine the system output (Soman 2000).

2.8 LEAN PRODUCTION THEORY

Definition: Lean production is the adaptation of mass production in which workers and work cells are made more flexible and efficient by adopting methods that reduce waste in all forms (Groover 2001). Lean Manufacturing is a term describing the TOYOTA Production System (TPS). Lean systems are called by various names: Integrated Pull Manufacturing System by AT&T; Kanban System by many companies in Japan; JIT; Total Quality Control (TQC) by Schonberger; Stockless Production by Hewlett Packard; Continuous Flow Manufacturing (CFM) by Chrysler; and Zero Inventory Production Systems (Black 2000). Lean production systems have been used in manufacturing industries for many years, and have recently begun to be adopted by service industries (Womack et al., 1990; Womack and Jones, 1996). Rapid change industries have recently adopted lean production versus mass production as a growth paradigm (Sanchez et al. 2001). According to (Black 2000), the basics of lean production theory are:

1) Cost not price determines profit. Customer determines price, plant determines cost;

2) Elimination of waste;

3) Standardization;

4) Education to all levels of workers and commitment by the management.
2.8.1 Steps of Implementation

1) Redesign the factory floor into linked U-shaped cells;
2) Rapid exchange of tools and dies: Setup time reduction (Shingo 1985) to reduce lot size.
   Setup time is the delay time affecting the lot size;
3) Integrate Quality Control (Shingo 1986): Multi process-Inspector (worker);
4) Integrate Preventive Maintenance (Nakajima 1988). To make machines operate reliably;
5) Level, Balance and Synchronize. Level the entire manufacturing system (smoothing of the production) in order to produce a mix of final assembly products in small lots. The objective is to reduce the severity in demanding component parts and subassemblies from feeder stations;
6) Cycle Time Standardization: The cycle time equals one, divided by the production rate. The production rate equals the daily demand (number of units), divided by the available hours in a day. The daily demand equals the monthly forecast and customers’ orders, divided by the number of days in the month. Leveling and balancing the system will result in smoothing out the flow of materials (Monden 1983);
7) Integrate inventory control to: reduce WIP (i.e., the inventory between the cells) and control the quantity of materials in the links (Black 1991);
8) Integrate the suppliers, which are remote cells in the L-CMS of the factory;
9) Use automation and computerization to solve system bottlenecks;
10) Restructure the production system into a JIT manufacturing system;

The lean manufacturing system affects the product design, tool design, engineering, production planning, inventory control, purchasing, quality, and inspection. The lean system
results in significant savings over a two to three year period, due to reduction in raw materials, in-process inventories, setup costs, throughput times, labor costs, and the cost of bringing a new design to the line (Black 2000). Robertson 1999 characterizes the lean systems as having five key principles:

1 Value: Specify value by specific product and redefine the whole product through the eyes of the customer;

2 Value stream: Identify the value stream for each product. This is the entire set of actions required to bring a product from its raw materials to the customer;

3 Flow: Make value flow without interruption to eliminate departmentalization and batch processing, so that the process flows smoothly;

4 Pull: Let the customer pull value from the producer. If lead-times are reduced, then a producer can design, schedule, and make exactly what the customer wants, when he wants it, rather than rely on a sales forecast. In practice, pull is usually achieved by using the system known as JIT. JIT is a system whereby an upstream process does not produce parts until requested to do so by a downstream process;

5 Perfection: Pursue perfection through continuous improvement.

Close co-operation with suppliers and empowerment of the workforce are also key characteristics of the lean organization (Robertson 1999).

2.8.2 Cellular Design

Cellular manufacturing is the powerful solution for resolving process problems and bringing both high productivity and high flexibility to the small to medium sized batch production fields. Cell configuration includes the determination of the layout of machines and auxiliary equipment within the cell and the cell layout on the shop floor. Both layout planning
should be performed to minimize the work flow time and realize the smooth material flow. Cellular design is proposed as a flexibility objective to handle changes in product design and external customer needs. Moreover, skills in machine design and system design are needed for an integrated efficient production (Black 2000). Cellular design is an essential part of a JIT system. It involves continuous improvement (re-engineering, reconfiguring, or redesigning) of the manufacturing system. The future factories will be cellular-designed within a material and control pull-system. Downstream process dictates upstream production rates. The following section describes the JIT system.

2.8.3 JIT Manufacturing System

JIT manufacturing is a leading-edge manufacturing technique, also termed as the lean manufacturing system. The JIT technique describes a production system identified by a quick response to the market demand within a very short lead time (Baker 1994, Suri 1998). Adoption of JIT systems requires the organization to change or modify its operating procedures, production system, and organizational culture. Plant layouts have to be adjusted, relationships with suppliers and customers have to be modified, quality circles have to be installed, and an accurate demand forecast has to be achieved by removing offline centralized push control and installing kanban systems (Bowman, 1991; Cook, 1996; Hobbs, 1997; Storhagen, 1995; Vokurka and Davis, 1996, Wafa 1998). Successful application of a JIT system requires the following:

- Cooperation from vendors in the form of consistent lead times and capacity constraints imposed by suppliers;
- Direct linkages with vendors to become a remote component of the organization;
- Flexible movement of workers among work centers, as needed;
- An accurate forecasting system, which enables on-time deliveries to customers.
2.8.4 Kanban Control System

Kanban is a Japanese term, meaning a poster or a card. It is closely linked with the JIT production system, and it serves as an important tool for transferring information among processes in the system. Usually a kanban contains the following information:

1. Item name;
2. Item identification number;
3. Container type and capacity;
4. Name of the preceding and/or the following process.

JIT is a pull system, in which only the required items are produced in the required quantities at the required times. And its main thrust is to reduce all forms of waste in production, especially those associated with inventories. This pull system of production contrasts with the traditional push system, in which items are produced by a preceding process and stocked for the following process, without particular consideration of the process needs. Two of these traditional push systems are the Re-Order-Point (ROP) system and the Material Requirement Planning (MRP) system. The former operates simply as an observe-and-order system. That is, when inventories are observed to be depleted or low, then an order is placed for more parts. The latter is a computer information system, which uses data about the master production schedule and anticipated lead times, to plan the production or ordering of items. Since they are basically batch oriented, inventories are comparatively larger than a JIT system, though smaller than a ROP system. One very important benefit of kanban within the JIT pull system is that it greatly simplifies production control and eliminates costs. For example, costs for: preparing detailed schedules, dispatching, and expediting are eliminated (Encyclopedia of Industrial Systems).

The number of kanbans measures the amount of inventory in the system. It serves as a
useful tool for monitoring this important parameter. Usually the number of kanbans circulating between any two processes is kept constant, unless altered by management to either increase or drain the system of kanbans. Intentional draining of the system of kanbans is sometimes used as a management tool for improving processes. Since the ultimate aim of the JIT system is to approach continuous flow, the system involves continuous improvement and gradually reduces the number of kanbans. Theoretically, the number of kanbans can be reduced to zero. This implies that the processes in question have been perfectly synchronized. Although this might be difficult to achieve practically, it is an ideal vigorously pursued.

Implementation of Kanban: The kanban system is implemented in a number of ways. Two of them are briefly described below:

**One-card Kanban:** The one-card kanban system is a simplified version of the classic two-card kanban system, in that it involves the use of only one kanban type, known as the withdrawal (W), or conveyance kanban. Consider two typical work centers as shown in Figure 2.13: the preceding work center (PWC) and the subsequent work center (SWC). When the parts in the container at the SWC have been completely used up, the worker places the withdrawal kanban attached to this container into the kanban post. These kanban sheets are collected periodically (every hour or so) and taken to the stock point of PWC. Each sheet is placed in a full container of parts, and these are then taken back to the SWC (Encyclopedia of Industrial Systems). The empty containers at the subsequent process are periodically conveyed to the preceding process, where they are used for parts as they are produced. This is the classic system proposed by Toyota Motor Corporation. In addition to the withdrawal kanban, used in the one-card kanban system above, there is the production-ordering (P) kanban, which releases instruction to the preceding process to produce parts (Encyclopedia of Industrial Systems).
In Figure 2.14, a worker takes the withdrawal kanbans from the post where they are stored in the subsequent process and transfers them to the preceding process. Each kanban is equivalent to an empty container. The worker detaches the P-kanban sheets attached to the full containers of parts and replaces each of them with the W-kanban. The detached P-kanbans are
then placed in a post where they are regularly collected and used as an order for production. As products are manufactured in the preceding process, a P-kanban sheet is attached to a full container of parts. On the other hand, the full containers of parts whose P-kanbans have been exchanged with W-kanbans are moved to the subsequent process, where they are required. As each full container of these parts is used up, the W-kanban is placed in the W-kanban post, until it is again collected for withdrawing parts at the preceding process (Encyclopedia of Industrial Systems).

As can be observed from the operation of the one-card and two-card kanban systems, the latter has a better control of inventories at both work centers. While the one-card kanban system would suffice for relatively simple production systems, the two-card kanban system would be more effective in a complex environment (e.g., in automobile manufacturing systems, where many parts and many model variants are involved).

**Number of Kanbans:** Since each full container contains a kanban, the number of kanbans is a measure of the level of inventory between any two processes. The number of kanbans is expressed by the equation: $N= \frac{QT (1+c)}{C}$. Where:

- $Q$: average daily demand;
- $T$: lead-time;
- $c$: safety coefficient;
- $C$: container capacity.

The safety coefficient provides for a small allowance in inventory. It is especially necessary for new systems, where the processes are still undergoing improvements (Encyclopedia of Industrial Systems).
2.9 PRODUCTION PLANNING SYSTEMS

The production planning deals with the following (McMahon 1998):

1) Deciding which products to make, how many of each and when they should be completed;
2) Scheduling the delivery and production of the parts and products;
3) Planning human resources and equipment to accomplish the production plan.

Figure 2.15 Corporate Production Planning

Source: Based on Groover (2001)

Figure 2.15 shows the three levels of the corporate structure: (i) the aggregate planning at the strategic level matches the capacity of the facility to the demand, (ii) the tactical level planning is responsible for preparing the master production schedules and material requirements, and (iii) the operational level is responsible for executing the production plans by planned order releases. There are four types of production planning sub-systems used in manufacturing
(McMahon 1998): (i) aggregate production planning, (ii) master production schedule, (iii) material requirement planning, and (iv) capacity planning.

2.9.1 Aggregate Production Planning

The aggregate planning develops mid-term planning schedules for the materials and available resources (i.e., planning up to 6 months ahead). It involves planning the production output levels for major product lines and amounts of products of each house size category to be produced on a weekly basis up to 6 months ahead. It results in reducing overloading and/or underloading, which result in reduced production costs. It also results in planning production capacity to meet demand even in times of peaks and valleys in demand.

2.9.2 Master Production Schedule (MPS)

The master production schedule (MPS) sets the quantity of each end item to be completed in each week of a short-range planning horizon (i.e., up to six months).

![Diagram of production planning process](image)

**Figure 2.16** Master Production Schedule


The MPS is a plan for future production of end items, set by market forecasts, customer
orders, inventory levels, and other information necessary to make correct schedules. The aggregate production plan must be converted into a master production schedule (as shown in Figure 2.16), which specifies the quantities to be produced of individual models within each product line and number of every model of every size needed to be produced per week.

**Figure 2.17** Algorithm of the Master Production Schedule

Source: Suer (1998)

The following rules (priorities) are followed in scheduling the production order:
1) First come first serve: jobs processed in order they arrive;

2) Earliest due date: earliest due dates of delivery to customers receive higher priority;

3) Least slack time: slack time equals the difference between time remaining until due date, and the process time remaining. Orders with least slack time are given highest priorities;

4) Critical ratio: the critical ratio equals the ratio of time remaining until due date, divided by the progress time remaining. Orders with lowest critical ratios are given higher priorities.

Relative priorities may change due to: (i) changes in demand, (ii) equipment breakdown may cause delay, (iii) cancellation of an order, and (iv) defective raw materials.

Figure 2.17 depicts the flow logic of the MPS. The MPS schedules the products according to the prioritized rules: (i) earliest due date and (ii) product mix by assigning similar product sizes for the same batches to insure similar processing conditions.

The Order Release phase provides the documentation needed to process a production order through the factory. The collection of documents is sometimes called the shop packet. It consists of:

1) The route sheet which documents the process plan for the item to be produced;

2) Material requisitions to draw the necessary raw material for inventory;

3) Job cards to report direct labor time devoted to the order;

4) Move tickets to authorize material handling personnel to transport parts between work centers;

5) Part lists if needed for assembly jobs.

The order release module is driven by two inputs:

1) Authorization to produce (derived from MPS);

2) Product structures and process planning (from data bases).
2.9.3 Material Requirement Planning (MRP)

A technique that translates the MPS of end products into a detailed schedule for the raw materials and component parts used in those end products (weeks or months). This detailed schedule identifies quantities of each raw material and component item. It also indicates when each item must be ordered and delivered. MRP is a method for inventory control by determining quantities of dependant demand items (i.e., an item that is directly related to the demand for some other items). However, the inventory control using order point system is used to determine independent demand quantities.

![Diagram of Material Requirement Planning](image)

**Figure 2.18** Raw Materials- Products Flow

### 2.9.3.1 Inputs of the MRP

MPS identifies types and quantities of end products to be produce within a certain time period called Time Buckets (months or weeks). The following inputs are used in the calculations of the MRP:
1) Bill of Materials (BOM): defines what raw materials and components are needed for each product. It is used to compute raw materials and component requirements for a product as shown in Figure 2.18.

2) Inventory record file or item master file: contains data on current and future inventory status on each product, component, and material. It includes the following types of data:

–Item master data: items identification (part number, quantity, lead time);

–Inventory status: this provides the time phased record of inventory status (e.g., gross requirements, scheduled receipts, on-hand status, planned order releases);

–Subsidiary data: e.g., purchases orders and scrap or rejects.

The MRP uses data contained in the MPS, BOM and the inventory record file. The MPS specifies the period by period list of final products required. Then the MRP computes how many of each component and raw materials are needed each period by exploding the end product requirements into lower levels in the product structure. Quantities of common use items (i.e., raw materials and components that are used on more than one product) must be combined during parts explosion to determine the total quantities required for each component and raw material in a given duration of the schedule. The quantities of components and raw materials needed each time period are termed the gross material requirements. The gross computed quantities must be adjusted for any (on hand or on order) inventories. This is called netting. The net requirements equal gross requirements, minus on hand and on order inventory quantities.

Finally, the Lead times for each item must be taken into account in ordering the net material requirements. Lead time is two types: (i) the ordering lead time, and (ii) the production lead time (i.e., station cycle time of a sub assembled component or the product cycle time of the product in the final assembly line). Figure 2.19 depicts a production planning system for MH.
2.9.3.2 MRP Outputs

The outputs of MRP are the order releases as shown in Figure 2.20. Planned order releases provide the authority to place orders that have been planned by the MRP system. There are two types:

- Purchase orders: Provide the authority to purchase raw materials or parts from outside vendors with specified quantities and delivery dates.
- Work orders: Generate the authority to produce parts or assemble products in the company’s own factory.

In addition to the above, the following reports are issued by MRP:

1) Rescheduling notices indicating changes in due dates for open orders;
2) Cancellation notices;

3) Reports on inventory status;

4) Performance reports (e.g., cost, item usage, actual versus planned lead time);

5) Inventory forecasts.

![MRP Inputs and Outputs](Figure 2.20)

Source: McMahon 1998

### 2.9.4 Capacity Planning

Capacity planning is concerned with determining what labor and equipment resources are required to meet the current MPS as well as long term future needs of the firm. It identifies the limitations of the available production resources to avoid planning an unrealistic master schedule. The master schedule must be consistent with the production capabilities and limitations of the production system that will produce the product. The firm must know its production capacity (productivity level) and must plan for changing its productivity to meet changing production requirements specified in the master schedule.

At the MPS stage a rough cut capacity planning (RCCP) calculation is made to assess the feasibility of the master schedule. This indicates any violations of production capacity in the
MPS. However, this does not validate the production schedule. This depends on the allocation of work orders to specific work cells in the plant. Therefore, a second capacity calculation (i.e., capacity requirement planning) is made at the time the MRP schedule is prepared.

The Capacity Requirement Planning (CRP) is a detailed calculation that determines whether there is sufficient production capacity in the individual department (or work cells) to complete the specific parts and assemblies that have been scheduled by MRP. Finally, if the schedules are not compatible with capacity then adjustments must be made either in plant capacity or in the master schedule.

**Table 2.2 MRP and Capacity Planning**

<table>
<thead>
<tr>
<th>Items</th>
<th>Production Planning</th>
<th>Capacity Planning</th>
<th>Resource Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product lines or families (Layout)</td>
<td>Aggregate Production Plan</td>
<td>Resource Requirements Plan</td>
<td>Plants</td>
</tr>
<tr>
<td>Individual Products</td>
<td>Master Production Schedule</td>
<td>Rough-cut Capacity Plan</td>
<td>Critical Work Centers</td>
</tr>
<tr>
<td>Components</td>
<td>Material Requirements Plan</td>
<td>Capacity Requirements Plan</td>
<td>All Work Centers</td>
</tr>
<tr>
<td>Manufacturing Operations</td>
<td>Shop Floor Schedule</td>
<td>Input/Output Control</td>
<td>Individual Machines</td>
</tr>
</tbody>
</table>

### 2.10 PRODUCTION CONTROL

1) **Shop floor control:** these systems compare progress and status of production orders in the factory to the production plans, *i.e.*, MPS.

2) **Inventory control:** includes a variety of techniques for managing inventory, *e.g.*, economic
order quantity.

3) Manufacturing resource planning (MRPII): combines MRP and capacity planning and shop floor control.

4) JIT production systems: scheduling discipline where materials and parts are delivered just prior to their being used. It aims to reduce inventory and waste (Groover 2001).

2.11 INVENTORY SUBSYSTEMS

Inventories are those materials and supplies carried by an organization to provide inputs to production processes or sales to customers. Generally, in any industry a large sum of money is appropriated for inventory. Good inventory management will hold down costs tremendously. There are three types of inventories associated with a production system (Encyclopedia of Industrial Systems):

1) Raw materials and sub-assemblies: items purchased from the vendors to be used as inputs to production processes;

2) Work-in-process (WIP): Partially processed materials inside the production area. A proper plan for WIP reduces production costs and congestion. However, some WIP may help support any unforeseen shortage of materials;

3) Finished goods: These inventories are the completed products, or manufactured sub-assembly modules, which are ready for sale to customers. In the case of make-to-stock products, there can be a fairly large amount of stock of finished products.

Inventories in the production system represent a tied-down capital, whether finished products or in-process inventories. Therefore, reduced inventories result in high capital turnover, and more investment opportunities. Excessive inventories have excessive cost implications, which negatively impact the firm's financial position (Encyclopedia of Industrial Systems).
Consequences of high level of inventory: high level inventories insure that the factory will meet unexpected demand (demand variations) since it will never run out of materials. This method smoothes seasonal or cyclic demand and hedge against price increase. Moreover, it takes advantage of price discounts because of the big quantities of materials. It is an easy way of managing stock. However, it is expensive in stock costs (Groover 2001).

Consequences of no or low levels of inventory: known as Just in Time (JIT), which is cheap in stock costs, however, expensive in management costs with suppliers (Groover 2001).

Costs Associated to Inventory

1) Holding costs: (i) storage costs, rent/ depreciation, labor, (ii) overheads (e.g., heating, lighting, security), (iii) money tied up (loss of interest, opportunity cost) • obsolescence costs (if left with stock at end of product life), (iv) stock deterioration and waste (lose money if product deteriorates whilst held).

2) Ordering costs: (i) clerical/labor costs of processing orders, (ii) inspection and return of poor quality products, (iii) transportation costs, and (iv) handling costs.

3) Shortage Cost: temporary or permanent loss of sales when demand cannot be met.

Inventory Control Methods

• Fixed-order-quantity system (Continuous): constant amount ordered when inventory declines to predetermined level.

• Fixed-time-period system (Periodic): order placed for variable amount every time-duration.

ABC Classification system

• Demand volume and value of items vary;

• Classify inventory into 3 categories.
Table 2.3 Illustration of ABC Classification System

<table>
<thead>
<tr>
<th>Class</th>
<th>% of Units</th>
<th>% of $</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5 -15</td>
<td>70-80</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>50-60</td>
<td>5-10</td>
</tr>
</tbody>
</table>

**Economic Order Quantity**

Reorder Point refers to the level of inventory at which to place a new order as shown in Figure 2.21 (Groover 2001). The reorder point is computed by the equation: \( R = D \times L \). Where, \( D \): demand rate per period and \( L \): lead time.

The assumptions of the economic order quantity are: (i) demand is known with certainty, (ii) demand is relatively constant over time, (iii) shortages are not allowed, (iv) lead time for the receipt of orders is constant, and (v) the order quantity is received all at once.

![Inventory Order Cycle (Groover 2001)](image)

**Figure 2.21** Inventory Order Cycle (Groover 2001)
2.12 CHAPTER REFERENCES


Monden, Yashimoro, (1998) "Toyota Production System (3rd edition)", Published by IIE.


CHAPTER 3
MODELING EXISTING MH PRODUCTION SYSTEMS

3.1 INTRODUCTION

MH systems are evaluated by analyzing two MH production systems. A simulation model was developed for the first production system in Abu Hammad (2001). However, the simulation model for the second production system is developed and presented in this chapter. The production system of the two case studies is analyzed. Activities at every station of the two systems are observed; moreover, activity relationship flow charts are developed to show the existing dependencies and sequence of activities. It is observed that the two systems have differences that contribute to the effectiveness of the overall production process.

The objective of this chapter is to develop a simulation model specific to case study factory 2 constraints (the simulation model for case study factory 1 is developed and documented in (Abu Hammad 2001)). Presently, the manufactured housing factories have either a linear layout or a U-shape layout with material stacks in close proximity to the various stations. The data required for the simulation study is obtained from on-site observations at the various factories supporting this research (syal and Hastak 2000, Hastak and Syal 2002). These factories are located in northern Indiana. Abu Hammad (2001) presents the simulation model developed for MH case study factory 1. The model is developed by using the following methodology:

1 Understanding the system by:
   a. Mapping the factory shop floor;
   b. Analyzing the assembly stations, subassembly stations, feeding stations and storages;
   c. Studying the material flow in the system;
   d. Analyzing the activity relationships within the stations. Pictures 1-8 show the different
stations of the assembly line at one of the factories (Abu Hammad 2001).

2 Develop a computer simulation model for the manufactured housing process by:

a) Observing the production operation and the production unit and by breaking them down according to their impacts on the process time;

b) Define the types of data needed for the simulation model: inter arrival time, processing time, transfer time, and rework time, etc.;

c) Collect the needed data from the factory;

d) Verify the model according to the modeling assumptions;

e) Validate the model with the real performance measures from the factory.

The simulation model represents the main stations of the assembly line. The first step of the research methodology is to understand the system by mapping out the system components and then collect cycle time data for the stations as well as the station’s sub activities. The data is converted into probability distributions by using the input analyzer tool (built into Arena). The output analyzer tool is utilized to compare the average time intervals for the 95% confidence of the system output-parameters. Verification of the model is achieved using the 3D animation interface of the model. The simulation modeling of advanced layout designs represents a case in which a virtual simulation is developed to represent a virtual factory setting. The actual data collected from the real systems are standardized by associating lists of MH activities and times to defined building blocks. Therefore, each building block has a defined work content and processing time distribution. These building blocks are primarily used in creating new layouts by organizing them around varied shapes of flow patterns. Therefore, cycle times for the virtual simulation models are determined by using the real data of existing factories.
3.2 DATA COLLECTION PROCESS

As shown in Figure 3.1; the first step of modeling a system is to observe the system in order to understand the interrelations between the activities on one hand and to realize the process constraints and logic of the process on the other hand. The factory stations and feeder stations were tabulated with their respective activities. Moreover, processing time data were collected for the stations and feeder stations, as well as for the activities running within. In
addition, the time between arrivals and transfer time between stations were recorded. System constraints pertaining to product movement, sequencing, crew size, and materials were also observed. Modeling assumptions were proposed according to system constraints pertaining to floor type, sizes, and floor sequence.

The data are collected with respect to station cycle time, activity duration at each station and the related feeder station. Similarly, information was gathered at each main and feeder station with respect to material used and crew composition. Ten data points were collected for each activity and activity. The movement of the floor between the stations defined the station cycle time, which began when the floor entered the station and ended when the floor left.

A major constraint to the data collection process was that the workers would often continue their tasks on top of the floor even though the floor was moving to the next station. It was observed that whenever activities at a certain station were finished - and there was no space available for that particular floor at the next station - the workers would leave their original station to help others at other stations. This procedure created many problems as far as data collection was concerned, since it was not possible to follow each worker leaving his station to work at other stations.

Four methods are proposed to better organize the data collection process. The first method is to follow the activity rather than the worker. The second method is to collect data for at least ten cycles at each station. Data collection for more cycles is not possible due to the long cycle time, and the fact that data should be collected for each distinctive floor size separately. The third method is to collect data over several one-day trips. This is not a good strategy since changes in station conditions and fluctuations in the labor force caused inconsistencies in the data. Therefore, data are collected on three consecutive day trips. The fourth method is to collect
data on the production of a full house over two day trips.

The data are collected for every activity and activity cycle time at each station. Data are also collected for the inter arrival times, travel times between stations, labor force size, and material used in each operation or activity. Data are collected from production group leaders for piping and drainage networks and assembly of interior walls at feeder stations, since it is very difficult to visually track the production process and relate it to individual floors. Another type of data is estimated on site, such as the rework durations and percentage of work rejected by inspectors.

All processing times are found to be probabilistic rather than deterministic. The processing times are measured in minutes using stopwatches. The processing time is defined as the time span from entry to the station to the end of process completion. Case study 1 is presented briefly in the following section (as an introductory for the comparative analysis with the other case study factory) based on (Abu Hammad 2001, Abu Hammad 2002a, Abu Hammad 2002b).

3.3 CASE STUDY 1

3.3.1 Production Process Description

The manufactured housing production process was observed (in detail) at two different factories located in northern Indiana. The factory names have not been disclosed due to reasons of confidentiality. Based on the observations at the two factories, a streamlined production process was developed for an efficient MH system. The generic factory layout and the data collection were designed to facilitate the development of a simulation model for production analysis.

The typical plan for a MH factory is square, with a U-shaped assembly line. The
inventory materials and finished housing units are stacked outside the factory. The production capacity of the two factories covered in this research is up to 9 units /day. The cycle time of a double bay housing unit is at least two days. A service road runs between the material stacks and the factory. The service road is used to move the required material from the stacks to the stations and feeders through several gates located at the four sides of the factory.

**Production Unit Description**

The housing section, depicted in Figure 3.2, is the production unit of the system. It might form either a full house or half a house, termed as a single bay housing unit or a double bay housing unit respectively. Units of either type have multiple design modules. The dimensions of the module are: varied width of 20-32 feet, and varied length of 38-84 feet.

The two sections of the double bay house were designated as (a) and (b) as shown in Figure 3.2, where (a) is the section that does not include bathrooms and kitchen and does not need to be processed at the floor tile station (station 2). Section (b) is the second part of the house that includes kitchen and bathrooms and needs to be processed at station 2.

![Diagram of Housing Sections A and B](image)

**Figure 3.2** Housing Sections: A and B (Abu Hammad 2001, Abu Hammad 2002b)
Figure 3.3 Case study 1 Flow Pattern
Production Line Breakdown: The generic assembly line of a manufactured housing factory consists of four main assembly operations: The Floor Construction, Wall Construction, Roof Construction, and Finishing-Testing.

Each manufactured housing factory has its own scenario for transforming the generic operations into a specific production line. Figure 3.3 shows the main stations of case study factory-1. The first three operations are distributed over multi substations, consequently shaping the physical setting of the factory assembly line. The station’s name follows the corresponding main assembly activity.

3.3.2 Activity Relationship

Station 1: Floor Construction Substations

1a (Chassis preparation), 1b (Floor build), 1c (Floor decking), and 1d (Vinyl tile)

Chassis preparation (1a) is the first station of the assembly line as shown in Figure 3.3, where a crane lifts the chassis in order to fix the air hoses and air pads to the corners of the metal chassis. Two workers process all activities in station (1a). An air pad system is used at several factories to provide temporary locomotion of the floors from station to station, as shown in Figure 3.4. When the floor reaches the end of the production line air pads are removed and a set of axles with tires is fitted to the housing unit ready for shipment outside the factory.

It is determined that the temporary mobility system using air pads is not an efficient way to move the house between the stations, because the floor occupies space and consumes processing time at the first station while the pads are being installed. In addition, whenever the unit is moved, the hoses need to be reconnected to the air outlets scattered alongside the stations.
Figure 3.4 Substation 1a

Figure 3.5 Substation 1b

Figure 3.6 Substation 1c

Figure 3.7 Substation 1d

Figure 3.5 shows the workers fixing the main lines for the hot and cold water supply, the drainage, and the heat ducts along the length of the section. The drainage and water networks are prepared at the piping feeder station opposite to station 1c, where the sub-activities are running in series at this station.

At substation 1c, as shown in Figure 3.6, the activities include installing then insulating secondary heat ducts, gluing the interior main frame, and fixing the floorboards after drilling the needed holes for future installations.

At substation 1d (Vinyl tile), all sections that have kitchens and bathrooms (55b, 80b, and
single bay) are processed at this station. Figure 3.2 shows the different section types (a and b). Sections of type (a) are not processed at this station and wait in queue until the other section of the same housing unit is finished in order to follow it to the next station (interior wall station).

One worker is in charge of floor sanding, gluing, water insulation and tile fixing. Sometimes another worker would help in these activities. Figure 3.7 shows the different tile rolls stationed at the beginning of substation 1d.

**Station 2: Wall Construction Substations:**

**Substation 2a: Plumbing fixtures**

After fixing the vinyl tile, the section moves next to the storage stacks of material and the cabinet feeder station. Two plumbers work on transferring bathtubs, sink cabinets and kitchen counters from their feeders to the floor. Then the two plumbers start connecting these fixtures to the connections coming out of the section deck.

**Figure 3.8 Substation 2b**  
**Figure 3.9 Substation 2c**

**Station 2b: Interior partition walls:**

The main activity in this station is to fix the interior partition walls as shown in Figure 3.8. After the installation of the interior partition walls, an electrician starts installing the interior wall wiring. Figure 3.10 shows the activity relationships at station 2.
Rework was observed during data collection causing a very long processing time. Rework at the interior wall station was due to an error in positioning the drainage outlets inside the floor.

Figure 3.10 Station 2: Interior Wall Station (Abu Hammad 2001)

Station 2c: Exterior Wall: sidewall and marriage wall fixing

At this station, the side, and marriage exterior-wall components are fixed to the section as shown in Figure 3.9. Marriage walls are the exterior walls of the double section housing unit that are shared by both section.

The sidewalls are matched together temporarily for the double bay units. Two workers are in charge of fixing the different components of the exterior wall using powered screwdrivers. Two plumbers work on fixing the bathroom and kitchen fixtures. In addition, two electricians work on wiring the exterior walls and the main electric lines.
Substation 2d: End wall & Face wallboard:

Interior face wallboards are prepared at a feeder station; one worker measures and cuts the needed boards. Another worker fixes these boards on the exterior and interior walls. An electrician works simultaneously on fixing electric switches to the face walls.

The matching of the two sections happens only at station (3a), where the laborers make sure that the two roofing trusses are at the same level. Then they separate the floors again before
they move them to station 3b. See Figure 3.11 of the activity relationship diagram for this station.

**Station 3: Roofing Construction Substations**

The main activity at station 3 is the roofing activity. In addition, there are three sets of activities running simultaneously at station 3: roofing activities, interior finishing activities, and exterior finishing activities.

![Figure 3.12 Roof Jig](image1)

![Figure 3.13 Substation 3a](image2)

The roofing station has three sub stations: 3a, 3b, and 3c. Figure 3.12 shows the Roof Jig Subassembly station. The roof Jig provides assembled truss components to the first two roofing substations 3a and 3b as shown in Figure 3.13. The roofing mechanism for the double bay house is as follows:

At station (3a), Figure 3.13, the first roof truss section is fixed on top of section (a) of the house. After the roof truss is fixed, the section moves to sub station (3b) where the same section gets insulated by one worker using a long 4 inch hose to fill the interior space of the truss with rock wool material pumped through the hose. Afterwards, section (b) of the house enters substation (3a) and the second half of the roofing truss is temporarily attached to it. Meanwhile, the two parts of the house are attached together in order to make sure that both trusses are
properly aligned. Then the second roof truss is permanently fixed to section (b) by two workers using power screwdrivers. With both trusses fixed on top of the housing unit, the sections are detached again and transferred to substation (3c) for the installation of roof boards, insulation and roof shingles.

**Substation 3a: Roofing activities, Interior finishes, and Exterior finishes:**

The roofing activities at this station consist of attaching the roof truss to the first floor section (a), matching the truss of the second section with the truss of the first section, and fixing the second section (b). The roofing activities consist of placing the truss. At station 3a, the roofing activities run in parallel with other two sets of activities: the interior finishes and the exterior finishes.

The interior finishes activity at this station consists of the following: fixing kitchen cabinets (upper), fixing electric switches, and taping the wallpaper joints (interior wall partitions). The exterior finishes activity at this station is the exterior wall boarding.

**Substation 3b: Roofing activities, Interior Finishes & Exterior finishes:**

The main roofing activity at substation 3b is to insulate the truss by filling it with rock wool material. The roof boarding activity might start either at this substation or at substation 3c. In addition, there are several other activities to be performed inside and outside the floor unit. The “Interior Finishes” activities include fixing electric fixtures, shelves, wall-ceiling cornice, and interior doors. The exterior finishes at substation 3b include fixing exterior doors and windows.

**Substation 3c: Roofing activities, Interior Finishes & Exterior finishes:**

When the section enters this station, the same three sets of activities may continue followed by other sub activities that start only at this particular station. The roofing sub activities
at this station include placing the roof boards, covering the roof deck with paper, waterproof insulating, and fixing of roof shingles. The first roofing activity might start at the previous substation 2c with the rock wool insulation processed at the second exterior wall substation.

Interior finishes at this station include the following tasks: fixing the interior doors, fixing window lintels, fixing the secondary carpet (foam), fixing the carpet, fixing skirt panels, fixing the cabinet shutters, and fixing the interior doors. The exterior finishing activities include fixing the exterior wall shingles (sometimes this activity was observed to start at the previous substation 3b).

**Station 4: Wheels, Appliances & Paint**

Station 4 is the last station in the production line. At this station, two workers transfer the appliances to the floor. The appliances are: furnace, mirrors, fireplace, and refrigerator. All appliances are stacked in storage areas beside the station.

![Diagram of Station 4]

**Figure 3.14 Station 4 (Abu Hammad 2001)**
After installing the appliances, factory inspectors carry out check tests for the hot and cold water and drainage network as a final inspection to make sure that everything is working well before the house is shipped out. Refer to Figure 3.14 for activity relationships at this station.

**Subassembly Stations and Inventories**

Subassembly stations are located in close proximity to the assembly stations that they provide components to. However, many inventory stack and many types of building materials were observed to be scattered around and at the middle of the layout.

The subassembly stations include the following: (i) Heat Duct Subassembly, (ii) Main Frame Subassembly, (iii) Drainage network, Cold water, and Hot Water Network Subassembly, (iv) Cabinets, Sinks, Kitchen Counters, Drawers, and Shelves Subassembly Stations, (v) Interior Wall Partitions Subassembly, (vi) Exterior Wall Subassemblies (3 Stations) for the Side Wall, Marriage Wall, and the End Wall fabrication, (vii) Roof Jig Subassembly (2 stations), and (viii) the Interior Doors subassembly station.

The main inventory stacks (storage areas) include: Mainframe and interior framing storage, Bathtubs, Cabinets & Sinks, Kitchen Counters, Interior Walls, Exterior Walls, Furnaces, Refrigerators, Mirrors, and Axles & Wheels.

### 3.3.3 Simulation Model For Case Study Factory 1

Figure 3.15 depicts the animation display of the simulation model (Abu Hammad 2001, Abu Hammad 2002b). Different entity sizes (products) are created in the arrive module and stamped with specified attributes and sequence.

The two distinct housing sections (a, b) are combined together at the (match module) and they enter each station successively without being interrupted by other floors.

The entities follow a sequence that is different for floor (a) than floor (b). The entity has a
unique processing time for each floor at any particular station. These entities pass through four inspection stations and when finished they leave the model (get disposed). At the end of the run, the software provides a report containing the data for the performance measures.

![Diagram](image)

**Figure 3.15** The Simulation Model of Case Study Factory 1 (Abu Hammad 2001)

Figure 3.15 is a display of the model network logic (Abu Hammad 2001, Abu Hammad 2002b). Finally the model was verified and validated by comparing the model measures with the performance measures of the original system.

### 3.3.4 Guidelines for Improving Existing Systems

#### Analysis of Station Performance

Balancing the station’s activities is essential to streamline the process. Substantial improvements on the productivity can be achieved after balancing the assembly line, since line balancing procedure eliminates the time wasted between the processes. Moreover, balanced
activities are bottleneck free because all stations have approximately the same process time. Therefore, no station waits for another station because they start and finish at the same time, yet this theory is undermined by the mixed model manufacturing (i.e., processing different sizes of sections in the same production line).

The subassemblies production should be adjusted for two floors ahead in order to keep the main assembly line running smoothly.

The reduction of cycle times for congested stations can be further investigated using the line balancing technique and the sub-activity relationship diagrams developed in (Abu Hammad 2001). The simulation model results serve as time guidelines that indicate the required processing times during which the assembly line stations should function within.

Suggestions aiming to reduce the station cycle time may include changing the tools used with ones that are more efficient. New manufacturing procedures (i.e., hopper storage) could be used to improve the process and make it time effective. Partial automation solutions might be suggested after a cost and value analysis is conducted to evaluate the associated cost and accrued gains resulted from the production improvement.

Additionally, the factory layout has a direct impact on the overall system efficiency and should be investigated to achieve a comprehensive improvement to the MH system.

1) Line balancing technique

Line balancing technique is used in manufacturing to streamline the sub activities and to improve the overall station performance. Furthermore, line balancing technique will equalize the station utilization of the production line, rather than equalizing the capacity of the stations. The technique will fine tune the production system and would balance the stations to work in sync together in processing the different housing products.
1) Steps for line-balancing the assembly line

1) Calculate the required cycle time for the station to work in sync with the system via the simulation model.

2) Reduce the congested-station cycle time by paralleling the sub activities without violating the required sequence.
   
   A) Rescheduling the activities within the station. Cycle time reduction of the congested station can be further investigated using the activity relationship diagrams and actual cycle time data that were collected at the case study factory.

   B) Redistribute the resources efficiently on the activities by assigning adequate resources for the lagging activities.

   C) Replacement of the existing tools used for processing various activities with more efficient tools. Innovative processing methods could be employed to improve the process and make it time-efficient.

3) Check the system performance using the simulation model after entering the new cycle time in the module menu.

2) Redesign of the Production System Layout

   The factory layout is the actual setting of the final assembly stations and subassembly stations. Facility design includes the material handling system in the factory. Therefore, it is the architecture of the process that has endless conceptual design solutions. Although a unique optimum layout solution does not exist; nevertheless, a multiple number of optimum solutions might be realized. Simulation models can be used to test the performance of different settings and then monitor the direct effect of layout setting on production rate, or any other performance
measures.

Changes of layout design might include the minimization of the number of stations (merging stations together) and/or apply parallel processing of certain stations without violating the required sequence of the operation.

Layout redesign involves reengineering the system and analyzing the impact of possible changes to the facility layout (configuration).

Finally, comprehensive analysis of various layout designs will be investigated in the following chapter (Chapter 4).

3) Overcoming Rework Drawback

Reducing the time consumed in reworks is essential for the improvement process. Reworks were observed during the data collection as a major cause of bottlenecks at the interior wall station due to new hiring of plumbers responsible for piping and drainage subassemblies with no sufficient experience. Overcoming this drawback can be achieved through extensive training sessions held for new workers to insure performing the work with minimum faults.

3.4 CASE STUDY 2

A simulation model is developed to represent the production system at another existing manufactured housing factory. This model provides an efficient tool for evaluating and analyzing the MH production system for potential bottlenecks that could hinder the productivity.

The activities of the system under study are mapped and process time data are collected for all activities at all assembly and subassembly stations. Additionally, total station cycle time for the assembly and subassembly stations are collected. Modeling assumptions are proposed based on the real system constraints that are observed during the data collection process. The
observed constraints included the types and sizes of the housing units produced and the ways those types are processed through the system. The simulation model is developed with respect to the system constraints. Finally, the simulation model is validated by comparing the performance measures of the 95% confidence interval statistics to the real system outputs.

3.4.1 Production Process Description

The U-Shape flow pattern is observed as a dominant physical shape of MH assembly lines. The case study facility has a U-Shape flow pattern. Additionally, the facility employs double section processing, which enables the processing of one full house (two sections) simultaneously at the station. The floor subassembly (floor jig) provides assembled floor sections to the floor decking assembly station shown in Figure 3.16. The ready floor components are placed in a hopper or overhead storage that enables continuous processing of the next component while the ready component is attached to the chassis at the floor Decking station. Roofing activities were observed to be independent from the activities of the exterior and interior finishes, where the three operations occupy three successively independent stations. The material handling system (the mobility system for the housing sections) permits the movement of the sections in the lateral direction of the layout by using bearing-wheeled U-sections attached beneath the wheels of the housing sections.

Although the product types and sizes are similar to other case study factories (Abu Hammad 2001) with approximately similar labor force size, the production of this factory was observed to have higher productivity output of 10 sections/ day, instead of 7 sections/ day observed at other comparable factories (Abu Hammad 2002). However, a comparative study of two case study factories was analyzed in (Abu Hammad et. al. 2003), one of them (termed as case study factory 2) was used to develop the simulation model presented in this paper. Figure
Figure 3.18 depicts the real factory layout and the exact distribution of operations and their respective activities throughout the different assembly and subassembly stations. Figure 3.19 shows the building components of the existing factory layout. The building units are the basic stations of the assembly line associated with time durations (Station Processing Time) that have direct impact on the total product (Housing Unit) cycle time. Additionally, the building units diagram shows the exact sequence of stations and dependencies between the different operations running within the factory shop floor. The station processing times were collected from the real system and will be discussed in the following section. The simulation model will simulate the building units as processors and will utilize specified real time data for every processor of the system.

From the above discussion, the physical shape of factory 2 flow pattern is U-Shape layout similar to case study 1. The following points summarize the differences between the two cases:

1. This facility uses double processing stations that enable the processing of one full house (2 sections) simultaneously at the station.
2. The floor building assembly station observed in case 1 (1b) became a subassembly station in case 2 as shown in Figure 3.18.
3. The system utilizes hopper storage concept for ready floor components
4. The roofing activities are independent from the exterior finishes and the interior finishes.
5. The material handling system is different than that of case study 1; the mobility system consists of bearing U-sections allowing lateral movement of the housing sections. However, the mobility system in case study 1 consisted of the air pads.
Figure 3.16 Different Stations of the Production Line

Figure 3.17 Different Stations of the Production Line
Although the product types and sizes are similar to those of case study 1 and the labor force size is approximately the same, factory 2 was observed to have higher productivity output of 10 sections/day, instead of 7 sections/day produced at factory 1. Figures: 3.16 and 3.17 show different stations at case study factory 2.

**Table 3.1 Case Study 2 Stations (Mehrotra 2002)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Station Name</th>
<th>Description of Stations Sub activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I-Main assembly stations</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Chassis Entries</td>
<td>Chassis on wheel and axle pulled into the factory, main wood frame is fixed</td>
</tr>
<tr>
<td>2</td>
<td>Floor Decking</td>
<td>Place assembled floor frame with insulation, ductwork and wiring over the chassis, fastening, floor decking</td>
</tr>
<tr>
<td>3</td>
<td>Interior Walls</td>
<td>Placement of Vinyl tile. Placement of interior walls (one sided studs panels)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Placement of cabinets, toilet compartment, bathtub, kitchen sink.</td>
</tr>
<tr>
<td>4</td>
<td>Exterior Wall Station</td>
<td>Placement of exterior walls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rough electrical and mechanical, and final exterior walls installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Installation of all electrical and mechanical equipment</td>
</tr>
<tr>
<td>6</td>
<td>Roofing</td>
<td>Roof installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Installation of shingles on the roof and cut outs for doors and windows</td>
</tr>
<tr>
<td>7</td>
<td>Exterior Work</td>
<td>Exterior wall finishes and installation of side shingles. Installation of door &amp; windows, and trim</td>
</tr>
<tr>
<td>8</td>
<td>Interior Work</td>
<td>Begin interior finishes- install carpet foam, complete interior drywall finish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Install carpet, final electrical and plumbing finishes, install marriage walls.</td>
</tr>
<tr>
<td>9</td>
<td>Cleanup and testing</td>
<td>Interior Finishing and cleanup, placement of material to be installed at site</td>
</tr>
<tr>
<td></td>
<td>II-Feeder Stations or Sub-assembly stations</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Heat duct&amp; Networks</td>
<td>Fabrication and storage of ductwork and plumbing, and placement of tires.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>11</td>
<td>Floor Building feeder</td>
<td>Assemble floor frame- place water insulation, place heat insulation (rock wool), place floor joist, place wire and duct work, stapling</td>
</tr>
<tr>
<td>12</td>
<td>Interior wall feeder</td>
<td>Sub-assembly of interior walls</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Assembly of cabinets, kitchen, and toilet sinks</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Sub-assembly station for roofing main activity stations.</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Fabrication of roof truss, installation of ceiling board, painting, drying</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Installation of loose and rigid insulation</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>III-Storages</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>Storage of ductwork and plumbing pipes</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>Storage of cabinets</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>Storage of drywall panels</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>Storage of drywall, doors and windows, and sheathing.</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>Storage of roof shingles</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>Storage of foam and carpet and drywall (marriage)</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>Storage of wall boards and tools</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>Storage of mirror, and appliances.</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>Storage of drapes and appliances.</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>Storage of toilets and materials to be shipped to the site for onsite installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Storage of drywall panels and wooden members for roof frame fabrication</td>
</tr>
</tbody>
</table>
Figure 3.18 Case study 2 Flow Pattern

1. Fix floor to chassis, open heat connections, glue, put boards, open holes to access installations, staple boards.

2. Roof Jig Feeder

3. Roof Jig F

4. Material Storage

5. Truss A, Truss Inter face


7. Material Storage.

8. Material Storage.


10. Cleaning, testing

11. OUT

12. 15 Final, Cleaning

13. 14 Appliances,

14. Feeder

15. Appliances Storage


17. Frames

18. 1 Decking

19. Ext. Wall

20. Ext. Wall

21. Roof Jig Feeder

22. Material Storage.

23. Material Storage.

24. Material Storage.

25. Material Storage.

26. Ceiling wiring, roof decking, paper cover and shingles, exterior boards, doors and windows, siding.

27. SW of A, MW of B, plumbing, Elec., Cabinets, Interior walls insulation-joint, paint, Ext. wall wire insu.

28. Install Cabinets, fireplace, wire insulation, exter. Wall joint, install bathroom, fix face board.

29. Fix floor to chassis, open heat connections, glue, put boards, open holes to access installations, staple boards.

30. Fix, put tiles, install cabinets and setting, load baking parts, final and cleaning.

31. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

32. Vinyl tile cut, glue, fix tile, interior walls cabinets and setting, load baking parts, final and cleaning.

33. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

34. Insulate A, insulate B, insulate board, exter. Siding boards.

35. Foam, fix carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

36. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

37. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

38. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

39. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

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69. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

70. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exter. Siding boards.

71. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exterior walls installation-joint, paint, Ext. wall wire insu.

72. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exterior walls installation-joint, paint, Ext. wall wire insu.

73. Fix, put carpets, join marriage wall sections, drapes & mirrors, clean up, board exterior walls installation-joint, paint, Ext. wall wire insu.
The production process was mapped out at all assembly and subassembly stations. Table 3.8 shows the activity distribution on the assembly and subassembly stations of the factory. Furthermore, the factory production line and the actual flow of materials and products through the system were observed as shown in Figure 3.18 in order to understand the system behavior and to determine the system constraints, which will be used later in developing the simulation model. The data collection process was part of an ongoing project (Syal and Hastak 2000) sponsored by the National Science Foundation through the Partnership for the Advancement of Technology in Housing (PATH).

Two types of process time data were collected from the factory: i) the total station cycle...
time, and ii) the process time of all activities running in the station.

Figure 3.1 depicts the methodology steps used in developing any simulation model (Abu Hammad 2001). The upper part of the flow chart includes the steps required to be conducted on the real system. On the other hand, the lower part of the flow chart includes the virtual modeling steps. The chart defines the relationship between the two parts when the real system data are utilized in the virtual model development. The real time data (station cycle times) was transformed into stochastic time distributions using the Input Data Analyzer tool provided by the simulation software. Arena simulation software was used as a developing environment for the simulation model. The simulation model was developed and modified consistently to match the model assumptions. As mentioned before, the modeling assumptions define basically the logic and constraints of the real manufacturing system.

Arena simulation software was used because it is specific to industrial and manufacturing applications. Furthermore, Arena has an efficient interface capability (animation display) that enables the modeler to follow the model logic and verify it. Additionally, Arena software includes two statistical interfaces: the Input Data Analyzer and the Output Data Analyzer. The two statistical tools were used to convert the real time data into stochastic distributions and to obtain the 95% confidence intervals of the model performance measures respectively. The model provides a run report that includes statistical data of many performance measures of interest such as: i) the mean product cycle time, and ii) the mean queue time at every station of the assembly line. The performance measures provide a clear idea about how the system operates and the system-specific characteristics. Moreover, the model outputs identify the problems (process bottlenecks) of the simulated system. The final step is to insure that the model provides the same outputs as the real system (model validation). The model validation is preceded by a process
termed “model verification”. Model verification involves a detailed check in which the model incorporates all the real system operations, such as: i) station sequencing (i.e., organization of the factory shop-floor layout); ii) floor sequencing (i.e., the flow logic of the floor units between the stations); iii) inspection and rework that are included in the simulation model as approximate data (estimated by the production manager of the factory). At each development of the model, a continuous verification process is done to assure that the model assumptions are fulfilled, building the model right. The model validation process involves a comparison of the real system outputs and the simulation model outputs for the 95% confidence interval on the mean production rate value, building the right model.

3.4.3 Simulation Model for Case Study Factory 2

Different modules of the simulation model are depicted in Figure 3.20, based on the actual sequence of stations observed in Figure 3.18. The Arrive Module is the first module of the system in which all entity sizes (45ft, 55ft, 65ft, 75ft, 85ft) are generated. The entities are generated according to an assigned accumulative probability. For example: [DISC(0.2,1,0.4,2,0.6,3,0.8,4,1,5)] is entered in the Assign Attributes menu at the Arrive Module. The expression means that the Arrive Module will create entities according to the following percentages: 20% of entities would have an attribute of value 1 (i.e, size 45ft), another 20% have an attribute 2 (i.e, size 55ft), another 20% have an attribute 3 (i.e, size 65ft), 20% of entities have an attribute 4 (i.e, size 75ft), and finally 20% of entities have an attribute 5 (i.e, size 85ft). Adding up all the previous percentages would equal to 100%. Referring back to the expression above, it is observed that the percentage for entities of assigned attribute 2 is entered as .4 that means the percentages of the model mix are controlled and assigned as accumulative percentages that adds up to 100%. The time between entity arrivals is a triangular distribution.
[TRIA(30, 40, 50)], that means the Arrive Module creates one entity every time duration of a triangular distribution with a minimum value of 30 minutes, average of 40 minutes, and maximum value of 50 minutes. The maximum batch size is set in the Arrive Module menu to 50 entities.

![Simulation Model of Case Study 2](image)

**Figure 3.20** Simulation Model of Case Study 2

The two sections, (a) and (b), of the double bay house move together through the system. Therefore, the two entities are joined together at the Choose Module. Thus, the Choose Module is included in the model logic to accumulate two similar entities together, based on their assigned attribute. The if-statement of the Choose Module joins the two entities together according to
similar assigned attribute numbers 1-5. The attribute numbers refer to different entity sizes. When two similar entities are accumulated in the Choose Module, they are directed immediately to the Pick Queue Module. The Pick Queue Module keeps the two entities in a storage state until they are sent directly to the Match Module. The function of the Match Module is to match the two entities together, so that they move together through the rest of the system’s modules. All house entities exit the five match modules corresponding to each house size, and enter the first Server Module (station 1: the floor decking assembly station). Then it is sent to stations 2 and 3: the interior wall assembly station and the queue paint station, respectively. The entities are processed inside each server according to an assigned process time that is referenced in the Sequences Module. The function of the Sequences Module is to specify, in a list format, the time distribution associated with every entity size at every Server Module.

As shown in Figure 3.18, all the stations after station 3 are observed to be double section processing stations. The double section processing describes the station that processes one full house (two sections) simultaneously. Therefore, in the simulation model, a cluster of different modules is used (Choose Module and Batch Module) to capture the logic of the double section concept. The two entities leave the Batch Module as one entity. After station 12-13, the two entities are split, using a Split Module, into two independent entities and then processed independently at the last two stations 14 and 15: the appliances and final cleaning stations, respectively.

All entities leave the last station and enter into the Leave Module. The function of the Leave Module is to collect different statistics for the specified performance measures listed in the Module’s menu and in the Sets Module menu.

The Simulate Module is added to the model as an independent component. The function
of the Simulate Module is to specify the number and length of replications needed to make the model run over a specific period of time. The model collects the performance measures of interest in the form of a report at the end of the run.

<table>
<thead>
<tr>
<th>COUNTERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier</td>
</tr>
<tr>
<td>floors 65 ft productio</td>
</tr>
<tr>
<td>floors 75 ft productio</td>
</tr>
<tr>
<td>floors 85 ft productio</td>
</tr>
<tr>
<td>floors 45 ft productio</td>
</tr>
<tr>
<td>floors 55 ft productio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier</td>
</tr>
<tr>
<td>TAVG(FLOORS 65 FT CYCL)</td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL)</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL)</td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL)</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL)</td>
</tr>
</tbody>
</table>

Figure 3.21 Production Counter Results of the Simulation Model

3.4.4 Run Results and Discussion

The run results for 100 replications are included in Figures 3.21-3.26. Figure 3.21 shows the output values of the production counter relative to each product size. The total production rate is equal to 48 sections per week. One week’s production is equivalent to 7 hours per day, five days per week. Figure 3.22 displays the 95% confidence intervals (CI) of the production rate relative to each product size. The production rates vary for each product size according to the percentages assigned at the Arrive Module (the assigned model mix). Figure 3.23 depicts the CI for the truncated production values over the 100 runs. The production measure of the model matches the actual production of the factory.
Figure 3.22 95% Confidence Intervals of the Mean Production Rates

Figure 3.23 95% CI Statistics for the Truncated (Interpolated) Productivity Values
### ARENA Simulation Results
Ayman Abu Hammad - License #9400000

Output Summary for 100 Replications

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Average</th>
<th>Half-width Minimum</th>
<th>Maximum</th>
<th># Replications</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAVG(FLOORS 65 FT CYCL</td>
<td>297.39</td>
<td>1.2757E-13</td>
<td>297.39</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL</td>
<td>392.74</td>
<td>6.9586E-14</td>
<td>392.74</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL</td>
<td>297.98</td>
<td>9.2779E-14</td>
<td>297.98</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL</td>
<td>281.32</td>
<td>1.2757E-13</td>
<td>281.32</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL</td>
<td>386.82</td>
<td>1.1597E-14</td>
<td>386.82</td>
<td>100</td>
</tr>
</tbody>
</table>

Simulation run time: 0.03 minutes.
Simulation run complete.

**Figure 3.24** Run Results for 100 Replications of the Simulation Model

**Figure 3.25** 95% Confidence Intervals of the Mean Product Cycle Times
The actual production rate at the factory was observed to be 9-10 sections per day. Therefore, the model is considered to be a good representation of the real system. This model could be used in system improvement scenarios. Figure 3.24 shows the run result statistics of the average product cycle time. The average product cycle time ranges from 281.32 minutes to 392.74 minutes. However, Figure 3.25 displays the 95% CI of the average station cycle time. The results compare the cycle time of the different product sizes. It is concluded from the Figure 3.25 that the CI of the different products should be similar, in order to obtain a bottleneck-free system. The average queue time statistics indicate station 1 (Appendix 9.2) as the only bottleneck station having a relatively high average queue time. The average queue time of station 1 is approximately equal to 1 hour per week of operation, which can be considered as an acceptable delay value for 5 operating days. It is concluded from the run results that the system is streamlined and has no process-bottlenecks. The long queue time at station 1 is related to the waiting state for two entities to accumulate in the Batch Module, in order to be sent as one full
house to station 1. Additionally, another factor causes the long waiting time at station 1; that is, the long time between arrivals [the triangular distribution: TRIA (30, 40, 50)], coupled with a low batch size of one entity at a time. Therefore, station 1 does not have a bottleneck. The run report shows that most of the other system servers (stations) have an average queue time of zero. Additionally, the same is observed for the number in queue statistics at all the servers of the system.

3.4.5 Sensitivity Analysis

The simulation model is sensitive to changes to the station cycle times (by entering the new time in the processor menu directly, hence, the model will process the entity according to the new value not the times stored in the sequences module). Therefore, if the cycle time of a particular station is changed, a corresponding change to all the model performance measures will occur (*i.e.*, the number of entities in queue, the average queue time at the following and succeeding stations, and the station utilization). However, it was observed that the production rate remains unchanged after modifying the time of a particular station. This is justified since the product cycle time is very long compared to the difference in station cycle time. Thus, it will not be substantial to cause any change to the production rate. Finally, changes to the flow of logic will consequently impact all the output performance measures including production rate.

3.4.6 Concluding Remarks on System Improvement

Based on the above results, there is no need to alter the station processing time or conduct any procedure to increase the productivity of the system. Nonetheless, the streamlined system observed in this case study is further improved by eliminating queue spaces that create waste in the factory area. Station 3, for example, has the same processing time as station 2, and there are no activities running at that station other than the painting activities. Moreover, the interior
finishing and exterior finishing activities are not integrated with the roofing activities, as observed at other MH factories.

In the previous sections, the production system of two case study factories is mapped out and modeled using an independent simulation model for each system. It is important to conduct a comparative analysis for the two systems in order to define the efficiencies and deficiencies of each system. Results of modeling the two case studies are utilized in designing a generic system for MH production systems that incorporate the benefits of the two layouts and exclude all the observed drawbacks. Generic building blocks for a most efficient U-shape system is proposed based on the generic system components. The building blocks are very helpful for evaluating and improving real MH systems. Moreover, they are very helpful in constructing then evaluating new systems under fixed (cellular) operating conditions. Thus, the building blocks are used in Chapter 5 to develop other layout design scenarios. Simulation models for the new layout designs have used the data of case study factory 2, since the cycle time distributions of case study 2 are streamlined as observed from case study 2 run results.

3.5 CHAPTER SUMMARY

In this chapter, the production process of existing manufactured housing systems is illustrated. The production process of the two existing factories is analyzed for improvement under fixed flow pattern design constraints. Some of the problems of the current layouts are related to the material handling system and unbalanced production line. The processes are not streamlined properly; therefore, the overall system suffers from process bottlenecks.

Simulation models offer a low cost tool for analyzing the system and locating process bottlenecks. Two real time simulation models are presented in this chapter, which facilitate evaluating and further improving the productivity of existing manufacturing systems. A
stochastic simulation model has one or more random variables as inputs. The output can only be treated as a statistical estimate (confidence interval estimate) of the true characteristics of the real system (Kelton 1998, Huang 2001). Arena simulation software is designed for modeling business processes and other applications in support of high-level analysis needs. Therefore, Arena is used to model the manufactured housing factory, since it has advanced capabilities of mimicking the behavior of the real system: components, layout, and flow logic. Moreover, it has the advanced capabilities of producing data distributions, confidence intervals, and display animation.

Validation is the last step of the simulation model development. Model validation is conducted by comparing the statistical measures of the simulation model with the factory output measures. The statistical measures were found to be similar; therefore, the model is validated.
3.6 CHAPTER REFERENCES


CHAPTER 4

COMPARATIVE ANALYSIS, BUILDING BLOCKS, AND OPTIMIZATION MODELS
FOR MH OPERATIONS

4.1 INTRODUCTION

A detailed description of two existing U-shape MH factories is presented in Chapter 3. The production operations and processes are explained. Additionally, the time data is collected for all stations and activities at both factories. A comparative study is conducted in this chapter for the two existing systems. Each production system is analyzed to observe the layout-specific efficiencies and drawbacks. The observed efficiencies (beneficial aspects of both factories) are combined to form a virtual system utilizing a streamlined production process. In other words, the streamlined system (generic system) is the most efficient layout for U-shape MH systems. Results of this analysis define generic building blocks of a streamlined system for manufactured housing facilities. Additionally, the generic building blocks are used later in Chapter 5 to construct new layout design alternatives. In this chapter the building block times of the streamlined system are minimized by using an optimization model. By reorganizing the activities, the optimization model provides an interactive tool for users to control the station cycle time and, consequently, the overall system time. Moreover, the overall streamlined system time will be optimized (minimized) by using the optimization model.

The following steps are used in achieving the goal of this chapter.

Step 1: Conduct a comparative analysis of the two case study systems:

Developmental research done in this area is documented in Abu Hammad (2002a) and Abu Hammad (2003a&b). The analysis conducted at the two MH production systems is very useful in defining the general system components and in capturing the logic and nature of the
Abu Hammad (2002a) has illustrated the production process at an existing MH factory in northern Indiana. The results and analysis are essential in defining the existing stations and their related activities. In addition, activity relationship diagrams are necessary in developing the arrow diagrams that formed the basic step in scheduling the station’s activities. The activity relationship diagrams are used to define the required sequence and existing dependencies between the activities.

**Step 2: Collect cycle time data for the stations and for the activities running inside the stations:**

Abu Hammad (2001) has documented the data collection process at an existing MH factory, termed as case study 1. Moreover, data is collected at another MH factory, termed as case study 2. The second case study factory is used in developing the optimization model. Data is collected for 22 products (housing sections) at case study factory 1.

In addition, data is collected for another 44 sections at case study factory 2. Each data set includes the following: i) the station cycle time, ii) the processing times for all the activities running inside the station, iii) total number of workers at the station, and iv) number of workers associated with each activity at every station.

The data collection process is part of an ongoing project (Syal and Hastak 2000) sponsored by the National Science Foundation through the Partnership for the Advancement of Technology in Housing (PATH).

**Step 3: Define the basic system components of MH operations (building blocks):**

The basic building blocks of the system are the abstract units of a minimum number of
stations that are required to perform all the activities needed to produce an MH product. Abu Hammad (2003a) has conducted a comparative analysis of existing manufactured housing systems. A streamlined system for MH operations is proposed as a result of the analysis. The streamlined system includes the minimum number of working stations required for an efficient MH production line. The results from step 1 and step 2 above (the activity relationship diagrams and the data associated with the activities respectively) are used to define the exact number of resources and time needed to perform each activity (the micro-level building units of the system) within a certain sequence illustrated by the relationship diagrams.

**Step 4: Streamlining the activities at each station and optimizing the station cycle time (developing optimization models for the stations):**

Step 3 employs a minimum number of stations to form the production line. This step develops optimization models to minimize the station cycle time. Independent models for every station are developed. Therefore, a minimum cycle time for each station is obtained.

Sub-step 4.1: Developing arrow diagrams for the activities of each station. The activity relationship diagrams mentioned above are used in developing the arrow diagrams. The arrow diagram shows the sequence of operations and specific precedence requirements for each activity.

Sub-step 4.2: Preparing tables of activities and precedence requirements for each activity. The table includes the time duration and respective number of resources required to finish the activity.

Sub-step 4.3: Setting the constraints of the optimization models and the objective functions, both of which will be explained in the next section.
Step 5: Streamlining the stations within the overall production system (developing an optimization model for the overall production system):

The final step is to develop the macro level optimization model for the overall production system. The macro level optimization model includes the stations as building blocks of the system. The processing times of the stations are minimized in the previous step using independent models. The optimization model is developed in the same way used for developing the models on the station level. The main difference is that the activity information is mapped, using arrow diagrams, and is listed in the table. However, the activity at the micro level is equivalent to a whole station at the macro level. The optimal time of the station at the micro level is used as duration for the respective station at the macro level. Moreover, the number of resources at the station would not remain the same as the number obtained from the original data, since the minimum time of the station is obtained through scheduling the operations in a more efficient way by paralleling the activities. Therefore, it is possible for the scheduler to estimate the extra number of workers needed to perform the paralleled activity. Serial activities usually require the same resources working on multiple activities in a serial manner. However, in paralleling an activity, it is assumed that an extra number of workers and equipment should be added to the original crew size, in order to process the paralleled activity.

The following section presents the comparative analysis of the two existing systems (step 1 above).
4.2 A COMPARATIVE ANALYSIS OF EXISTING MH SYSTEMS

The main objective of this section is to define the most efficient components of a streamlined system (at the macro level) by investigating the efficiencies and drawbacks associated with the different configurations of two existing MH facilities. This step is preceded by a general comparison of different system configurations via a questionnaire (Abu Hammad 2001). Thirty five questionnaires were sent from the University of Cincinnati to the industry. Only five responses were returned. Another thirty questionnaires were sent from Michigan State University. Only six responses were returned. Therefore, the total number of responses is eleven, out of sixty five questionnaires, sent out to the industry (Abu Hammad 2001).

The second step is to conduct a comparative study of two existing MH case studies, which are selected from the pool of the responded questionnaires. The comparative study is based on full understanding of the activity interrelationship and the specific nature of the processes at the two factories. Additionally, the study has analyzed the system limitations with respect to the layout configuration, materials, and equipment used. Finally, criteria of advantages and drawbacks are prepared for each system. Then the combined efficiencies are employed in defining the building units (stations) of a streamlined production process for MH.

4.2.1 Components of Existing MH Systems

The following notes are based on a preliminary comparison of the master plans provided by the responding factories:

1) Most of the systems are observed to share the same flow, which is a U-shape pattern as shown in Figure 4.1.

2) The manufacturing processes are two types: final assembly and subassembly processes.

3) All assembly processes are included under four major operations through the production line:
1) Floor construction.
2) Wall construction.
3) Roof construction.
4) Finishing, painting, appliances, and testing.

The above operations are sequential; hence all factories have the same assembly flow that starts with the construction of the floor on the metal chassis. The metal chassis is manufactured in a separate facility and could not be integrated in the layout for safety purposes. Nevertheless, the last operation can be broken down and integrated with the activities and sub activities of the previous three operations.

![Material Flow Diagram](image_url)

**Figure 4.1** U-Shape Flow Pattern for a Typical Manufactured Housing Facility

4) Some facilities are designated to produce single bay units. Other facilities are producing both types of single bay and double bay units. Recently, the manufactured housing industry has started to produce two story units.
| Table 4.1 Comparison of Five Factory Layouts |

**(Factory Case Study 1)**

1- Floor building station (four stations). 2- Floor tile (two spaces). 3- Cabinets and interior walls (three spaces). 4- Sidewall (two spaces). 5- Roof set four stations (jig, spray-two stations). 6- Dry wall finishes, doors windows, fixtures, and installations (four stations). 7- Fixtures, testing (six stations). 8- Rework (two stations).

**(Factory Case Study 2)**

1- Chassis. 2- Floor decking. 3- Interior wall. 4- Exterior wall. 5- Roofing. 6- Exterior finishes. 7- Interior finishes. 8- Cleanup and testing.

**(Factory 3)**

1- Floor jig. 2- Plumbing. 3- Frame tile. 4- Interior walls plumbing. 5- End walls. 6- Side walls (double-station). 7- Roof set (frame-mud-spray). 8- Electrical. 9- OSB hangs. 10- Vinyl. 11- Shingles. 12- Doors. 13- Molding. 14-16 Water, electrical testing. 17- Clean up. 18- Final.

**(Factory 4)**

1- Floor framing. 2- Floor decking. 3- Floor finish. 4- Cabinets and interior walls. 5- Sidewalls and electrical installations. 6- Roof set. 7- Roof insulation and electrical. 8- Roof decking. 9- Roof paper, shingles, doors and windows. 10- Roof shingles and sidings. 11- Interior doors and moldings. 12- Moldings. 13- Carpet pad. 14- Carpet. 15- Finish (two stations). 16- Chassis mounting and plumbing test. 18- Final finish.

**Factory 5**

1- Chassis, frame, sub floor and decking (four stations). 2- Interior wall (double-station). 3- Exterior walls. 4- Roof assembly (double-station). 5- Exterior finishes, doors, and windows (double-station). 6- Electrical and mechanical (double-station). 7- Interior finishes (double station). 8- Fixtures. 9- Testing.

Source: By researcher based on the questionnaire responses (Abu Hammad 2001).

5) Some facilities included two or multiple plants with independent production lines. While some other facilities included multiple plants with one common production line.

6) The housing products are varied in terms of size, dimensions, architectural design. The nature of the manufacturing process of multiple product types and sizes is termed as “mixed model manufacturing systems.”

Part of the questionnaire results are tabulated in Table 4.1. The production system components of the different factories are observed carefully and compared in the table.
4.2.2 Comparative Analysis of two MH Case Study Factories

In this section, the two case study factories are investigated in more detail. Figures 4.2 and 4.3 depict the physical setting at the two case studies.

The two factories have similar layout shape (U-Shape). The U-Shape flow pattern is a dominant shape for most of MH facilities (observed through the questionnaire responses and personal factory visits). MH systems are not the same in terms of the distribution of the manufacturing processes at different stations and feeders. The following factors are found to be major causes of layout variation:

1. The breakdown to activities and sub activities;
2. The breakdown to stations and feeder stations;
3. The processing of two floors simultaneously (double station). This process would enable the
working team to process one full house simultaneously;

4. The utilization of different building materials;

5. Variation of the material handling system.

Table 4.2 lists the assembly line components for the two case studies relative to the shop floor layout of each layout as shown in Figures 4.2 and 4.3 above.

<table>
<thead>
<tr>
<th><strong>Table 4.2</strong> Comparative Analyses of Case Studies 1 and 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(Factory Case Study 1)</strong></td>
</tr>
<tr>
<td><strong>1- Floor Construction</strong></td>
</tr>
<tr>
<td>1a: Chassis Preparation: Temporary air pads &amp; hoses</td>
</tr>
<tr>
<td>1b: Floor Building Station</td>
</tr>
<tr>
<td>1c: Floor Decking Station</td>
</tr>
<tr>
<td>1d: Floor Tile</td>
</tr>
<tr>
<td>1E: Bathtub and Cabinets Transfer</td>
</tr>
<tr>
<td><strong>2- Wall Construction</strong></td>
</tr>
<tr>
<td>2a: Interior Wall Station</td>
</tr>
<tr>
<td>2b: Exterior Wall Station</td>
</tr>
<tr>
<td><strong>3- Roof Construction</strong></td>
</tr>
<tr>
<td>3a: Truss Fixing Station</td>
</tr>
<tr>
<td>3b: Truss Insulation Station</td>
</tr>
<tr>
<td>3c: Decking and Insulating, and Shingles</td>
</tr>
<tr>
<td><strong>Appliances and Testing</strong></td>
</tr>
<tr>
<td>6a: Permanent Wheels</td>
</tr>
<tr>
<td>6b: Appliances or Painting and Testing</td>
</tr>
</tbody>
</table>

Table 4.3 presents a comparative study of the advantages and drawback for the two case studies.

Figures 4.2 and 4.3 present the actual setting for each factory. Table 4.2 shows the distribution of activities at the stations and feeders of the two factories. As mentioned above, the two factories have a similar layout shape and a different distribution of operations at the stations and feeders. The crew members move among stations at case study 1, while they remain stationary at the other factory.
Table 4.3 Advantages and Drawbacks of Case Studies 1 and 2

<table>
<thead>
<tr>
<th>(Factory Case Study 1)</th>
<th>(Factory Case Study 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td></td>
</tr>
<tr>
<td>The operations of roofing, interior-finishing, and exterior-finishing are integrated and well balanced at the roofing substations.</td>
<td>Permanent wheels are fixed at the beginning of the line, enabling transition between stations. Trolleys are fixed after the interior wall station for lateral direction movement.</td>
</tr>
<tr>
<td>The floor tile is applied at the interior wall station and does not occupy an independent station.</td>
<td>The floor tile is applied at the interior wall station and does not occupy an independent station.</td>
</tr>
<tr>
<td>Bathtub and cabinet transfer activities take place at the interior wall station.</td>
<td>Bathtub and cabinet transfer activities take place at the interior wall station.</td>
</tr>
<tr>
<td>Painting activities are integrated in all stations, feeder stations, and storages.</td>
<td>Painting activities are integrated in all stations, feeder stations, and storages.</td>
</tr>
<tr>
<td>Double-section processing starts after the interior wall station, which doubles the capacity of the station by processing the two section housing units simultaneously.</td>
<td>Double-section processing starts after the interior wall station, which doubles the capacity of the station by processing the two section housing units simultaneously.</td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td></td>
</tr>
<tr>
<td>The mobility system is not efficient. Time to fix the temporary mobility system can be utilized in fixing permanent mobility wheels. There is a lot of time lost in connecting the hoses to air outlets every time the section is moved.</td>
<td>Interior and exterior finishing operations are not integrated with the roofing activities and occupy additional work spaces.</td>
</tr>
<tr>
<td>The vinyl tile activity occupies a whole station space.</td>
<td>Interior finishing activities occupy additional double stations.</td>
</tr>
<tr>
<td>Extra space is required to transfer bath tubs and cabinets to the housing section.</td>
<td>Exterior finishing activities occupy additional double stations.</td>
</tr>
<tr>
<td>Drywall painting is processed at the end of the line. The cycle time required to finish each house is lengthened by 8 working days.</td>
<td></td>
</tr>
<tr>
<td>Permanent wheel fixing activity occupies an extra station.</td>
<td></td>
</tr>
<tr>
<td>The layout uses the double-processing system. However, the factory processes only one section at a time at each station. The two sections are joined momentarily to match their size and height.</td>
<td></td>
</tr>
</tbody>
</table>

Moreover, case study 2 employs the double processing operation, while at case study 1; the system employs a single processing operation. Double processing enables the crew of a particular station to process one full house (two sections) simultaneously. The evaluation of the layout advantages and disadvantages was based on the observed impact of each layout
component on the assembly station-cycle time and the overall system performance. The two simulation models developed for each case study factory are utilized in evaluating the overall performance. Run reports of the two models are discussed in the previous chapter. Run reports provide output performance measures of interest, \textit{i.e.,} station utilization, product cycle time, mean queue time, average number of entities waiting in queue, and the production rate.

\subsection{4.2.2.1 Comparative Advantages and Drawbacks}

\textbf{Advantages of the Two Systems}

Table 4.3 lists one advantage and six drawbacks for the layout of case study 1. The roofing station is observed to have an efficient composition because it includes three operations running simultaneously (parallel operations): (i) the roofing operation, (ii) the exterior boards siding, and exterior windows and doors (termed in the research as exterior finishes), and (iii) the interior molding, framing, interior doors, and cabinets (termed as interior finishes). Figure 4.4 depicts the case study 1 efficiency at the roofing station. This figure shows the building blocks of case study 1, which are numbered relative to case study 2 stations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{BuildingBlocks.png}
\caption{Building Blocks of Case Study 1}
\end{figure}
Disadvantages of the Two Systems

The following four drawbacks are observed at case study factory 1:

1) The mobility system used to transport the housing sections between the stations is not efficient. Station 1a, at case study 1, is totally dedicated for fixing the mobility system to the metal chassis. However, this operation can be redesigned to cover the processes of fixing permanent axils and wheels to the metal chassis, instead of having those processes located (in a redundant way) at the end of the production line. By doing this, a whole station processing time can be eliminated.

2) The floor tile activity, station 1d, occupies an independent station. Therefore, an activity with a short processing time is processed solely in a station. However, this activity can be integrated with other activities of the following station, as observed at station 2 in case study factory 2.

3) The plumbing activity is processed in an independent station, and could be integrated with the activities at the following stations.

The above drawbacks cause the total product cycle time to extend beyond the needed time. However, the elimination of station 1a from the production line besides the integration of the floor tile and plumbing activities with other activities of the preceding or following stations, would result in a substantial reduction in the total product cycle time.

4) The drywall finishing activities are not integrated with the activities of the whole production line. Therefore, the housing units remain at the end of the line (approximately 8 days) for painting. At case study 2, the painting activity is integrated with other activities throughout the production line (e.g., subassemblies of the interior wall components are painted while they are at the interior wall feeding station, then painting resumes after fixing the partitions on top of the section). In this way, painting, which takes a long processing time, can be processed
simultaneously with the other activities at all the production line stations.

5) The system does not employ the double section processing; which enables the processing of two housing sections simultaneously at the station.

**Figure 4.5** The Building Blocks of Case Study 2

### 4.2.2.2 The Generic U-Shape System

A generic (streamlined) system is developed based on the comparative analysis results for factories employing the U-shape flow pattern. The streamlined system has eight stations, which follow the numbering of case study 2: 1) floor decking, 2) interior wall, 4-5) exterior wall, 6-7) roofing, interior, and exterior finish, 8-9) roofing, interior, and exterior finish, 10-11) roofing, interior, and exterior finish, 14) appliances, 15) clean up and testing.

The above stations are backed up by sufficient subassembly stations and raw-material workshops (the same as in case study factory 2). The material handling system consists of cranes and forklifts. Wheeled U-section components are proposed for the lateral movement of the
floors, similar to the components used in case study 2. Since this design is a redesign alternative, a comprehensive analysis and modeling is performed in Chapter 5 to test the performance of the proposed system.

4.3 **BUILDING BLOCKS OF AN EFFICIENT MH SYSTEM**

4.3.1 **MH Production Process**

The production process is mapped out for all assembly and subassembly stations at two MH factories located in northern Indiana. Abu Hammad *et al.*, (2002a) have illustrated the production process of existing MH factories. The U-shape flow pattern is a dominant physical shape of most MH assembly lines. Figure 4.6 shows the activity distribution over the assembly and subassembly stations of case study factory 2. Furthermore, the factory production line and the actual flow of materials and products through the system are observed, in order to understand the system behavior. Moreover, Figure 4.6 shows the exact distribution of operations and their respective activities throughout the different assembly and subassembly stations. Additionally, the facility employs double section processing, which enables the processing of one full house (two sections) simultaneously at the station. The floor subassembly (floor jig) provides assembled floor sections to the floor decking assembly station as shown in Figure 4.6. The ready floor-components are placed in a hopper or overhead storage that enables continuous processing of the next component, while the ready component is being attached to the chassis at the floor decking station. Roofing activities are observed to be independent from the activities of the exterior and interior finishes, where the three operations occupy three successively independent stations, as shown in Figure 4.7.
Figure 4.6 Case Study 2: Material Flow Pattern, and Activity Breakdown
Figure 4.7 Activity Relationship Diagrams at Case Study 2
The mobility system for the housing sections permits the movement in the lateral direction of the layout by using bearing-wheeled U-sections. The U-sections are attached beneath the wheels of the housing section whenever a movement to the other direction is needed.

Figure 4.4 shows the basic building units of case study factory 1. However, Figure 4.5 depicts the building units at case study factory 2. The building units are the basic stations of the assembly line associated with station processing time. The building units have direct impact on the total product (housing unit) cycle time. Additionally, the diagram of the building units shows the exact sequence of stations and dependencies between the different operations running within the factory shop floor. The station processing times are collected from the real system.

4.3.2 Basic Building Units of a Generic System for MH Operations

The generic system shown in Figure 4.8 combines the advantages of the original two existing systems. The major operations of the integrated system are rescheduled by paralleling the two double stations 6-7 and 8-9 with the stations: 2, 4-5, and 10-11, as shown in Figure 4.8.
**Figure 4.8** Generic U-Shape System

1. **Decking & Tile:** Glue-vinyl tile, load cabinets & various materials.
2. **Interior Wall:** Interior walls insulation, all.
3. **Double station:** Fixtures, vent & GFI, foam, carpet, drapes & mirrors, vacuum carpet, kitchen appliances, remove belly carts.
4. **Exterior Wall Feeding:** Ext. EW & SW, Ext. MW.
5. **Material Storage:** Cleaning, testing, and shipping.
6. **Framing & Wheels:**
7. **10-11 Roofing Ext. & Int.:** Roof decking (cont.), paper cover and shingles, exterior boards, exterior siding.
8. **8-9 Roofing Ext. & Int.:** Roofs, installation, exterior placement, fix face board.
9. **14 Appliances:** Fixtures, vent & GFI, foam, carpet, drapes & mirrors, vacuum carpet, kitchen appliances, remove belly carts.
10. **14 Appliances, Double station:**
11. **8-9 Roofing:**
12. **10-11 Roofing:**
13. **14 Appliances:** Fixtures, vent & GFI, foam, carpet, drapes & mirrors, vacuum carpet, kitchen appliances, remove belly carts.
14. **15 Cleanup & Testing:**
15. **Material Storage:**
16. **Appliances Storage:**
17. **IN**
18. **OUT**
Figure 4.9 Combined Efficiencies of the Two Systems

Figure 4.10 Paralleling 6-7 and 8-9 with 2, 4-5, and 10-11
Figure 4.11 Paralleling Station 14 with Station 15

Figure 4.12 Paralleling Station 2 with Station 4-5 and Time Scale the Operations
Table 4.4 Stations and Respective Activities of the Streamlined System

<table>
<thead>
<tr>
<th>Station 1</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Setting Floor &amp; Cut Edges</td>
</tr>
<tr>
<td>B</td>
<td>Glue Frames &amp; Transfer boards</td>
</tr>
<tr>
<td>C</td>
<td>Drill Holes &amp; Fix the Boards</td>
</tr>
<tr>
<td>D</td>
<td>Fix the Boards in Place</td>
</tr>
<tr>
<td>E</td>
<td>Sanding the Surface</td>
</tr>
<tr>
<td>F</td>
<td>Finish</td>
</tr>
<tr>
<td>G</td>
<td>Transfer to Interior Wall Station</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 2</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Floor Vinyl Tile &amp; Cover</td>
</tr>
<tr>
<td>B</td>
<td>Cabinets &amp; Plumbing</td>
</tr>
<tr>
<td>C</td>
<td>Interior Wall Setting</td>
</tr>
<tr>
<td>D</td>
<td>Transfer to Exterior Wall Station</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 4-5</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Side Wall A</td>
</tr>
<tr>
<td>B</td>
<td>Marriage Wall A-B</td>
</tr>
<tr>
<td>C</td>
<td>End Wall A-B</td>
</tr>
<tr>
<td>D</td>
<td>Side Wall B</td>
</tr>
<tr>
<td>E</td>
<td>Plumbing</td>
</tr>
<tr>
<td>F</td>
<td>Main Electric Cabinet</td>
</tr>
<tr>
<td>G</td>
<td>Interior Wall Insulation</td>
</tr>
<tr>
<td>H</td>
<td>Interior Wall Joint Tape</td>
</tr>
<tr>
<td>I</td>
<td>Exterior Wall Wire Insulation</td>
</tr>
<tr>
<td>J</td>
<td>Interior Wall Paint</td>
</tr>
<tr>
<td>Station 6-7</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>A</td>
<td>Kitchen Cabinets Installation</td>
</tr>
<tr>
<td>B</td>
<td>Fireplace Installation</td>
</tr>
<tr>
<td>C</td>
<td>Wire Insulation</td>
</tr>
<tr>
<td>D</td>
<td>Exterior Wall Joint</td>
</tr>
<tr>
<td>E</td>
<td>Bathroom Face board</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 8-9</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fixing Roof Truss A</td>
</tr>
<tr>
<td>B</td>
<td>Fixing Roof Truss B</td>
</tr>
<tr>
<td>C</td>
<td>Insulation of Roof A</td>
</tr>
<tr>
<td>D</td>
<td>Insulation of Roof B</td>
</tr>
<tr>
<td>E</td>
<td>Interior Wall Face Board</td>
</tr>
<tr>
<td>F</td>
<td>Ceiling Wiring</td>
</tr>
<tr>
<td>G</td>
<td>Trim Interior Doors</td>
</tr>
<tr>
<td>H</td>
<td>Exterior Wall Boards</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 10-11</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fix Fire Place</td>
</tr>
<tr>
<td>B</td>
<td>Wire Insulation</td>
</tr>
<tr>
<td>C</td>
<td>Exterior Wall Joint</td>
</tr>
<tr>
<td>D</td>
<td>Fix Bathroom Face Board</td>
</tr>
<tr>
<td>E</td>
<td>Roof Decking</td>
</tr>
<tr>
<td>F</td>
<td>Exterior Windows &amp; Doors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 14</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Paint Cleanup &amp; Touchup</td>
</tr>
<tr>
<td>B</td>
<td>Drapes</td>
</tr>
</tbody>
</table>
In Figure 4.11, station 14 and station 15 are scheduled to be in parallel. The final step of streamlining the major operations of the existing system is to schedule station 2 and station 4-5 to be in parallel as shown in Figure 4.12. Furthermore, a time scale is imposed on the scheduled operations shown in Figure 4.12. Table 4.4 presents all the stations of the streamlined system and their respective activities.

The optimization model for the overall production system employs the streamlined system shown in Figure 4.12. However, this should be preceded by optimizing the station cycle time of each block (station) shown in Figure 4.12. The following section illustrates the optimization model method and formulation. The section includes an application example on the activity level for one of the main stations of the production line.
4.4 AN OPTIMIZATION MODEL FOR MH SYSTEMS USING THE CRITICAL PATH METHOD (CPM)

This section presents the optimization model, which is developed specifically for MH production processes. The model provides an efficient tool for the manufacturers in evaluating and streamlining their systems for potential resource-waste that could hinder the overall system performance. Manufactured Housing (MH) production systems are not balanced. Optimizing the production process is an essential step in identifying minimum processing times required for the stations and the system. Moreover, minimum processing times identify a system that has a minimum product cycle time, hence, maximum productivity. The proposed model uses the Critical Path Method (CPM) for locating the critical path of activities that control the total time of the respective station. Arrow diagrams are prepared for the activities at each station. Activity tables include the required sequence and existing dependencies among the activities.

The optimization model is used in analyzing the production process of an existing MH facility and includes the main stations and their respective activities in the final assembly line. The optimization model offers a front line tool for evaluating and streamlining the overall system performance, thus targets the overall system improvement. Simulation models that were developed in the previous chapter have employed the results of the optimization model as input data for the simulation model. However, the optimization model provides a basic tool to balance the loads, and to compare the work allocated to each resource within the available time frame. Static evaluation models (e.g., optimization models) assume a deterministic environment (i.e., predictable schedules, no breakdowns, and part availability). These models do not include dynamic interactions in the system. However, they provide a rough estimate of the system performance. Deterministic outputs of the optimization model can be used later as inputs to the
simulation models. Therefore, the production manager can obtain an evaluation of dynamic interactions of the system (Mahmoodi 1999).

The overall goal of modeling MH operations is to improve the productivity of MH production systems, by identifying minimum times required for the construction operations involved in producing the MH. Improved productivity would consequently improve the affordability of manufactured homes in order to continue serving the crucial demand of the middle and low-income households in the United States.

The specific goal of this section is to develop a model that can be used to streamline the activities at an MH production system. The production manager can input: (i) processing times and (ii) number of workers associated with each activity. The following can be obtained as outputs: (i) the minimum time required for that station to process the product (station cycle time) and (ii) the minimum time required for the system to finish the product (product cycle time). Furthermore, the production manager can manipulate the system variables by paralleling critical operations or adding resources to lagging operations, in order to decrease the overall time and, thus, increase the overall system productivity. Since the system employs a model mix manufacturing process, the model inputs and the model outputs are mean values of the performance measures. Although the optimization model provides a rough estimate of the system performance, parameters of the deterministic time/labor outputs of the optimization model can be used later in the other type of evaluation (i.e., the simulation model), in order to evaluate the other dynamic interactions of the system that this method alone cannot predict (Mahmoodi 1999).

An optimization model is developed using the critical path method (CPM) to achieve the above goal. CPM was first proposed and used by the U.S. Navy in the year 1958 in scheduling
their operations. The CPM theory was consistently evolving since that time until it was finally used for scheduling the construction activities. Moreover, the critical activities are the serial activities that control the overall time of the operation, and on a bigger scale, the project due date. A delay in any critical activity within a certain amount of time causes a delay to the project with the same amount of time.

The optimization model can be used by the production manager as a tool to reschedule the manufacturing operations by changing the system variables: activity processing time, number of workers, and station cycle time. System alteration and system reconfiguration can be conducted to balance the loads and to solve the system bottlenecks with the help of the simulation model. The optimization objectives are as follows:

1) Finding the minimum processing time needed by the station and the system,
2) Planning the activities and operations,
3) Finding the critical path for the activities and operations using a fixed-labor content per station without violating the required sequence of the activities or operations,
4) Manipulating the system by crashing the lagging activity of the operation, in order to reduce the operational cycle time, based on the bottleneck analysis results conducted via the simulation model.

4.4.1 Model Formulation

*Variables*

The decision of “when to begin and end each of the activities” is a main variable involved in the scheduling process. Nodes are used to model the start time and end time of the activities. Nodes are defined as discrete events in time. In other words, they occur at one exact point in time. The decision variables are the time values for the events \( r_i \). The term \( r_i \) is defined as the
time at which node \( i \) occurs; \( t_i \) is the time at which all activities preceding node \( i \) have been completed. \( t_0 \) is always equal to zero (i.e., the first activity at any station starts at time zero).

**Constraints**

i) Each activity has a fixed duration (mean value of the real data).

ii) Precedence relationships among the activities should be respected.

iii) Time values should be always > 0.

**Optimization Constraint**

There is only one constraint. For each activity \( x \), let the time of its starting node be represented by \( t_{sx} \) and the time of its ending node be represented by \( t_{fx} \). Let the duration of activity \( x \) be represented as \( d_x \).

For each activity \( x \), \( t_{fx} - t_{sx} \geq d_x \)

For each node \( i \), \( t_i \geq 0 \).

4.4.2 The Optimization Model for the Activity Level

The first step in developing the optimization model for the activity level is to draw the arrow diagram as shown in Figure 4.13. Arrow diagrams are prepared for the activities, based on the activity relationship flow charts prepared during the data collection process shown in Figure 4.7. Arrow diagrams are prepared for each block (station) of the flow chart shown in Figure 4.12.

**Demonstration Example**

The optimization model for the floor-jig station will be demonstrated in this section. Table 4.5 depicts the activity information at the floor subassembly station. The third column of the table is the activity duration.
Table 4.5 Activity Information at the Floor Subassembly Station

<table>
<thead>
<tr>
<th>ID</th>
<th>Activity</th>
<th>Duration (minutes)</th>
<th>Predecessors</th>
<th># of Workers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Water Proof</td>
<td>1.147058824</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>Rock Wool Insulation</td>
<td>1.235294118</td>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>Heat Duct and Networks</td>
<td>2.058823529</td>
<td>B</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>Drainage and Maine Frame</td>
<td>17.17647059</td>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>Intermediate Joists</td>
<td>18.20588235</td>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>Fix water proof to MF</td>
<td>4.941176471</td>
<td>E</td>
<td>2</td>
</tr>
<tr>
<td>G</td>
<td>Lift Ready Floor to Hopper</td>
<td>1</td>
<td>G, D</td>
<td>1</td>
</tr>
</tbody>
</table>

Activity durations are the mean value of the data that is collected from the existing case study factory 2. The fourth column, namely: predecessors, lists the activities that should be finished before the start of each activity. The fifth column lists the number of workers working at each activity. The total number of workers at the station can be computed by summing up the workers of the paralleled activities. Eight workers are assigned to the floor subassembly station, since the three activities E, C, and D are in parallel. Therefore the total number of workers at this station is equal to the sum of: 3, 4, and 1, respectively. Activity E is found to be in series after activity D and before activity F. Additionally, the duration of activity E is approximately 18 minutes. The process is redesigned by paralleling activity E with the system by assigning an extra worker to be in charge of activity E. Thus, the station time is decreased by 18 minutes.

Figure 4.13 shows the arrow diagram of the activities at the floor jig station. The circles are the nodes (events) and the rectangles are the activities. Node zero is the start event of activities A and E. However, node 1 is the end event of activity A, and, at the same time the
starting event of activity B, etc. The arrow diagram provides a flexible tool for scheduling the activities. The scheduler can parallel any activity that might be in series with the other activities, in case a time reduction is required for balancing the station time with the other stations.

**Figure 4.13** Arrow Diagram for the Activities at the Floor Jig Subassembly

![Arrow Diagram](image)

**Figure 4.14** Optimization Model for the Floor Subassembly Station
Figure 4.14 shows the optimization model structure using the spreadsheet. The information of Table 4.5 is filled in the spreadsheet table; in addition, a matrix of zeros, ones, and negative ones is prepared to set up the model constraint. The green column K19:K25 includes sum product functions that multiply each row Dx-Jy with the row D16:J16 for setting up the model constraint.

However, the matrix of zeros, ones, and negative ones (D19:J25) is a means for setting up the two constraints: \( t_{fx} - t_{sx} \geq d_x \) and \( t_i \geq d_x \)

![Spreadsheet Image](image-url)

**Figure 4.15** The Objective Function and the Model Constraints

The sum product functions in K19:K25 calculate the elapsed time between relevant pairs of nodes corresponding to the various activities. The duration times of the activities are in
Figure 4.16 Report Types Selection

Figure 4.16 shows the solver results window, where the reports of interest are selected. Excel provides the following reports: the answer report, the sensitivity report, and the limits report. Figure 4.17 shows the optimization model results. The time values of the events are
shown in cells E16:J16. The time value of the last event t6 at cell J16 is the minimized time of the station. The optimized station time is equal to 25.5 minutes. However, the original mean station cycle time of the data is equal to 43.7 minutes. Therefore, a substantial station time reduction of 18.2 minutes is achieved using the optimization model. Figure 4.18 shows the answer report provided by Excel. The answer report lists the slack data of the activities, where the critical activity has a zero slack value.

Figure 4.19 shows the sensitivity analysis report of the model results. The sensitivity report is provided by Excel.

Figure 4.17 The Optimization Model Result
### Figure 4.18 Answer Report and the Critical Activities

![Image of Answer Report and Critical Activities](image1)

### Figure 4.19 Sensitivity Analysis Report

![Image of Sensitivity Analysis Report](image2)
4.4.3 The Optimization Model of the Overall Production System

Figure 4.20 depicts the arrow diagram for the streamlined system, presented in Figure 4.12. Figure 4.21 depicts the optimization model of the streamlined system. The optimization table contains the station information: sequence, existing dependencies, and duration. The duration of each station is linked to the optimized cell of the micro optimization model developed specifically for the station. The matrix of zeros, ones, and negative ones is prepared to set up the model constraint, as is explained in the preceding demonstration example. The value of t0 at cell D245 is set at zero. Finally, the sum product functions are included in cells K248:256.

![Figure 4.20 The Arrow Diagram of the Production System](image)

Figure 4.22 displays the solver parameters, in which the target cell I242 is set to be minimized by changing the values of the cells E245:J245. Then the model constraints are added to the solver menu.

Figure 4.23 shows the sensitivity analysis report provided by Excel. The report indicates the stations on the critical path having zero slack value. The critical stations are: floor decking, exterior wall, three roofing stations, and appliances. The non-critical stations are: floor subassembly station, interior wall station, and interior finishing station. The non-critical stations have a slack value of 34.63 minutes, 9.56 minutes, and 100.81 minutes, respectively.
Figure 4.21 The Macro Optimization Model of the Production System

Figure 4.22 Setting the Solver Parameters
Figure 4.23 Answer Report

Figure 4.24 depicts the limits report, which provides the values of the target cell and the values of the adjustable cells t1-t6. In addition, the report provides the upper and lower values of the adjustable cells.

Figure 4.25 shows the sensitivity analysis report of the optimization model. This report provides information about the allowable increase and allowable decrease values for all events t1 to t6. Additionally, the same parameters are provided for all the stations.
Figure 4.24 Limits Report

Figure 4.25 Sensitivity Report
The product cycle time is the total time needed to process the housing unit inside the factory. The optimal (minimum) product cycle time is equal to 312 minutes, compared to the cycle time of the housing section inside the production line (at case study 2), which is equal to 960 minutes (2.28 working days).

4.5 SUMMARY

An optimization model is developed for manufactured housing production processes. This model offers a low cost tool for evaluating the system performance. Moreover, it provides an effective tool for balancing the work loads of the stations. This paper presents a real time
optimization model, which targets minimizing the overall system cycle time (at the macro level), by minimizing the station cycle times (at the micro level). The overall system cycle time reduction would lead to improving the productivity of the manufacturing system. The inputs of the deterministic optimization model are the mean processing times of the activities. The output is the optimal station cycle time (at the micro level) and the optimal product cycle time (at the macro level). The model is programmed using Excel spreadsheets.

Although the optimization model provides a rough estimate of the system performance, outputs of the optimization model can be used later as inputs for the simulation model. Thus, the simulation model would employ accurate data, in order to evaluate the dynamic interactions of the system that optimization models alone cannot predict (i.e., average station queue time, number of products waiting in queue, production, and resource-station utilization, etc).

An optimization model is developed using the critical path method (CPM), which is only used for scheduling construction activities. Moreover, the critical path describes the serial activities that control the overall time of the operation and, on a larger scale, the project due date. The objective function involves minimizing total station cycle time at the micro level, which results in total product cycle time reduction at the macro level. The model constraint is that the sequence requirement must be respected in scheduling the station activities at the micro level and the system stations at the macro level.

The proposed optimization model provides a flexible tool for the production manager to schedule the manufacturing activities in a balanced and streamlined manner. Finally, it is concluded that the optimal cycle time of the production system is equal to 312 minutes. However, integrating the results of this model with simulation models is essential to obtaining accurate estimates of the dynamic variables of the system.
4.6 CONCLUSIONS

The following steps, concluded from the comparative analysis of the two MH systems, are used to streamline the production process of any existing MH system:

1- Employ a minimum number of serial assembly line stations, relative to the four major operations needed to construct the MH unit. The assigned assembly stations should be backed up by an adequate number of subassembly stations and workshops to prepare the raw materials and provide required components. The following procedures can be applied to facilitate the achievement of the above goal:

A) Move stations from the assembly area to the subassembly area. For example, in case study 1, the floor building station becomes a feeder station in case study 2. This arrangement reduces the production cycle time by the amount of that station’s processing time.

B) Split activities requiring a large number of workers in one station into two distinct parallel sets of activities distributed at a station and a feeder station. This process will improve mobility of workers in the station with a large number of activities (e.g., station 1b in case study 1 layout). Additionally, this would reduce the processing time of the original station.

C) Merge a station requiring a small number of workers with the preceding or following stations. For example, station 2 in case study 1 includes a single activity of one worker. However, in case study 2, this single activity is merged with the activities in the following station (i.e., the interior wall station). The advantage of this step is to reduce the total number of stations and transition time from one station to the next. In addition, the elimination of a station reduces the production area needed for manufacturing.

2- Integrate the operation having a long cycle time throughout the production line (i.e., the drywall painting operation in case study 2).
3- Reduce the longest station cycle time by paralleling the activities as much as the sequence and assigned resources will permit. For example, in case study 1, painting exceeds 8 working days. However, in case study 2, painting is integrated simultaneously with other assembly and subassembly operations.

4- For each activity, use the material handling system having the shortest transition time. Furthermore, the mobility system for moving the sections from station to station should be automated to replace existing non-efficient systems (e.g., the air pads in case study 1). Mechanical systems solving the problem of transferring the housing sections from station to station should be considered.

5- Use double-section processing, *i.e.*, processing of the two housing unit sections simultaneously at a station. This method is applied in case study factory 2 after the interior wall station. The double-section processing offers the following advantages:

A) Elimination of the in-station queue time by providing two products for assembly. If the work stalls in one section, it could continue in the other.

B) Increases the capacity of the station without any accompanying increase of the resources. Greater efficiency in utilizing the material handling system, *i.e.*, moving the two sections together, rather than in succession.
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CHAPTER 5
EFFICIENT PRODUCTION PLANT LAYOUT (INNOVATIVE DESIGN ALTERNATIVES FOR MH FACILITIES)

5.1 INTRODUCTION

This chapter discusses the production plant layout of four distinct design alternatives. A streamlined process, using existing case study factories, is developed in Chapter 3. This streamlined process is the generic process for MH production systems, which include the minimum number of basic stations (building blocks). The building blocks are real components of real systems that have: (i) a defined relational flow, (ii) defined durations, (iii) defined work content or activities, and (iv) a defined number of workers responsible for each activity. As explained in Chapter 4, the generic scenario of the activities’ sequence at each building block can be altered, for balancing purposes, using the optimization model. A scenario is a specific ordering of the activities (depicted by the arrow diagram) at each building block. Different activity relationships form new scenarios, which can be proposed for balancing the entire system. The optimization model is an efficient tool for keeping track of the workforce assignments for a specific scenario. The purpose of optimization is to reduce the processing time of the building block (station), indicated by the simulation model run results, through a bottleneck analysis. Therefore, each design alternative can be balanced, using the optimization model based on the simulation model run results. An independent simulation model is developed specifically for each design alternative. Thus, the exact change in the workforce needed for each design alternative can be determined through this method.

The first alternative design is the generic U-shape system, which is an efficient production system employing the generic building blocks. The generic U-shape system is
considered to be a design alternative, because it combines all the efficiencies observed at the two case study factories and eliminates their drawbacks. Moreover, this system is considered to be a generic system for U-shape MH factories. A simulation model is developed for the generic U-shape layout, in order to measure the performance of the new system.

The methodology steps shown in Figure 5.1 are followed to generate the alternative designs for the other layout alternatives: the spine layout, the J-shape layout, and the central layout.

![Methodology Steps Diagram](image)

**Figure 5.1 Methodology Steps**

A conceptual diagram is developed to solve a specific problem or set of problems observed at existing MH systems. A sequence diagram superimposes the building blocks upon the conceptual diagram. The material flow of the new system defines the material handling
system and the control system. The next step is to balance the system by using the optimization model and the simulation model of the new design. First, the run results of the simulation model are observed for potential process bottlenecks. Then the optimization model for the most severe bottleneck station is used to minimize the total station cycle time by reordering the activities at the station or by crashing one or more of the critical activities at the station. The new cycle time is entered in the simulation model menus. Run results for the modified SM are checked again for new bottlenecks. The process is repeated, using the two models until the system has no bottlenecks. Finally, the performance of the new design is compared with the performance of other existing systems.

Figure 5.2 illustrates the three main steps included in the flow chart of Figure 5.1. This figure shows the design process of a new system, based on the knowledge gained through existing systems. The two boxes in Figure 5.2, highlighted by an ellipse, are further illustrated in Figure 5.3.
Four distinct system designs are proposed and documented in this chapter. Although the four systems use the streamlined building units, each system has a different flow pattern, a different capacity limit (productivity), and a different size of resources at the assembly and subassembly stations. Simulation models are developed to model the final assembly stations, assuming that the subassembly stations are capable of supplying the required semi-assembled components, just in time. Furthermore, each design alternative follows an algorithmic (heuristic) approach. A rigorous analysis of MH problems and the specific nature of MH processes, conducted in Abu Hammad 2001, are employed in this approach.

5.2 EFFICIENT PLANT LAYOUT ALTERNATIVES

Generating efficient systems involves a two-fold rigorous analysis of existing systems: The first one analyzes the efficiencies and drawbacks of real systems, *i.e.*, the needs and problems of existing MH production systems. The second one proposes system solutions for the observed problems using a heuristic approach. The word “heuristic” is derived from a Greek
word meaning “discovery.” Heuristics are decision rules (rules of thumb), governing how a problem should be solved. Design guidelines for each design alternative are presented at the end of this chapter. These guidelines include a trial-and-error experience to describe the specific procedures followed in reaching the targeted solution (Turban 2001).

Figure 5.4 depicts a conceptual framework for the algorithmic process. Alternative generation employs a proposed idea (conceptual idea) to transform the whole system (Turban 2001). According to Figure 5.4, testing of the generated solution is a major step in measuring the performance of the advanced system. The alternative design is transformed into a defined scenario. A “scenario” is a statement of assumptions about the operating conditions of a system and the decision-situation setting. A scenario describes the uncontrollable variables and parameters of a model and may provide procedures and constraints for the model (Turban 2001).

![Algorithmic Process for Developing an Optimal Solution](source)

**Figure 5.4** An Algorithmic Process for Developing an Optimal Solution

Source: Turban 2001, pp.59

Scenarios can be done through goal-seeking analyses and what-if scenarios. What-if scenarios cover a whole range of possibilities and illustrate what will happen to the solution if an input variable, an assumption, or a parameter value, is changed. Scenarios are conducted through what-if analyses using simulation (Turban 2001).
Figure 5.5 combines the two above concepts of using heuristics in a layout generation process, which is tested via a simulation. This figure presents the testing process by using a simulation model that can further be used in conducting what-if scenario analyses to locate and solve the system bottlenecks. Figure 5.5 depicts the logic of generating alternatives using existing case studies. The logic starts with understanding how existing MH systems operate. This step is achieved through analyses conducted by Abu Hammad (2001) and explained through the comparative analysis presented in Chapter 4. Furthermore, this step assists in defining the flow and configuration of the virtual system. The next step is to design the shop floor configuration and the material handling system. The new layout is tested via simulation. Bottleneck analyses
are conducted, in case the desired performance is not reached. Bottleneck analyses using simulation involves system modifications, followed by continuous testing by observing the effect on the model performance measures. Finally, the process ends when the required performance is achieved (desired production level).

The following sections discuss each layout design alternative and the simulation model developed specifically for each alternative.

5.3 THE GENERIC U-SHAPE LAYOUT

The comparative analysis shows that the integration of parallel processing with a minimum number of stations will reduce substantially the total product cycle time. Figure 5.6 shows the generic U-shape layout. This layout will be simulated, in order to test the performance of the new system. Finally, the performance results will be compared with the productivity of the original two systems.

5.3.1 Shop Floor Layout Description

The generic MH layout design depicted in Figure 5.6 below, shows respective lists of activities per station. The layout includes thirteen assembly stations, numbered relative to the station sequence of the case study 2 system: (0) frames and wheels, (1) floor decking, (2) interior wall, (4-5) exterior wall, (6-7) roofing, interior and exterior finish 1, (8-9) roofing, interior and exterior finish 2, (10-11) roofing, interior and exterior finish 3, (14) appliances, (15) clean up and testing.

The above assembly stations are assumed to be backed up by a sufficient number of subassembly stations and raw material workshops. The material handling system consists of cranes and forklifts. Belly carts laterally move the housing sections. However, the permanent wheels underneath the units move the sections to the other direction. A comprehensive analysis
and modeling is performed in the following section to test the performance of this proposed system.

The generic U-shape layout employs the exact number of building blocks, developed in Chapter 4. However, the detailed flow of the activities is presented in the following section. Figure 5.6 depicts the shop floor layout of the system showing the main assembly stations and their respective activities.

**Station 0: The Decking Station**

One worker attaches the outrigger frames (which support the exterior walls) to the four sides of the metal chassis. Another worker fixes the remaining wheels to the axles of the chassis. These wheels are used as a permanent mobility system for the housing section inside the factory and for transportation on the highway.

**Station 1: The Decking Station**

The floor components are delivered by the floor subassembly station (floor jig) and are attached to the metal chassis at this station. Four workers apply glue to the top side of the floor primary frame and secondary frames. A fifth worker, who is responsible for attaching the floor to the chassis, cuts openings in the sides of the main frame to connect the heat duct branches with the other housing section. Two of the five workers spread the floor boards. Then they open holes through the floor boards and pull the ends of the installation lines (*i.e.*, water pipes and electric roughing wires) through the openings. Three workers staple the boards to the previously glued primary frame and secondary frames.
Figure 5.6 Generic U-Shape Layout
Figure 5.7 Station 2: Floor Decking

One worker sands the floor board joints after hammering down uneven stapling. Another worker applies adhesive material to the areas underneath the vinyl tile; then he applies water insulation material around the exterior edges and drainage openings inside the floor. The other two workers cut the vinyl tile sheets and fix them in place; then they cover the tile sheets with a nylon cover to protect the tile throughout the following processes.
**Figure 5.8** Station 2: Interior Walls

**Station 2: Interior Wall, Side Wall of A, End Wall of A**

Section A enters station 2; the three processes of interior partitions, side walls, and end walls take place simultaneously (parallel processes). Section A moves directly to station 5. During this time the second part of the house (section B) enters station 2. Only the interior partitions are placed on top of section B. Section B then moves to station 4, to join (match) section A at station 4-5.
Figure 5.9 Station 4-5: Exterior Walls

Station 4-5: Exterior Walls (Double Station)

At this station, the two parts of the house are joined together. The two sections are split at station 12.

Only sections of type B are processed at station 2. Two workers fix the components of end walls, marriage wall, and side wall at the four edges of section B. Only sections of type A are processed at station 5. At this station the interior face boards are fixed, followed by the paint sub-activities, electricity, and plumbing. The marriage wall is fixed and matched with the marriage wall of section B.
Station 6-7: Roofing (Double Station)

The two sections of a one full house enter to station 6-7. Truss A is fixed on top of section A, followed by fixing truss B on top of section B. The two trusses are matched together on the housing units while they are insulated by rock wool material pumped through a 4 inch-hose. The interior finishing activities (i.e., upper cabinets, interior doors and frames, panels, ceiling cornice, and fixing the interior face boards,) are processed at the same time with the exterior finishes (i.e., exterior wall boards and engrave the exterior windows and doors) and the above roofing activities.
Figure 5.11 Joining the Two Housing Sections at Station 4-5

Station 8-9: Roofing (Double Station)

Three parallel operations take place at station 8-9: the roofing activities (i.e., fixing the ceiling electrical wires and the roof deck boards), interior finishes activities (i.e., fixing the fireplace, fixing the face boards at the bathrooms), and exterior finishes activities (i.e., fixing the exterior wall joints and fixing the exterior windows and doors).

Station 10-11: Roofing (Double Station)

Three parallel operations take place at station 10-11: the roofing activities (i.e., fixing the remainder of the roof deck boards and fixing the paper cover and roof shingles), interior finishes activities (i.e., fixing the carpets, drapes and mirrors), and exterior finishes activities (i.e., fixing
the exterior wall siding).

**Station 14: Appliances**

The two housing section are split at this station. Additionally, the belly carts are removed from underneath the wheels to move the units to the other direction. Finally, the kitchen appliances are fixed in place between the kitchen cabinets.

**Station 15: Final and Clean Up**

The shipping parts are included with each housing unit. The housing units are covered with nylon sheets to protect the unit while it resides in the storage area and shipped on the highway. Final interior cleaning of the housing units is done at this station. Finally, all the fixtures, appliances and installations are tested at this station. The swing group or worker fixes any problems discovered through inspection before the housing unit is ready to be shipped out of the production line.

**5.3.2 Simulation Model for the Generic U-Shape Layout**

A simulation model is developed for the first layout alternative using Arena software. The modeling logic used for developing the two simulation models for the existing factories is modified to include the predefined building blocks for the generic U-shape system.

The logic of flow of this model is as follows: all the entity types are created in the arrive module. Every two section of the double bay housing units are then matched together, in order to follow each other throughout the assembly line servers (*i.e.*, stations). Then the two housing sections are batched to become one entity before entering server 4-5. The two bay housing sections are then processed simultaneously at the servers 4-5 up to 10-11. The two entities of the two bay housing units are then detached and they enter stations 14 and 15 independently and successivley. The entities exit the model at the depart module where all the performance
measures are collected at this module.

Figure 5.12 Simulation Model Display for the Generic U-Shape Layout

Figure 5.12 depicts the simulation model for the U-shape system. The model modules are arranged as follows:

1) Arrive Module: generates entities of 5 types (entity sizes) according to the different product sizes.

2) Choose, Pick Queue, and Match Modules: The function of this cluster of modules is to match every two sections of types A and B, in order to follow each other through the first two stations of the assembly line.

3) Server Modules: The server modules simulate different station processing times. All
processing times are entered in the sequences module menu.

4) Batch Modules: The function of these modules is to join the two housing sections into one entity. Then each two united entities are processed simultaneously at the following stations of the assembly line.

5) Split Module: This module is used after server 10-11 to split the two sections.

6) Depart Module: the function of this module is to collect all performance measures of interest (i.e., production, cycle time, average queue time).

5.3.3 Run Results and Analysis

Figure 5.13 shows the production counter results. The U-shape system’s productivity over a one week period at 5 working days per week, at 7 hours per day, is equal to: 14, 8, 10, 10, and 6 for the 45 ft. sections, 55ft. sections, 65ft. sections, 75ft. sections, and 85ft. sections, respectively. The total production rate of the new layout is the summation of the above production rates per section sizes (i.e., 48 sections per week).

<table>
<thead>
<tr>
<th>COUNTERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier</td>
</tr>
<tr>
<td>floors 65 ft production</td>
</tr>
<tr>
<td>floors 75 ft production</td>
</tr>
<tr>
<td>floors 85 ft production</td>
</tr>
<tr>
<td>floors 45 ft production</td>
</tr>
<tr>
<td>floors 55 ft production</td>
</tr>
</tbody>
</table>

**Figure 5.13** Production Counter Results for the U-Shape Generic Layout

Figure 5.14 shows the average section cycle time in the system. That is the average time the section spends inside the system from the entry point, in the form of a metal chassis, until it is shipped out in the form of a finished housing section.

The average cycle time for each product size is as follows: 860.25 minutes, 677.89
minutes, 873.86 minutes, 905.71 minutes, and 725.54 minutes for the 45ft., 55ft., 65ft., 75ft., and 85ft., respectively.

The housing unit sizes of 75ft. length have the maximum average cycle time of 905.71 minutes. That is equal to 2.15 days, which is the result of dividing the cycle time value (in minutes) by 420 (60 multiplied by 7). However, the average cycle time of the full house (two sections) should be more than that of one housing section.

<table>
<thead>
<tr>
<th>ARENA Simulation Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ayman Abu Hammad - License #9400000</td>
</tr>
</tbody>
</table>

Output Summary for 100 Replications

<table>
<thead>
<tr>
<th>identifier</th>
<th>Average</th>
<th>Half-width</th>
<th>Minimum</th>
<th>Maximum</th>
<th># Replications</th>
</tr>
</thead>
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<tr>
<td>TAVG(FLOORS 65 FT CYCL 873.73</td>
<td>277.86</td>
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<tr>
<td>TAVG(FLOORS 85 FT CYCL 725.54</td>
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<td>1462.8</td>
<td>1756.0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL 677.89</td>
<td>189.56</td>
<td>1909.8</td>
<td>2989.6</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL 860.25</td>
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<tr>
<td>TAVG(FLOORS 75 FT CYCL 905.71</td>
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<td>1391.7</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.14** Product Cycle Times for the U-Shape Generic Layout Model

### 5.4 THE SPINE LAYOUT

The spine design proposes an efficient production plant layout. This design employs the efficient production process developed in Chapter 4. Moreover, the design incorporates advanced theories used in industrial engineering discipline, such as the lean production theory (LPT). LPT is applied to the MH production system to generate an efficient design alternative for MH facilities. The application of LPT emphasizes cost reduction to improve the production and the overall organizational profitability. Although LPT aims to reduce cost, eliminate waste, increase capacity, and dramatically improve cycle times, vast improvement on low cost productivity is also achieved. The performance of the empirical layout can be used to evaluate the performance
of existing systems. Moreover, it can be used to design new facilities. The integration of lean manufacturing practices, process technology, and manufacturing technology, is essential in effecting an efficient production system.

5.4.1 Shop Floor Layout Description

The assembly line consists of 10 cellular stations distributed on both sides of the main spine of the assembly line. Every two opposite stations operate in parallel (simultaneously) on two sections passing through the assembly line. The resulting efficiency is a double processing operation, coupled with a dual station processing. The material flows from the right and left behind the cells and then branches out to the cells. A card system (*kanban*) is used between each two cells to control the material supply, using the advantage of a pull system. The station sequence along both sides of the assembly line is shown in Table 5.1. The scheduled operations are shown in Figure 5.15. The material handling system consists of the following components:

1. A mechanically driven assembly line with a tow cable, which drags the two lanes of sections simultaneously, as shown in Figure 5.16.

2. Forklift tractors to deliver material and pick up waste from pallets. The movement of the forklifts will use the main paths and branches of the material flow.

3. Crane systems adjusted at proper heights above each station. The cranes are adjusted for the roofing stations to permit the assembly of two-story units.

4. Truck tractors to pull the finished house from the assembly line.

5. Mechanical board containers that release one board at a time to the specific workplace. Two of these machines are needed at the floor decking station and at the roofing station.
### Table 5.1 Station Breakdown

<table>
<thead>
<tr>
<th>Left Side Stations</th>
<th>Subassembly</th>
<th>Assembly</th>
<th>Right Side Stations</th>
<th>Subassembly</th>
<th>Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frames and decking</td>
<td>Floor jigs, piping, drainage, and heat duct</td>
<td>Floor decking</td>
<td>Frames and decking</td>
<td>Floor jigs, piping, drainage, and heat duct</td>
<td>Floor decking</td>
</tr>
<tr>
<td>Interior wall</td>
<td>Cabinets, drawers, and shutters</td>
<td>Fix tile and interior wall components</td>
<td>Exterior wall</td>
<td>Bathroom, kitchen fixtures</td>
<td>Exterior walls and face board</td>
</tr>
<tr>
<td>Roofing 1 and finishing 1</td>
<td>Truss jigs</td>
<td>Fix truss and insulation</td>
<td>Roofing 1 and finishing 1</td>
<td>Truss jigs</td>
<td>Fix truss and insulation</td>
</tr>
<tr>
<td>Roofing 2 and finishing 2</td>
<td>Fix roof boards</td>
<td></td>
<td>Roofing 2 and finishing 2</td>
<td></td>
<td>Fix roof boards</td>
</tr>
<tr>
<td>Roofing 3 and testing</td>
<td>Roof shingles</td>
<td></td>
<td>Roofing 3, appliances, and clean up</td>
<td>Roof shingles</td>
<td></td>
</tr>
</tbody>
</table>

#### Figure 5.15 The Building Blocks of the Spine System
Figure 5.16 The Spine (Lean) Production System
5.4.2 Simulation Model for the Spine Layout Design

Figure 5.17 is a display of the simulation model for the spine system. The model modules are arranged according to the following order:

1) Arrive Module: generates entities of the 5 different sizes.

2) Choose and Batch Modules: The function of these modules is to join two sections, to be processed simultaneously at the different stations of the assembly line.

3) Server Modules: The server modules simulate different station processing times. All the processing times are entered in the sequences module menus.

4) Split Module: This module is used after server 10-11 to split the two sections.

Figure 5.17 Simulation Model Display of the Spine Layout Alternative
5) Depart Module: At this module all the performance measures of interest (i.e., production, cycle time, and average queue times) are collected.

5.4.3 Run Results and Analysis

The simulation model is used to test the performance of the spine layout. The upper part of Figure 5.18 shows the production counter results for 20 replications of the simulation model. The results are 16, 20, 22, 18, and 22 sections for 45ft., 55ft., 65ft., 75ft., and 85ft., respectively. The total production rate equals 98 sections per week. One week equals 5 working days, at 7 hours per day. The productivity of the spine system is almost double the productivity of existing U-shape systems. Moreover, it is reasonable to expect such improvement, because the system employs a double-section processing, coupled with a dual-station processing. These two procedures cause the cycle time to decrease substantially and, hence, allow such a high throughput.

Figure 5.18 shows the output summary of 20 replications of the simulation model. The figure shows the average product cycle time for each product size. The longest average cycle time for the 45ft. product is 12,922 minutes. However, the shortest product cycle time for the 65ft. size is 9,650 minutes.

5.4.4 Balancing the Spine System Using the Simulation Model

The substantially long product cycle times imply a further analysis of the system bottlenecks. Thus, Figure 5.18 shows the results of the tally-variables. The figure shows the following average queue times at each station: 59.3, 6.1058, 1706.4, 13.801, 1709.3, 15470, and 0.000 minutes at stations 1, 2, 4-5, 8-9, 10-11, 14, and 15, respectively. Therefore, the run results indicate a severe bottleneck at station 14, which has a maximum queue time of 15,470 minutes in one week of operation.
A what-if scenario analysis is conducted by trial and error, using the simulation model. The processing time of station 14 is changed, and the resulting bottlenecks are observed.

![Simulation Model Output](image)

**Figure 5.18** Output Performance Measures for the Spine Layout Model

The simulation model of the spine layout is modified by changing the processing time of station 14 to 30 minutes, instead of a mean time distribution of 45 minutes. Figure 5.19 shows the tally variables of trial 1 run results. It is observed that the average queue time of station 14
has dropped to 22 minutes over one week of operation, which is acceptable.

![Summary for Replication 20 of 20](image)

**Figure 5.19 Tally Variables of the Spine Simulation Model**
Additionally, it is observed from Figure 5.20 that station 10-11 is the most severe bottleneck, having an average queue time of 1,830 minutes. The simulation model is altered for the second time by setting the processing time of station 10-11 at 100 minutes, instead of a mean
time distribution of 192 minutes.

Figure 5.21 shows the tally variables of trial 2 run results. Station 4-5 is observed to have an indirect (transitional) average queue time of 1,802 minutes.
A transitional queue is a delay not caused by the station. It is, however, caused by (or transitioned from) a preceding or a following station. Thus, the accumulated long queue time at station 4-5 will not be removed by changing the processing time of the station. The bottleneck is...
removed by altering the processing times of the previous two stations and indirectly causing the transitional bottleneck. Therefore, the processing time of stations 1 and 2 is set at 100 minutes each, instead of 19 and 21 minutes, as before (by trial and error). Moreover, the processing time for station 14 is set at 25 minutes, instead of 19 minutes, as before (by trial and error).

Figure 5.22 shows the tally variables of trial 3 run results. The simulation model of trial 3 is a balanced system, because the system bottlenecks are eliminated by employing new processing times for some of the stations. The figure shows the following tally variables: 2311, 0.00, 13.954, 5.6117, 19.817, 18.250, and 00.02133 minutes for the stations 1, 2, 4-5, 8-9, 10-11, 14, and 15, respectively. The long queue time at station 1 (2,311 minutes) is not a severe bottleneck, which could affect performance. However, it indicates that time between arriving entities does not follow the assigned probability distribution entered in the arrive-module menu. This makes sense, because the original time between arrivals relates to the original station processing times. Since those processing times are changed by the three trials, a new time between arriving entities should be assumed, in order to match the new timing of the stations. Hence, the bottleneck at station 1 is eliminated.

Figure 5.23 shows the output summary of 20 replications of the balance spine system. The figure shows substantial reduction in the product cycle time output measures. The average 45 ft. product cycle time becomes 5,120 minutes, compared to 12,922 minutes recorded at the original simulation model of the spine layout (Figure 5.17). The actual cycle time of the 45 ft. product size equals 2,809 (i.e., 5,120 minus 2,311) minutes, where 2,311 minutes is the average queue time at station 1.
Therefore, the average queue time at station 1 should be subtracted from the average of each output value of the product cycle times (shown at the bottom of Figure 5.23) to obtain the actual product cycle times.

Figure 5.23 Output Summary of 20 Replications of the Balanced Spine System
5.5 THE J-SHAPE LAYOUT

5.5.1 Design Assumptions

1) At the subassembly station bathroom fixtures are permanently affixed to the two sides of face boards attached in advance to a tiled floor board. Thus, the bathrooms are assembled in independent modules at subassembly stations. The whole bathroom unit is then lifted by an overhead crane and positioned on top of the housing section. The assembly of the bathroom units away from the final assembly line will decrease the throughput time substantially. At the assembly station the plumber’s task is to connect the bathroom fixtures to the main lines inside the floor.

2) Interior wall partitions and exterior wall components are fully assembled at their respective subassemblies, with all electrical installations and switches, face boards, and framed doors and windows in place.

5.5.2 Shop Floor Description

Three conveyer belts deliver floor boards to three double-floor jigs. The three floor jigs are scheduled to deliver all components of one double-section housing unit every 30 minutes. Actually, it is reasonable to assume ½ hour feeding time, which allows each floor jig to produce one double-section floor every 45 minutes to 1 hour, coupled with a probable storage of one extra double-section floor every hour. The chassis entries are calibrated accordingly to deliver two chasses of one double-section house every 30 minutes. The floor components are attached to their respective chasses at the assembly station 1, shown in Figure 5.24. All related bathroom and kitchen modules are delivered to assembly station 2 from the subassemblies opposite the stations.

Wall components are set on top of the housing sections at the assembly stations 2 and 3. Similarly, the roof units are constructed in three roof jigs, where the roof boards are supplied by
three roller conveyors. The ceiling painting takes place at the three spray booths directly located opposite the three roof jigs, as shown in Figure 5.24. Finished roof sections are left by an overhead crane and placed on top of the housing units at assembly stations 4 and 5.

According to the above proposed sequence of operations and respective processing times, the double-section house moves approximately every $\frac{1}{2}$ hour from one assembly station to the next. The production capacity of this layout is expected to be approximately 16 houses per day. That is equal to 32 sections per day (i.e., 16 houses, multiplied by 2 sections per one double-bay house). Therefore, weekly production is expected to equal 160 sections (i.e., 32 sections per day, multiplied by 5 days per week).

The required raw materials are supplied to the subassembly stations via two main feeding lines, as shown in Figure 5.24. The upper flow delivers raw materials to the floor construction operations and the subassemblies for cabinets and bathrooms. The lower flow delivers raw materials to the roofing and wall subassemblies. In addition, the lower flow delivers appliances, mirrors, carpets, and fireplaces to the receiving docks.
Figure 5.24 Lean J-Shape Layout
5.6 THE CENTRAL LAYOUT

Innovative ways for advancing the MH technology are investigated through this alternative by proposing design alternatives of high throughput and then testing those virtual designs, using simulation.

The concept of this design variation is to assign an independent assembly station for each unique house. Therefore, each house will be assembled with zero waiting time, or zero number of waiting units. The number of assembly stations is determined by the required levels of productivity. On the other hand, subassemblies of similar components are fully assembled in production lines. Then the subassemblies feed the components directly to the final assembly stations. Finally, simulation is used to investigate the accrued efficiencies associated with this design configuration.

5.6.1 Shop Floor Layout Description

The assembly line consists of 3 cellular feeder stations distributed on the perimeters of a circular shape layout, as shown in Figure 5.25. Each feeder station provides ready components of floors, walls, and roofs to the main assembly line. The main assembly line is located in the middle with a capacity to process the desired number of full houses (two sections or more) up to 10 houses. Thus, the system employs a double section processing and triple station processing at the same time.

Each of the assembly line stations has 2 setters. The task of the two setters is to use the central material handling system and the conveyor belt to bring ready components from the three main feeders (floors, walls, and roof) then to assemble them according to the specified sequence.

As mentioned above, the material flow system passes alongside the assembly stations on a conveyor belt to transfer the small and medium components directly from the storage areas to
the floor decks waiting aligned in the assembly line, such as ready assembled bathroom units, furnaces, cabinets, fireplace units, trimming materials (i.e., interior doors, frames, cornices, carpets, curtains, and appliances). The conveyor belt is divided into multiple spaces. Each space is filled with components assigned to the respective house of the assembly line. The central crane system consists of multiple overlapping crane girders, which allow transferring the wall and roof components from the respective feeder stations to the assembly line stations. The girders are placed on 15 feet height above each other on a central core, and each crane moves a circular motion of 360 degrees. The station sequence along both sides of the assembly line is shown in Table 5.2.

### Table 5.2 Feeder Station Breakdown

<table>
<thead>
<tr>
<th>Stations</th>
<th>Shops</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors</td>
<td>Piping+ Drainage+ Heat duct</td>
<td>Provide ready floor units on wheeled chassis</td>
</tr>
<tr>
<td>Interior &amp; Exterior Walls</td>
<td>Cabinets+ Drawers+ Shutters</td>
<td>Build Interior wall and exterior wall components</td>
</tr>
<tr>
<td>Roofs</td>
<td>Truss Jigs</td>
<td>Assemble the truss, insulation, decking, waterproof insulation and roof shingles fixing.</td>
</tr>
</tbody>
</table>
5.6.2 Simulation Model for the Central Layout

The central layout is tested using a simulation model. Two different simulation models are developed for the central layout design. The first model consists of three arrive modules, which produce the floor, wall, and roof components at three major subassembly stations. The entities of the three types are sent to the match module. The match module consolidates the three entities (one entity of each: floors, walls, and roofs) into a single full-house entity. The three
components are provided to the assembly station that processes each component in an assigned processing time entered in the sequences module.

The above model’s shortcoming is that the different product sizes and mixes are not identified in the model logic. Thus, the next step is to develop new logic for receiving product mix data of different housing unit sizes. The product mix data for the exact sizes of the batch correspond to specific processing times at the assembly station for each product. Figure 5.26 shows the final simulation model achieving the above objectives. It includes three modules: arrive module, processor module, and leave module. The model logic is imbedded in the following modules: sets, sequences, simulate, and variables. The logic of the refined simulation model for the central layout design is as follows:

The arrive module creates three entities of double-bay house components. These entities are: floors, walls, and roofs. The batch size is set at 200 entities in the arrive module menu. The full-house entities of the five different sizes (45ft., 55ft., 65ft., 75ft., and 85ft.) are assigned to attributes (integers 1,2,3,4,5), and each integer is associated with specific cumulative percentages (1, 0.2, 0.4, 3, 0.6, 4, 0.8, and 5, 1). These cumulative percentages may vary according to the model mix variation for a study horizon of 1 week, which is equal to 2400 minutes. This number is entered for the length of replication at the simulate module.

The full house entities created at the arrive module are routed to a sequence that sends them to the assembly stations module (i.e., processor module with a capacity of 3, which is the number of assembly stations at the center of the layout). Each full house is processed by one of the three assembly stations according to an assigned processing time provided in the sequences module.

The process time is the total time: (i) to fix the floor to the chassis, (ii) the time to fix the
interior and exterior walls, and (iii) the time to attach the roof to the housing unit. The interior and exterior finishes are planned to take place simultaneously with assembling the three above operations. After the assembly of the full house entity is finished, it exits the system via the leave module. At the leave module, all the required performance measures of the entities and their journey inside the model are defined, in order to be gathered and displayed via the run report.

![Simulation Model for the Central Layout](image)

**Figure 5.26** Simulation Model for the Central Layout

### 5.6.3 Run Results and Discussion

Figure 5.27 shows the production counter of the simulation model. The figure shows a total production rate of 200 sections per week. The cycle time measures of the product in the
assembly station are shown in Figure 5.28. The cycle times are substantially less than the cycle
time of the product at case study 1 factory, which are approximately 2 days as an average. The
total product cycle time ranges from 212 to 355 minutes (3.5 to 6 hours) after subtracting the
average queue time at station 1.

<table>
<thead>
<tr>
<th>COUNTERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifier</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>House 65 ft production</td>
</tr>
<tr>
<td>House 75 ft production</td>
</tr>
<tr>
<td>House 85 ft production</td>
</tr>
<tr>
<td>House 45 ft production</td>
</tr>
<tr>
<td>House 55 ft production</td>
</tr>
</tbody>
</table>

**Figure 5.27** Production Performance Measure for the Central Layout Model

![Figure 5.27](image)

**Figure 5.28** Product Cycle Times for the Central Layout Model

### 5.7 AN ADVANCED MECHANIZATION AND MATERIAL HANDLING SYSTEM DESIGN

Previous chapters attempt to develop a streamlined production process, efficient
operation sequence, and efficient MH layout designs. In this section, mechanization of each cell
will be proposed for the spine and J-shape layouts to guarantee better work quality, higher levels of safety, and timely productivity. Mechanization solutions are specifically proposed for operations that consume excessive processing time and, consequently, cause bottlenecks. Advanced mechanization systems, based on a preliminary investigation, are suggested to allow production during unstable labor availability. Thus, a feasibility study (i.e., cost and benefit analysis) is crucial to insure that each solution justifies any additional costs. Although each mechanized station can be regarded as a generic example applicable to all types of layouts, the processing time of the machine should be balanced with other labor-driven stations. In the following section, the layout type is considered for clarity purposes.

5.7.1 Mechanization Design for a Spine Shape System

The layout under consideration is a spine layout. The two sections of the housing unit will be consolidated to travel through the assembly line simultaneously. Subassembly stations will supply preassembled components to both positions of the two remaining sections. This is accomplished by delivering components from the subassembly station to both housing sections, using an overhead crane. The factory is equipped with three overhead cranes to service the parallel stations with assembled modules. The full house is fully assembled in one pass through the proposed spine layout, Figure 5.29.
Figure 5.29 Mechanized Spine Layout
Figure 5.30 The Mobility System of the Assembly Line
5.7.2 The Material Handling and Mobility System

Permanent wheels are attached to the chasses before they enter the assembly line. The present method of moving the product through the different construction operations is completely manual; that is, the workers push the assembly from station to station. This process causes back injuries and poses other safety risks to the workers. Therefore, a sub-floor conveyor cable is provided with motion sensors to move the products through the transitional operations. Figure 5.30 depicts a possible configuration for such a mobility system. An electric motor drives the conveyor cable via pulleys. Photo sensors position the housing sections in the proper station. The sensors signal the PLC to stop the conveyor when the hitch breaks its beam. The hitch is attached manually to the cable and the chassis. Raw materials delivery to the back-line-workshops is achieved by using forklifts to deliver materials and collect waste. The components or subassemblies are delivered to the final assembly line by using three overhead cranes. Each crane covers the span of the largest product size, in addition to the required allowances.

5.7.3 Shop Floor Description

Station 1- Floor Construction

Main frame and interior frames: Two computerized floor jigs are positioned at both sides of the final assembly flow. The code of the house is provided to the jig control display, consequently, the exterior jig frames will reposition to the exact size of the house dimensions. Two workers place the water insulation sheet on the jig; they spread the rock-wool insulation and place the manually assembled networks of the heat ducts, drainage, water pipes and electric roughing inside the jig. The floor jigs are provided with spacing panels to position the interior frames on exact grid inside the main frame, the same two workers place the wood frames and joists inside the jig panels. The exterior frame of the jig is provided with spaced stapling
machines on a ruler that moves vertically on the two long sides of each jig. After putting the last frame inside the jig panel, a sensor signals to the ruler to start moving vertically and at the same time the stapling machines will attach the main frame with the interior panels of the floor assembly.

A gantry-type robot provided with two dimensional rail systems to enable the movement in two directions is equipped with attachment heads that can also move vertically to adjust to the working surface using sensory system (as shown in Figure 5.31). The robot will process multiple activities using five attachments: gluing, marking, drilling access holes, sanding and finally, auto-feed stapling gun. The same sensor that signals the stapling mechanism to initiate will simultaneously signal to the gluing head to move through a trajectory path to pray liquid glue on the upper surface of the floor frame subassembly.

**Floor Decking:** A roller conveyer is positioned at the long side of the jig and slides the flooring boards previously cut to the exact width of the house module to be assembled. A forklift feeds the conveyer with the flooring boards. In order to press the boards in place before stapling, a hydrolytic ruler compress the decking to join above the interior frames. A sensor signals to the overhead robot to change attachment to the stapling arm, and the robot attaches the deck to the sub floor by moving on the same trajectory path used for the gluing. When the arm reached the end of the loop, a sensor signals to the robot to change the attachment to the marking devise, the robot marks the places of the interior walls to be positioned in the wall construction station. After completing this activity, a sensor signals to the robot to change the attachment to the drilling devise. Consequently, the robot drills out the floor panels for all the access holes for plumbing and fixtures. The same applies for floor sanding that takes place using a large drum sanding head equipped with a brush and vacuum head that sucks up the dust and debris produced during the
sanding operation. Finally, the same robot changes heads to glue, then to fix the vinyl tile at the bathroom and kitchen areas.

Station 2: Wall Construction Assembly

The ceiling of the assembly space must be of adequate height to accommodate exterior walls being moved above interior walls already in position. The activities of fixing the exterior wall components and the interior partition wall components are carried out simultaneously.

Wall construction Subassembly: Interior wall components are to be fully assembled. Pre-wiring, including switch installation, would reduce throughput time. Pre-drilled holes for wire routing through multiple walls along with temporarily attached longer leads of wire will also decrease the time required for assembly in the station. Interior doors frames are also attached to the interior wall subassembly. The subassembly for the exterior walls should have the same strategies mentioned above.

Station 3: Roofing

Two computerized roof jigs are positioned at both sides of the final assembly flow. The code of the house is provided to the jig control display, consequently, the exterior jig frames will reposition to the exact size of the house roof dimensions. Two workers place the required material inside the jig partitions. Rock-wool insulation process is applied using two pumping hoses adjusted at the ends of the roof jigs. Roof Boards are supplied using a roller type conveyer from both sides and nailed in place. Waterproof and roof shingles are both applied using similar overhead robot arm to that used in the floor construction processes and shown in Figure 5.31.
Figure 5.31 Multi Operations Overhead Robot
5.8 GENERIC GUIDELINES FOR MH FACILITY LAYOUT

An optimization model and advanced system designs, with their respective simulation models, are proposed. The procedural steps followed in developing each layout design will be documented in this section, which also documents steps for creating a streamlined layout design for manufactured housing.

The design guidelines under study investigate the factors that contribute to overall system performance and productivity. The design guidelines are basically the procedures used in the development of the advanced layout designs.

Moreover, a set of guidelines outlining the overall layout design procedure is developed from the work done in earlier steps. Design guidelines will be presented, using checklists and flowchart techniques accompanied with a detailed description of the multiple interrelationships among the factors forming the overall process design framework.

It is important to develop generic guidelines for a manufactured housing plant layout design, which can be used by the industry to evaluate various alternatives for its specific factory and production needs. From the previous work the detailed process of manufactured housing production will be compiled, and design guidelines will be developed. Design guidelines are presented in the following sections under three major topics: i) a lean manufacturing system, ii) streamlining an existing system, and iii) design guidelines developed specifically for the four layout-design alternatives: the generic U-shape system, the spine layout, the J-shape layout, and the central layout.
5.8.1 Guidelines for a Lean Manufacturing System

Figure 5.32 presents a framework for a lean manufactured housing production system. This framework is divided into three levels: coordination, execution, and formulation. These levels define requirements, implementation procedure, and physical output, respectively.

![Diagram of Lean Manufacturing System Framework]

**Figure 5.32** Generic Lean Guidelines for MH Production Process Redesign

At the coordination level the productivity is determined by the market demand (*i.e.*, market monthly demand and monthly forecast). Based on the threshold productivity value, the
station cycle time is calibrated to match the required production level, which is preceded by the identification of a minimum number of stations. This number is determined by product elemental tasks, precedence requirements, and efficient grouping of operations. Equalizing the stations cycle time is the next step to insure a bottleneck-free process. Assembly line sequencing and an inventory control system should then be implemented at the new layout. The lower row of the execution level represents policies to achieve the upper row goals. At the formulation level, the physical shape of a lean production system will be a cellular manufacturing system. The system will include a Kanban (card) control system. Lean systems are characterized by utilizing JIT manufacturing, in which the downstream pulls components from the upstream. JIT leads to a minimum in-house inventory level. Furthermore, JIT manufacturing insures that no component will be manufactured at the subassembly station, unless it is ordered via a card by the final assembly station.

Figure 5.33 illustrates the selection procedure for a suitable layout-form matching the required product design and execution requirements. Combining the logic presented in Figures 5.32 and 5.33, the following sequential steps are followed to generate a lean design:

1. Define major operations required to produce the product
2. Remove fabrication processes from Assembly station operations to the feeder stations
3. Group the maximum number of assembly operations in a minimum number of assembly stations
4. Compute the station cycle time based on product cycle time above
5. Select the Group Technology layout type or the Cellular Manufacturing System (CMS).
6. Apply the Cellular Manufacturing System based on the nature (interrelationship) of assembly operations, product and position of AS
7. Group the maximum number of fabrication operations in a minimum number of subassemblies


9. Define elemental tasks and their respective process times

10. Combine as many tasks as possible in the first station without violating the required compatibility and precedence. The second set of elemental tasks is assigned to station 2, and the same is done for the remaining stations.

**Figure 5.33** Steps for a Layout Selection
The following section includes lean guidelines for MH production systems. The design guidelines have been developed from the results of the comparative analysis of existing MH production systems, presented in Chapter 4.

5.8.2 Guidelines for Advanced MH Production Systems

Observed Problems: As mentioned in Chapter 1, problems of existing MH production systems stem from the current practices characterized by the limited application of technology and advancements in manufacturing and other types of industries.

1) Rework;
2) Labor-driven processes (e.g., unavailability of workers);
3) Inefficient mobility systems and/or material handling systems.

Proposed Solution: A line-balancing technique is suggested to remove any identified process bottlenecks. Line balancing involves paralleling the processes in the stations to reduce the station cycle time. Moreover, improving the station performance can be further achieved by utilizing efficient mechanization and advanced material handling systems.

Conclusion: The system capacity is constrained by the layout design and cannot exceed certain productivity limits. Therefore, layout shapes and material flow patterns are analyzed to generate alternative designs that can achieve higher productivity limits.

The following design guidelines are developed to streamline MH systems through changes that could be performed on the system components and station organization within the facility shop floor layout.

Based on the comparative analysis of MH case study layouts and lean criteria, as presented in Figure 5.32, the following steps illustrate a strategy for redesigning the production system to achieve optimal production and efficient processing.
1) Employ a minimum number of sequential assembly line stations, backed up by a sufficient number of subassembly stations and workshops.

2) Minimize the processing time of the assembly line stations. Minimum process time yields a maximum production rate and a minimum product cycle time.

4) Equalize the processing time of the final assembly line stations to eliminate process bottlenecks.

5) Split high number of activities associated to high number of labors existing in one station into two distinct parallel sets distributed at an assembly station and a subassembly station. This process will decrease crashing possibilities of workers in the station that includes many activities. Additionally, it has advantage in decreasing the total process time (station cycle time).

6) Merge a low number of activities associated with a low number of workers that occupy an independent station with the preceding or following station. The advantage is to reduce the number of stations and time for product transition from one station to the next. In addition, the elimination of a station will reduce the production area needed for manufacturing.

7) Integrate the operation that has a long cycle time through the production line. In other words, split the operation that has a long cycle time into a set of processes that are assigned to all possible assembly and subassembly stations and storages (e.g., drywall painting).

8) Reduce the longest station cycle time by paralleling the activities as much as possible.

9) Follow a hierarchy consisting of a final assembly station, front line subassembly station, material feeding station, and workshops. This sequence should be applied within a cellular design that insures a minimum transition time and maximum reduction of the final assembly cycle time.

10) Use an appropriate material handling system for each activity to minimize transition time.
11) Apply a smooth material flow planning to insure the fastest delivery time of materials to the cells and shortest service distances from materials stacks to the processing cells.

12) Use a double-section (full house) processing system to:
   a) Eliminate the in-station queue time by providing two products for assembly. If the work stopped on one section, it would continue on the other.
   b) Increase a station’s capacity without adding resources.
   c) Produce efficient resource utilization and an efficient material handling system.

   The above design guidelines are used to develop new layout alternatives. The following section includes the main steps to develop each design alternative. The following design guidelines document the actual procedures to integrate the streamlined production process into four distinct layouts.

### 5.8.2.1 Guidelines for the Generic U-Shape Layout

1) Run the maximum number of activities in the fewest stations without violating the sequence;
2) Merge stations with the fewest activities with preceding and/or following stations;
3) Distribute activities of a long operation (e.g., painting) among all assembly and subassembly stations;
4) Delete redundant stations;
5) Use storage for assembled components (hoppers);
6) Use double-station processing to process both sections of a double-bay house simultaneously.

### 5.8.2.2 Guidelines for the Spine Layout

1) Split into two independent zones the subassembly and the final assembly operations;
2) Produce final assemblies of the bathroom components in a subassembly station;
3) Merge the time of similar assembly stations in one process time (Parallel Stations). Allow
several stations to process the same product simultaneously (without violating the production sequence);

4) Group maximum number of fabrication operations in minimum number of Feeding stations (subassemblies);

5) Use a double-station, to allow processing of two sections (full double-bay house) simultaneously;

6) Solve problems of the material handling system; use a mechanically-driven mobility system;

7) Use a spine flow for the assembly line as shown in Figure 5.34, instead of a U-shape flow, to:
   a) Facilitate the product movement, without needing extra mobility components.
   b) Allow the installation of a straight mechanically pulled system to transfer the products simultaneously through the assembly line stations.

![Figure 5.34 Spine Layout](image)

8) Use a dual station system working at two sections simultaneously. The advantages of this system are:
   a) Eliminating the queue time in two station’s process time; hence, reducing the two station’s cycle time;
   b) Reducing the product cycle time to increase productivity;
c) Enabling identical operations to run simultaneously.

    The dual station processing is coupled with double-section processing, which would substantially reduce the total throughput time to 25% of the original product cycle time of the generic U-shape layout.

5.8.2.3 Guidelines for the Central Layout

1) Split into two independent zones the subassembly and the final assembly operations;
2) Place the final assembly operation in the middle of the layout;
3) Configure the subassembly operations of the three major components of the manufactured housing units into three independent production lines providing finished components to the center of the factory;
4) Produce 100% finished components at the subassembly stations;
5) Free the final assembly operation from any waiting state and allow the processing of different sizes independently. Thus, use multiple final assembly stations for each product size;
6) Use a central overhead crane system to deliver the finished components to the central assembly area. The material handling system is constructed according to the final shape of the shop floor layout;
7) Move the finished housing unit to the front, then lateral, directions to ship it out of the factory.

5.8.3 Criteria of a MH Layout Configuration

Product Design Variables:

    Based on the above discussion, Table 5.3 lists down the factors impacting the layout design. The factors are (i) the product design factors, (ii) the MH production process, and (iii) the lean factors for an efficient production system. Chapter 6 incorporates the sets of the three factors within a comprehensive framework of the decision support system.
### Table 5.3 Design Criteria

<table>
<thead>
<tr>
<th>Factors</th>
<th>Variables</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Design</strong></td>
<td>1. Proximity</td>
<td>Architectural standards data</td>
</tr>
<tr>
<td></td>
<td>2. Product size: length, width and height</td>
<td>Housing unit dimensions: Length: min. 45 - max. 90 ft. Width: min. 20 - max. 40 ft. Height: min. 8-12 ft.</td>
</tr>
<tr>
<td></td>
<td>3. Station dimensions: machines, tools and equipments</td>
<td>Height of roofing station permitting one story, two stories, and roof matching</td>
</tr>
<tr>
<td></td>
<td>4. Area of the working space around the product.</td>
<td>Standards data</td>
</tr>
<tr>
<td></td>
<td>5. Accessibility of labor force to material and equipments</td>
<td>Standards data</td>
</tr>
<tr>
<td><strong>MH Process</strong></td>
<td>6. Precedence of activities</td>
<td>Parallel is better than in series</td>
</tr>
<tr>
<td></td>
<td>7. Sequence of stations</td>
<td>Parallel is better than in series</td>
</tr>
<tr>
<td></td>
<td>8. Number of stations</td>
<td>The lower is the number-the more lean it will be</td>
</tr>
<tr>
<td></td>
<td>9. Processing of different floor sizes</td>
<td>Use separate feeders for different sizes, assign an appropriate number of workers to feeders to equalize cycle time.</td>
</tr>
<tr>
<td></td>
<td>10. Activity processing time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11. Number of labors</td>
<td>Increase workers to match the CT of stations and assembly line.</td>
</tr>
<tr>
<td></td>
<td>12. Type of material</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13. Station cycle time</td>
<td>Divide cycle time to 2 or 3 parallel activities to decrease station cycle time</td>
</tr>
<tr>
<td></td>
<td>14. Product cycle time</td>
<td>Sum of all station cycle times should be minimized</td>
</tr>
<tr>
<td><strong>Lean Production</strong></td>
<td>15. Production</td>
<td>Maximum production</td>
</tr>
<tr>
<td></td>
<td>16. Station design</td>
<td>Lead time, JIT supplies</td>
</tr>
<tr>
<td></td>
<td>17. Activity distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18. Workforce assignments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19. Cycle time synchronization to production based on the market demand</td>
<td>Minimum processing time, equal station processing times</td>
</tr>
<tr>
<td></td>
<td>20. Inventory control-Kanban</td>
<td>Number of Kanbans in the system</td>
</tr>
<tr>
<td></td>
<td>21. Flexibility to product changes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22. Level of automation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23. Supply chain management</td>
<td>Number of suppliers, lead times, and a barcode system, etc.</td>
</tr>
</tbody>
</table>
5.9 CHAPTER SUMMARY

Four alternative layout designs are presented in this chapter: the U-shape, the spine, the J-shape, and the central. The four layout designs are tested using independent simulation models. A unique simulation model is developed specifically for each design alternative. The four layout designs and their respective simulation models employ the building blocks of the streamlined system, developed in Chapter 4.

It is concluded from the simulation run results that each layout has a different productivity under the same conditions. It is shown in Table 5.4 that the productivity of the U-shape design is approximately 50 sections per week. Similarly, it is proven via simulation that the spine layout has a productivity of 100 sections per week, whereas the productivity of the J-shape and the central layouts are approximately 150 and 200 sections per week, respectively. Furthermore, statistical relationships between productivity and resources can be obtained by using the optimization models developed in Chapter 4. Thus, a specific layout design is recommended for a given level of performance. Each existing or proposed layout design can be balanced further, with respect to shop-floor processing times and number of resources, by using optimization models.

Table 5.4 Comparison of the performance of the four layout alternatives

<table>
<thead>
<tr>
<th></th>
<th>U-Shape</th>
<th>Spine</th>
<th>J-Shape</th>
<th>Central</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>48 sections/week</td>
<td>98 sections/week</td>
<td>150 sections/week</td>
<td>200 sections/week</td>
</tr>
<tr>
<td>Batch size variability</td>
<td>Difficult to be balanced</td>
<td>Difficult to be balanced</td>
<td>No effect</td>
<td>No effect</td>
</tr>
<tr>
<td>Material handling</td>
<td>Wheels-trolleys</td>
<td>Mechanical</td>
<td>Wheels-trolleys</td>
<td>Central crane</td>
</tr>
</tbody>
</table>
In conclusion, it is observed that the different layout designs proposed in this chapter vary in terms of the material handling system and size of resources. The workforce sizes associated with each system are not equal for two reasons. First, the workforce size of the final assembly stations varies due to the proposed flow of activities. Second, the size of the workforce in charge of the subassembly stations increases according to the timely demand for the semi-assembled components. Balancing an MH production system is achieved by using the simulation and the optimization models. The simulation model facilitates identifying the bottlenecks. Moreover, the model is used in “what-if” scenarios to define a new station processing time to eliminate the identified bottleneck. The final step in balancing the system is to calibrate the flow of activities by using the optimization model to apply the new processing time within the station’s activities.

Finally, this chapter includes methodologies and procedures to (i) balance existing MH systems, (ii) design lean MH systems, and (iii) generate layout designs for advanced MH production systems.
CHAPTER 6

A DECISION SUPPORT SYSTEM (DSS) FOR MH PRODUCTION PROCESS
PLANNING AND FACILITY DESIGN

6.1 INTRODUCTION

There is a need for the manufactured housing industry (manufacturers, production managers, and service managers) to assess the production efficiency of their existing factories. Such an assessment is essential for meeting the growing demand of customers with respect to the design and size of the housing products.

Systems are evaluated for several purposes: (i) to improve the productivity rates to satisfy the increasing market demand, and (ii) to know the maximum production limit of their systems without major changes in the layout configuration. It is very difficult for factory managers to assess the efficiency of their production systems. However, the factory decision makers need a tool that defines the relationship between the layout configuration and the overall system performance. This tool would provide assistance and support to the decision makers, which will enable them to quantify the impact of many complex variables of the production system.

Results obtained throughout the previous chapters are used to develop an integral framework that combines most of the decision variables. The framework uses data in order to provide support and assistance to the factory top management and/or the factory operations managers. In other words, a decision support system (DSS) is proposed to provide support on the strategic level and on the operational level. On the strategic level, the DSS supports the selection process of the most efficient design alternative that meets the user requirements. On the operational level, the DSS assists the production managers in analyzing the performance of their existing systems and in determining possible ways for modifying the production system to
improve the overall performance.

6.2 THE PRODUCT DESIGN AND THE PRODUCTION SYSTEM

Figure 6.1 Relationships of the Product Design and the Production System

The left side of Figure 6.1 depicts the market demand variables, in which the customer decides the type of the house (i.e., single section or double section, on a one-story or two-story height). Moreover, the customer defines the number of rooms and services of his housing unit. The number of rooms defines the overall size of the unit (i.e., 40, 50, 60, 70, 80 ft. length). Daily orders are placed by customers to the dealer; then the orders are sent to the factory in the form of a model mix batch. The factory schedules the products for manufacturing, based on the delivery due date to the customer.

Market trends are predicted through market surveys in order to detect the changes in customer demand regarding the type (i.e., single or double bay on one or two stories), floor plans (i.e., interior and exterior design), finishing specs, size, and building materials of the housing unit. A new design of the housing unit requires a specific set of operations and activities to be performed. Therefore, impacting the configuration and the work content associated with the
product. However, floor plans, finishing, and materials are not included in the model.

6.3 FRAMEWORK OF THE DSS

The DSS Framework endeavors modeling all variables impacting the layout design. Environmental variables (i.e., the location of the facility, transportation distance from vendors to the facility and from the facility to the dealer) are excluded from the DSS framework.

The DSS framework covers interrelated factors of (i) the market demand, (ii) MH organization, (iii) MH production process, and (iv) MH production system planning and facility design. Figure 6.1 shows the interrelationships between these different factors. The above four factors are broken down to one or multiple modules as follows:

Module 1: Market Demand

Specifications of the MH product (ordered by customers) represent the market trend. The market demand is sent to the factory in the form of a product mix orders. As a customer places an order, he specifies the type, size, finishing (materials), and the design of the housing unit. The housing unit specifications require a certain type of a production system. However, the production system should be capable to efficiently produce the batch. Moreover, the system should be able to adapt to future changes in the design of the housing product.
Figure 6.2
Framework of the DSS
Module 2: MH Organization

The second module covers the organizational factors determining the production. The factors are: (i) existing market demand for each product type, (ii) production costs (budgeted costs) associated with each product type and number, (iii) workforce size (summation of workman hours required for producing each product size), (iv) estimated net profit of each product size, and (v) total net profit of the production order. The objective of this module is to optimize the production mix using linear programming. Therefore, the outputs of the market module are refined through the organizational module, which exploits the firm available resources for estimating the production capacity.

Module 3: MH Production Process

The objective of this module is to identify the required MH operations and processes. The production process is mapped out for all assembly and subassembly stations at two MH factories located in northern Indiana. Abu Hammad et al, (2002a) have illustrated the production process at an existing MH factory. The MH processes consist of assembly and subassembly activities. The final assembly processes are four major sequential operations: (i) floors, (ii) walls, (iii) roofs, and (iv) Finishing and testing. The following section describes the development of the generic building blocks of the major assembly and subassembly processes.

Module 4: Building Blocks of an MH System

The objective of this module is to transform the existing MH system components into generic components, having a defined work and time contents. The basic building blocks of the system (covered in Chapter 4) are the minimum number of stations that are required to perform all the activities needed to produce an MH product.
Module 5: Layout Design Alternatives

As discussed in Chapter 5, the generic building blocks are used to develop new layout designs for MH production systems. Four designs are proposed as shown in Figure 6.3: (i) the generic U-shape layout, (ii) the Spine layout, (iii) the J-shape layout, and (iv) the Central layout. Each layout design is characterized by an improved performance (productivity). Simulation models (module 6) are used for testing the performance of each alternative.

![Layout Design Alternatives Diagram](image)

**Figure 6.3 Advanced Layout Designs for MH Systems**

A layout-design data base (DB1) is included in this module as shown in Figure 6.2 of the DSS framework. This data base includes layout design alternatives and respective simulation model for each layout alternative as follows:

1) Layout design: the data base is proposed to communicate with the BlockPlan software
(Mehrotra 2002) to draw the flow pattern and to measure the efficiency of the layout based on the proximity and closeness requirements;

2) Area of the facility, total workforce size, labor costs;

3) Number of stations (and subassembly and workshops), number of activities per station, number of workers per activity, equipment and machines per activity;

4) Simulation models for each design alternative, production rate for each layout alternative: number of houses per week and number of sections per day.

**Module 6: Simulation Models for Layout Design Alternatives**

This module includes simulation models for each layout design. The simulation model logic follows the logic used in developing the two simulation models for the existing case studies (i.e., Abu Hammad 2002b, and Abu Hammad 2003). The objective of this module is to provide a means for predicting the dynamic interactions of the new systems. Additionally, this module is used in tandem with the following module (optimization models) for conducting a bottleneck analysis of the production system.

**Module 7: Optimization Model for MH Production System**

An optimization model is developed for streamlining MH activities and systems. A detailed description and demonstration example are presented in Chapter 4.

**Module 8: Bottleneck Analysis Process**

After selecting the layout the user needs to balance the system activities and the workforce allocation to various assembly and subassembly stations. Thus, the user needs to utilize the optimization model for this task in obtaining optimal times for the different stations and efficient workforce distribution. The user would then enter the optimal processing times in the model servers, in order to conduct a bottleneck analysis for the system. In case a bottleneck is
located via simulation, the user needs to use the optimization model of the activities at the bottleneck station to decrease the total station processing time. Finally, the user utilizes the two model-base systems back and forth until the system has no bottlenecks. Therefore, the steps of the bottleneck analysis are as follows:

i) Both the activity streamlining model (ASM) and the simulation model (SM) produce standardized processing times that can be used initially by the user in balancing the system;

ii) The SM includes links to the optimal processing time cells at the activity streamlining model. Additionally, the SM includes links to the product size target cells of the product mix model (PMM);

iii) The SM is used in a bottleneck analysis to locate the system bottlenecks;

iv) The identified bottleneck station is further investigated by using the ASM, which generates optimal processing time of the delaying station for a specific ordering of the station’s activities;

v) The optimal processing time is linked to the SM; the user then generates a run report to investigate new system bottlenecks;

vi) The above steps (iv) and (v) are repeated until the system is finally balanced.

**Module 9: Material Requirement Planning for MH Systems**

Barriga 2003 has proposed an efficient data base system for planning the master production schedule and the material requirements for a MH facility. A material requirement planning data base (DB2) is depicted in Figure 6.4 and Figure 6.2 of the DSS framework. This data base includes information and specifications for each housing model. The product specifications include the following: different product sizes, product costs, products sales price, material quantities per size, material costs, material vendors, and material lead times.

Each model is identified by a unique barcode relevant to a specific design and size. List
of materials and respective material barcodes is associated with each product model. Suppliers and material lead times are listed per material type. This data base is essential for establishing an efficient supply chain management system for the MH factory.

![Material Requirement Planning System for MH](image)

**Figure 6.4** Material Requirement Planning System for MH

Outputs of the simulation models (*i.e.*, product cycle time) are essential for planning the master production schedule of the system. Moreover, the product mix model results (*i.e.*, the exact number of products of each category size) are used primarily in defining the exact amounts of materials to be ordered from suppliers. The optimized number of product mix and the product cycle times are integrated with the logic of the master production schedule as depicted in Figure 6.5.
Figure 6.5 Providing Data to the MPS. The outlined zone is based on Suer, 1998

6.4 DSS ARCHITECTURE

The DSS architecture includes four modules as depicted in Figure 6.6. The first module is an optimization model of the product mix. The second module is the selection process of the most efficient layout matching the user requirements. The third component is the optimization model for streamlining the production process. The last module includes the simulation models for different layout design alternatives. Each module processes the same data and is integrated to perform a specific purpose as follows:
1) The optimization model for the product mix receives inputs from the market and MH organization as constraints. The model outputs are the exact product mix for manufacturing. Thus, the model optimizes the production rate and product sizes by maximizing the operational net profit of the firm. Moreover, the product mix model can be used on the operational level to determine the exact mix that guarantees maximum profitability to the company.

2) The user interface allows the user to select the system variables: product mix, product type, and productivity. These three variables establish the required specifications of the production system. Therefore, the DSS outputs include one of four layout designs that have been designed, simulated, balanced, and finally, tested for their effectiveness. This component of the DSS is a

**Figure 6.6 DSS Architecture**
strategic tool because the layout redesign happens once each 3-4 years. The user inputs are: the production rate, and the product specifications. The user can use the results of the first component (*i.e.*, the product mix) in defining the First and the third inputs *i.e.*, productivity and product sizes, respectively. Then the DSS suggests one of four advanced layout designs. The four advanced designs are the generic U-Shape, the J-Shape, the Spine, and the Central layout. Each layout design has multiple alternatives (variations) to accomplish exact production output.

3) The third component of the DSS architecture is an optimization model for streamlining the activities and resources of the MH operations. This model is flexible to adapt to changing layout design and different levels of performance by allowing the production manager to control resource/activity scheduling within predefined processing times and durations.

4) The fourth component is the simulation model of the MH production system that could be easily customized for any specific layout design. The simulation model assists the user in locating the system problems (bottlenecks) and areas in the system suffering from low utilization or inefficient performance. Moreover, the simulation model assists the user in balancing the system loads and times. The above four components communicate internally in a process of selecting a most efficient layout design that matches the market, company, and system constraints. However, each layout design exploits all possible ways for reconfiguring an efficient system achieving optimal productivity rates. The following two sections presents the product mix model and the user interface modules. The other components of the DSS architecture are presented in the previous chapters.

6.4.1 Module 1: Product Mix Model (PMM)

A linear programming model using the simplex method is used to define the product mix according to the market demand and the organizational conditions (*i.e.*, budget, workforce
availability, and profit). Market demand, workforce availability, and profit are inherently tied together with the physical components of the production system in such a way that each influences the other or has a cause-and-effect relationship upon each other. Therefore, market factors and corresponding organizational strategies provide economic activity which sustains a certain level of productivity. The input variables of the linear programming optimization model (LPOM) are: labor size, material costs, monthly budget for material procurement, and net profit for each house size. The outputs are: total profit and number of housing units of each size.

6.4.1.1 Model Inputs:

- Profit of each product-size category
- Budget requirements
- Labor requirements
- Market need for each product-size category

The objective is to maximize the total profit variable, taking into account the limitations of budget, labor availability, and market demand for each product size. Optimization of the above variable functions results in the following outputs.

6.4.1.2 Model Outputs:

The model output are: (i) the total net profit of the company accrued by producing the identified model-mix, (ii) the optimum production rate of the system, and (iii) number of each product size of X1= 45 ft., X2= 55 ft., X3= 65 ft., X4= 75 ft., and X5= 85 ft. These five outputs are the inputs for the user interface module of the DSS architecture.

6.4.1.3 Demonstration Example of the PMM

1) Click Start: a message box displays “Welcome to manufactured housing (strategic-operational) model mix determination system.” Click OK (Figure 6.7).
Figure 6.7 Product Mix Model- Welcome Window

Figure 6.8 Product Mix Model- Username Tracking
2) Figure 6.8 shows a message box displays “What is your name?” The system keeps track of users by collecting information about the user’s name. Type your name “Ayman Abu Hammad.” Click OK.

![Microsoft Excel - User Interface](image)

**Figure 6.9 Product Mix Model- Information Window**

3) Another message box displays as shown in Figure 6.9: “Hello, Ayman Abu Hammad. This interface will lead you through the process of model mix determination for your factory. Click Clear Form to start.” Click Clear Form.
4) Another message box displays as shown in Figure 6.10 “Hello, please enter your system constraints data in the yellow area. Click the Submit button to get the results.” Click OK. Then
start filling the data, based on your market survey.

5) In Figure 6.11, the inputs are computed as follows: (i) labor Requirements = 4450 working hours, which is equal to 130 workers you have at your facility, or you expect the labor market to provide, multiplied by five working days per week, multiplied by seven working hours per day; (ii) budget requirements = $800,000, which amounts to a $16,000 weekly investment, multiplied by 50 sections per week; (iii) market demand on each category size of the product: 5, 20, 10, 20, and 10 for 45ft., 55ft., 65ft., 75ft., and 85ft., respectively; (iv) expected net profit for each category size of the product: $10,000, $12,000, $14,000, $16,000, and $18,000 for 45ft., 55ft., 65ft., 75ft., and 85ft., respectively.

6) Go to Tools- Solver as shown in Figure 6.12. The solver dialogue box is displayed. Then click Solve.

Figure 6.12 The Solver Window
Figure 6.13 Reports Selection Window

Figure 6.14 The Optimization Results
7) Select Solver Results, and select to keep solver solution. Then click OK (Figure 6.13).

8) The dark red band shown in Figure 6.14 is the total net profit in case the factory produced 5, 2, 10, 20, and 10 sections of 45ft, 55ft, 65ft, 75ft, and 85ft respectively.

### 6.4.14 Sensitivity Analysis

**Figure 6.15 Sensitivity Analysis**

9) Change the inputs to be $500,000, 6.11, 7, 25, 15, 25, 15, and 60 for the budget requirements, market need for 45ft, 55ft, 65ft, 75ft, 85ft, and weekly production capacity of the factory, respectively. The result as shown in Figure 6.15 is a total net profit of $500,000 in case the factory produced 0, 0, 2, 11, and 15 sections of 45ft, 55ft, 65ft, 75ft, and 85ft respectively. The results have changed after changing the inputs. The Following figures are output reports of the model.

10) Sensitivity report can be obtained from Excel for the optimization model as shown in Figure 6.16. In addition to the limits report and the answer report shown in Figures 6.17 and 6.18, respectively.
Figure 6.16 The Sensitivity Report

Figure 6.17 The Limits Report
6.4.2 Second Module: Activity Streamlining Model Using Critical Path Method (CPM)

Inputs:
- Process times for activities or tasks associated with predetermined labor size per activity or task;
- Precedence requirement of operations or activities.

Outputs of this module are:
- Efficient flow pattern;
- Efficient sequence of operations;

Figure 6.18 The Answer Report
• Optimal station cycle time associated with sufficient resources.

6.4.3 Third Module: Simulation Models for Evaluating System Performance

Inputs for this module are the recommended layout suggested by the DSS and the outputs of the 2nd module:

• Efficient flow pattern (logic of flow) optimal sequence of operations;
• Optimal station cycle times associated with optimal number of resources.

Outputs of the simulation model are the following performance measures:

• Production rate;
• Average time in queue at each production cell;
• Maximum number of products waiting in queue at each production cell;
• Total product cycle time in the system;
• Station utilization.

6.4.4 Fourth Module: The User Interface

The problems of MH facilities can be summarized as: (1) the existence of process bottlenecks, and (2) the unbalanced processes resulting from the nature of the mixed model manufacturing, which is employed in all MH facilities. These two problems are directly or indirectly related to the following: (1) the factory layout design, (2) the product mobility and material handling system, (3) the assembly line flow pattern, (4) the labor force assignments on the assembly and subassembly stations, especially during shortages in worker availability and production slowdowns due to decreased demand, (5) the breakdown of assembly and subassembly stations, and (6) the activity distribution on the different stations of the production line. The evaluation of the existing factory layout is based on:

1) Maximum level of production achieved;
2) Unit types intended for production (single or double bay sections, single or double story MH housing units, etc.);

3) Product size.

The decision support system guides the user in recommending a design solution to be applied to the existing layout components. This system will be used as a framework for recommending efficient layout designs for new MH facilities. The following three types of outputs are provided by the system:

1) Most efficient layout design;
2) Area of the facility;
3) Work content and distribution among the major operations.

The production manager can use the activity streamlining model (ASM) to control the system time so that it will be in sync with the production level of the planning horizon. The following are ASM outcomes, which are very important in defining the manufacturing resource planning of the facility (MRPII):

1) The size of work force needed to produce the batch;
2) The exact labor size allocated to the stations;
3) The schedule of activities within each station of the system;
4) Minimum cycle time for each station;
5) Minimum mean cycle time for the product in the system.

The minimized station cycle times are inputted in the menus of the simulation model. The simulation model will process these times and provide more accurate estimates of the product cycle time for each category size. Accurate product cycle times are necessary in defining the master production schedule.
6.4.4.1 Logic of the Layout Selection Process

The DSS recommends the suitable layout based on the production rate and the size variability of the batch. Table 6.1 includes the variables of the two factors and the corresponding layout recommended by the system.

Table 6.1 Layout Selection Process

<table>
<thead>
<tr>
<th>Size Variation</th>
<th>Production Level</th>
<th>Flow Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Central</td>
</tr>
<tr>
<td>Moderate to High</td>
<td>Moderate to High</td>
<td>J-Shape</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderate</td>
<td>Spine</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Generic U-Shape</td>
</tr>
</tbody>
</table>

6.4.4.2 Demonstration Example of the User Interface

Figure 6.19 DSS- User Interface
1) As shown in Figure 6.19: click “Start Here” Button to Start. A message box is displayed “Welcome to Manufactured Housing Facility Design System; a Strategic Decision Support System for Selecting Optimal Layout Design that Fit your Requirements.” Click OK.

![Figure 6.20 DSS- Tracking Usernames](image)

2) A message box is displayed as depicted in Figure 6.20: “What is your name?” Enter your name: “Ayman Abu Hammad.”
3) A message box is displayed as depicted in Figure 6.21: “Hello, Ayman Abu Hammad, Hit (Clear Form) to Start Inputting Desired Specs of Your System, then Click (Submit) to Obtain the Results, If you need help in determining some of the System Spec (i.e., Product Sizes); Go Directly to Sheet # 2- Model Mix Determination Support System.” The model Mix is demonstrated above. Click OK.
4) As shown in Figure 6.22, select the desired production level of the new facility or the maximum productivity of your current system “<50Sections/week”. Then enter the product type “Double Bay/ One Story”. Finally, enter the maximum sizes- “<(50ft*12ft). Click Submit- The output Sheet Number will be displayed “Output Sheet Number= 6.”
5) Open the output file number “6” as shown in Figure 6.23. The file shows the user inputs in a table format at the upper left corner of the output sheet file. Output 1 is the suggested layout design by the system that fits the user requirements, in this example the U-Shape layout is proposed to the user. Output 1 includes the assembly and subassembly stations with all respective activities. Moreover, the layout shows the required sequence of operations and relational proximity of the stations. Output 2 is the workforce content distribution on the factory major operations. The workforce size is linked from the activity streamlining model spreadsheet after balancing the system using the CPM model. Output 3 is the exact production area, and height based on the modular dimensions of the maximum size of the
product after adding suitable allowances for pathways for workers around the product. Click on the layout design picture to open a full screen size picture as shown in Figure 6.24. The full screen size picture depicts the layout design shape, sequence of assembly stations, detailed lists of respective activities per station, position of subassembly stations based on the proximity requirements to the final assembly flow and material stacks.

**Figure 6.24** Layout Design Output

**Alternative 1: GENERIC U-SHAPE LAYOUT**
6.5 DSS LOGIC

Figure 6.25 DSS Components

Figure 6.25 depicts the components of the proposed DSS (i.e., User interface, model base, and data base). The user interface is developed using Excel with VBA. The user inputs include: specific production level, types of products, and sizes of houses. The outputs include: a selected layout with a capacity and specifications that match the inputs, activity assignment per stations, and area of the facility based on the module size of the product. The model base components work in the background of the interface. The optimization model organizes an optimized processing time relative to the workforce assigned at each station. The optimized times are the inputs for the simulation model for that selected layout. Finally, the outputs of the simulation model are the relative product cycle times, queue times, and number of products.
waiting in queue (These are useful for the bottleneck analysis if the required system performance is not reached. Please refer to the right bottom section of the DSS framework, shown in Figure 6.2.

The objective of the data base component, shown in Figure 6.25, is to add new layout designs, or alternatives. Additionally, the data base management system is used to alter the model base component for balancing the system by conducting a bottleneck analysis. The task of the knowledge base component is to track statistics and performance measures for the different layouts, in order to establish relationships that are very important for predicting the behavior of the new layout designs.

6.6 VALIDATION OF THE DSS

Model validation includes three steps: (i) validation of the model logic, (ii) validation of the inputs and corresponding outputs, (iii) validation of the user interface. Therefore, two factories located in northern Indiana were visited, in order to obtain feedback from the manufacturers about the model logic, user interface, and model inputs and corresponding outputs. The candidate presented his work, using a power point (ppt) (90 slides) presentation and his results (spreadsheet programs and models). The optimization models and the user interface were presented and explained in detail. The candidate encountered an interactive response from the manufacturers and production managers toward his research outputs and received positive comments on the model logic, results, and the procedural methodology followed in developing the layout designs.

6.6.1 Feedback from Factory 1

Factory 1 was built in the year 1972 having a linear production line shape. The dimensions of the factory are 750 x 60 feet. The total area of the facility is 45,000 square feet.
The maximum product size is 28 x 68 feet. These are 14 foot-wide modules. The production line consists of 15 assembly stations. The current production rate at the factory equals 4 double-wide houses per 4 working days, which amounts to 8 modules in 4 working days. Therefore, the daily production of the facility equals 2 modules per day, using 60-65 workers. The maximum capacity of the facility is 10-14 modules per week (5 days), when sales are good, using 80-100 workers. Five workers are assigned to each station. The worker distribution among the different operations is as follows: six group leaders (i.e., floors, interior walls, ceilings and mill, electrical and exterior finishes, dry wall, and final finish). Four foremen, six electricians, three plumbers, and the remaining are semi-skilled workers.

The meeting took place on April 25, 2003, in the production manager’s office. The attendees of the meeting were:

1) The Production Manager and Vice President;

2) The Service Manager, Field Operations, and Warranties.

The meeting lasted 30 minutes. The candidate began the meeting with a brief presentation of the research objectives, results, the optimization model, and the DSS. During the presentation many questions were raised about the shop floor configuration of the proposed factory designs. The factory management demonstrated great interest in the research outcomes. The research ideas were perceived as future creative designs for MH factories, having higher throughput and efficient processes.

The management was positive about the simplicity and usability of the proposed models and the user interface of the DSS. The computer system of the factory included Microsoft Excel application, which can run the DSS and the optimization tools.
6.6.2 Feedback from Factory 2

The factory Chief Executive Officer (CEO) and the Production and Operations Manager were interviewed at Factory 2. The meeting started with a brief presentation of the research goal, objectives, and results (the optimization models and the DSS). The goal of the research was to advance MH technologies and practices, as in other manufacturing industries (e.g., the auto industry). Many questions were raised during the presentation and discussion about the shop floor composition of the proposed factories, the optimization model, and the DSS. The CEO has showed great interest in the ASM and expressed his interest in acquiring such a system for his company. The production manager of the factory mentioned that the work had a concise focus and was “neatly presented.” The two factory personnel stated that the focus of the study was of great interest to them and that they were constantly thinking of alternative methods for streamlining their factory operations, in order to increase their production output.

Q: The CEO has asked about the research procedure to maximize the production.

A: Lean production theory proposed minimizing the total number of assembly line stations and supporting them with a sufficient number of subassemblies. It was observed that the cycle time of the final assembly operations dictates the productivity of the whole system. Although the subassemblies are assumed to deliver the components on time when needed, their processing time does not impact the product (housing units) cycle time, hence, the system productivity. The optimization model is very helpful in listing the duration and sequence of the activities. The result is a minimum time for running all the activities. The optimization model was explained in detail at the meeting. Meanwhile, the CEO showed much interest in the model and stated that he would like to have such a tool in his facility to help the management streamline the factory operations.
Q: How can the cycle time of the floor subassembly station be minimized?

A: The optimization model includes the answer to this question. Station zero had two long activities: (i) the construction of the floor skeleton and (ii) the assembly of the other floor components in another jig. The two activities were planned in parallel (simultaneously), as shown in the arrow diagram. Consequently, the station time dropped from a high of 38 minutes to a low of 15 minutes. However, the utilization of the optimization model in decreasing the station cycle time should be done with respect to the simulation model results. Therefore, unnecessary reduction in station time is avoided. At this point, the simulation model terminology, mechanism, and utilization were explained in detail as a main tool for evaluating existing and new layouts.

Q: What is the most efficient way to get all stations to process different product sizes at the same processing time?

A: The proposed layout designs were shown, followed by a brief description of how the performance of each layout is tested. A more detailed discussion took place about the spine layout and central layout. The central layout was suggested to solve the model mix problem, while the other proposed designs were running mixed model manufacturing processes. The CEO has observed the central system closely and asked questions about the process and assumptions of the design and possible application at his facility.

It is concluded from the master’s thesis (Abu Hammad 2001) that changing existent system parameters does not increase the system productivity. However, substantial productivity improvement is expected after radical changes in the layout configuration.

The formation of a swing group assisting the workers at the troubled station was
suggested, in order to remove congestion at the bottleneck stations. However, the CEO replied that the factory already included a swing group. The CEO mentioned that, in practice, the swing group was used mostly to fill absentees’ positions, rather than to help workers at bottleneck stations.

**Q:** How can onsite operations benefit by the lean production theory (LPT)?

**A:** The LPT aims at minimizing costs through waste elimination. Construction operations usually result in large amounts of material waste (due to errors, changing orders) and waste of resources (due to inaccurate scheduling). The amount of construction waste ranges between 5 and 10% of the project cost. Therefore, it would be advantageous to apply LPT to eliminate waste and increase the overall company profitability.

**Q:** What are other effects (excluding factory operations) that determine factory productivity?

**A:** At this point, the model logic was explained in detail; the effects of the market were discussed. Moreover, the optimization model of the market demand was presented. The production manager mentioned that the candidate did a good job, which meets most of the manager’s concerns.

The existence of the chassis component causes a major problem for public acceptance or perception of MH. Unfortunately, this problem affects other types of factory-built housing, such as modular housing. Public awareness of the improved quality and durability of factory-built housing is countered by low credibility, compared to site-built housing. However, MH is still the only type of factory-built housing that offers the most affordable housing in the United States.

On the other hand, there is a problem accepting new techniques by the manufacturers of
the MH. The CEO elaborated that the society needs time to accept new technologies. Variability of the public acceptance is associated with the type of the product: rapid acceptance was observed for electronic products \((i.e., \ 1-2 \text{ years})\); the slowest was observed in domestic construction \((i.e., \ \text{up to } 40 \text{ years})\).

The CEO mentioned the following scenario from the auto industry: A decade ago, Ford offered a rigorous design for its product, which included versatility and a wide range of choices to consumers in terms of accessories, color, specifications, \(etc\). On the other hand, Honda restricted its offers of color, motor capacity, and specifications, compared to Ford. However, it was found that public acceptance of Honda vehicles far exceeded that of Ford vehicles. In this example, the performance (quality) of the product played a great role in determining market trend and customer choice. Honda engines proved to operate over 200,000 miles, compared to the Ford engine, which reached its limit at 100,000 miles. Therefore, the market preferred quality and reliability to design.

The candidate informed the CEO that the research team had been trying unsuccessfully to organize a meeting with the manufacturers, in order to disseminate the research results. The CEO has mentioned that the proper time for research and development activities is during the low sales season: winter. Finally, the candidate has expressed his gratitude to the factory management for its valuable feedback, time, and positive comments on his work.
6.7 CHAPTER REFERENCES


CHAPTER 7

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

7.1 SUMMARY OF THE DISSERTATION

Problems of existing MH systems are characterized by the following drawbacks: (i) adoption of a mixed model manufacturing process; (ii) unbalanced operations and potential process bottlenecks; (iii) inefficiency, since they fail to produce at desired production levels. In addition, rigid physical shapes and flow patterns prohibiting productivity; (iv) inflexibility, since they cannot adapt to changing trends in market demand; and (v) minimal use of recent advancements in: technology, material handling, production planning, and control paradigms.

This dissertation proposes the following three hypotheses, in order to solve some of the above manufacturing problems: (i) advanced layout designs are crucial in attaining higher productivity and improved performance; (ii) productivity improvement of MH systems is accomplished by balancing the system workloads and resources, thus eliminating potential bottlenecks in the production process and material flow; and (iii) a production planning system employing advanced tools and models is essential in achieving an efficient MH production process. Therefore, the dissertation objective is to develop a decision support system (DSS) that facilitates the design and development of an efficient production system layout to achieve improved system performance, given predefined limitations (user requirements).

Abu Hammad (2001) has identified process bottlenecks constraining productivity. However, a practical tool for streamlining production operations is crucial to balancing the system and removing potential bottlenecks. In addition, productivity improvement is constrained by the physical setting (i.e., layout) of the production system. Although process bottlenecks are solved (the generic U-shape), the system is not able to exceed a certain production limit without
changing the system configuration. System redesign endeavors to improve productivity by changing the original system configuration to a more efficient sequence and better distribution of operations for assembly and subassembly. The generic building blocks are based on the analysis of existing systems. Having fixed work content and defined processing time, the generic building blocks are fixed components of the macro production system. Four layout designs are developed by using these generic building blocks. Each design alternative (the spine, the J-shape, and the central layout) is simulated to test performance. These alternative designs have two, three, and four times, respectively, the productivity of a comparable existing U-shape system. Therefore the research methodology is defined by the following five steps:

1) Explore available process improvement techniques and industry practices in other industries and possible adoption in MH systems.

2) Define the generic building blocks of existing MH processes.

3) Develop an activity streamlining model (ASM) for MH operations using the critical path method (CPM);

4) Develop efficient layout designs and test their performance via simulation;

5) Develop a product mix model (PMM) for defining the optimal production mix with respect to the market demand and the available resources of the MH firm.

The decision support system (DSS) includes four components that were developed basically throughout the above five steps: the model mix, the user interface, the activity streamlining model, and the simulation models. The product mix model assists the decision maker in defining the exact model mix according to the firm’s constraints (budgeted costs, labor hours, and market need for each product size). The model mix determines (i) optimal productivity and (ii) product size. The model optimizes the profit and conforms to the firm’s
constraints: worker availability, market needs, and budget requirements. The user interface assists the user in selecting the most efficient layout design. The activity streamlining model assists the operational management in balancing work loads. This tool enables the production manager to control the processing time of each building block or work station, in order to work in sync with the macro system. Additionally, this tool is used to optimize the macro system’s time by defining the critical path and crashing the time of the activities on the micro level.

The user interface of the DSS includes three entries. The first one determines the required production level of the facility. The second determines the type of product, and the third entry defines the maximum product size. The three factors directly impact the layout design. The DSS automatically selects the most efficient layout design matching the above specs. The DSS output sheet includes: i) the inputs, ii) the layout design, iii) number and distribution of the resources, and iv) the area of the facility. Finally, feedback is received from the industry. This feedback is related to the usability of the DSS and the manufacturers’ evaluation of this tool in assisting them in production planning and manufacturing decisions. The factory personnel provided positive feedback concerning the DSS components, inputs, and results. Additionally, they showed interest in acquiring the DSS to improve the performance of their existing systems.

7.2 CONCLUSIONS OF THE RESEARCH

In spite of the growing demand and need for efficient production; the manufactured housing industry has not been able to emerge as a technologically advanced industry. The purpose of this research is to resolve some of the problems of the MH production system. The problems of the existing system, identified in the masters’ thesis Abu Hammad 2001, are (i) process bottlenecks hindering productivity, (ii) lack of streamlined operations, causing waste of material and resources, (iii) outmoded MH processes, characterized by major dependence on
workforce to run the manufacturing processes, and (iv) lack of technology and computerization in the existing MH operations. There is a crucial need for efficient MH production systems employing recent advancements in technology and manufacturing.

2- This dissertation research presents the state of the art in innovative layout designs by re-engineering existing models to advance the MH systems and streamline operations.

A decision support system for layout selection process has been proposed. The DSS provides the MH industry with an efficient tool for evaluating the performance of existing MH facilities and/or can be utilized in planning and designing new MH facilities. The DSS integrates some of the manufacturing theories i.e., Lean Production Theory. The expected results of this research include generic guidelines for developing a streamlined (efficient) assembly line specific to MH processes and a decision support tool that helps the user in the selection process of optimum production system meeting specified requirements. Moreover, the DSS will help the user in evaluating existing facilities with respect to productivity and overall performance. The following points are concluded in this research:

1) The DSS presents a comprehensive framework covering multiple interrelated factors in the market, organization, and MH production systems.

2) Current systems are constrained by (i) inflexible shapes, (ii) unbalanced manufacturing operations, (iii) irregular product mixes in a given batch size, and (iv) failure to adapt to changes in product design;

3) Radical changes in MH layouts have dramatically improved performance and production outputs;

4) Breakdown of production system components into smaller units (building blocks) facilitates constructing advanced layout design alternatives.
5) Spine and central shapes have offered improved performance and flexibility in production scheduling;

6) The activity streamlining model provides a flexible environment for the production manager to balance system loads and efficiently distribute manpower;

7) The simulation model and the ASM streamline, balance, and eliminate system bottlenecks.

8) The DSS components are flexible and, therefore, can adapt to new market trends and changing product design.

9) Problems with model mix processing systems are minimized in the new efficient production planning system that uses simulation results in developing the MPS and the MRP.

10) The PMM determines production capacity and product sizes within the context of organizational constraints.

7.3 LIMITATIONS OF THE RESEARCH

1) The scope of this research is limited to certain factors. Other factors having a great impact on the productivity and system performance are left for future research in this area;

2) Relationships between factors are assumed to be linear in the optimization models. However, linearity is not the case. The relationship is assumed linear for reasons of simplicity;

3) Improvement is limited to the in-factory operations. Onsite construction operations are not covered, due to concentration on the core production system.

7.4 CONTRIBUTION OF RESEARCH TO EXISTING KNOWLEDGE IN THE FIELD

A unique DSS for MH production planning and system design is developed to: i) balance MH activities and production processes, ii) select the best layout, and iii) reschedule construction operations in a more efficient way.
This dissertation is the first in MH operations research. It presents a comprehensive model for efficient MH production systems with respect to capacity planning, layout design, and material planning paradigms. Additionally, this research targets improving MH production system efficiency by using innovative layout designs.

Limited research work has been done in the area of MH. Moreover, no research so far has encompassed MH production efficiency and overall system improvement.

The major contribution of this dissertation is the DSS for MH production planning and system design that includes four major components: (i) a PMM for defining the optimal amount of productivity matching: a) market demand and b) organizational requirements; (ii) a decision model for selecting an efficient layout that adapts to required productivity and product specs; (iii) an ASM for scheduling production activities and resources; and (iv) an optimization and simulation decision models for balancing MH operations.

1) In addition, the three innovative layout designs have resulted in substantial improvement in productivity. Furthermore, the dissertation research provides the MH industry with a real time method to streamline activities, thus eliminating bottlenecks. The DSS facilitates the evaluation and selection of efficient MH production systems, customized to user requirements. Additionally, the DSS assists the decision maker throughout sophisticated strategic and operational decisions, e.g., by (i) defining the economical product mix for efficient production planning, (ii) streamlining the activities of the production system, and (iii) selecting the most efficient layout, customized to market and organizational requirements. Based on the above discussion; this dissertation research culminates in a major contribution, which is a computerized decision support system, which provides the MHI with a valuable tool for designing efficient MH facilities and for evaluating the performance of
existing facilities.

7.5 **RECOMMENDATIONS FOR FUTURE WORK**

1) Incorporating equipment and machinery in the logic of the DSS framework. Moreover, automation is an important variable influencing productivity;

2) Customizing new MH systems for new building materials, which are an important variable influencing: production line activities, manpower requirements, available technologies, and processing time;

3) Developing an efficient master production schedule (MPS) by utilizing the data of the simulation models, producing a more accurate production planning process for MH systems;

4) Incorporating the parametric design software within the DSS components [i.e., BLOCKPLAN for inputting new layout designs (Mehrotra 2002)].

5) Incorporating advanced material requirement planning databases (Barriga 2003) with the other modules of the DSS.

6) Study the impact of new building materials and automated equipment and machinery on performance.

7) Apply the DSS in a case study and measure its increased productivity, cost effectiveness, and overall production efficiency.
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Expert Systems with Applications, 8 (1), 23–32.


9 APPENDICES: Run Results of the Simulation Models

Appendix 9.1 Run Results for Case Study 1

Beginning replication 100 of 100

ARENA Simulation Results
Ayman Abu Hammad - License #9400000

Summary for Replication 100 of 100

Project: NSF Manufactured
Analyst: Ayman Abu Hammad

Replication ended at time: 240000.0

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### ARENA Simulation Results

Ayman Abu Hammad - License #9400000

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Appendix 9.2  Run Results for Case Study 2

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ARENA Simulation Results
Ayman Abu Hammad - License #9400000

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Analyst: Ayman Abu Hammad                   Model revision date: 11/24/2002

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<td>(Insuf)</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Server 14_R Busy</td>
<td>.00000</td>
<td>(Insuf)</td>
<td>.00000</td>
<td>.00000</td>
</tr>
<tr>
<td>Server 10_11_R Availab</td>
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<td>(Insuf)</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td># in Server 8_9_R_Q</td>
<td>.00000</td>
<td>(Insuf)</td>
<td>.00000</td>
<td>.00000</td>
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<tr>
<td># in Server 3_R_Q</td>
<td>8.2571E-04</td>
<td>(Insuf)</td>
<td>.00000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Server 12_13_R Busy</td>
<td>.00000</td>
<td>(Insuf)</td>
<td>.00000</td>
<td>.00000</td>
</tr>
<tr>
<td>Server 4_5_R Busy</td>
<td>.00000</td>
<td>(Insuf)</td>
<td>.00000</td>
<td>.00000</td>
</tr>
<tr>
<td># in Server 2_R_Q</td>
<td>.00114</td>
<td>(Insuf)</td>
<td>.00000</td>
<td>1.0000</td>
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Server 10_11_R Busy     .00000     (Insuf)    .00000     .00000     .00000
# in Server 1_R_Q      .02730     (Insuf)    .00000     7.0000     .00000
# in Server 12_13_R_Q  .00000     (Insuf)    .00000     .00000     .00000
Server 8_9_R Available 1.0000     (Insuf)    1.0000     1.0000     1.0000
# in Server 6_7_R_Q    .00000     (Insuf)    1.0000     1.0000     1.0000
Server 3_R Available   1.0000     (Insuf)    1.0000     1.0000     1.0000
Server 15_R Available  1.0000     (Insuf)    1.0000     1.0000     1.0000
Server 2_R Available   1.0000     (Insuf)    1.0000     1.0000     1.0000
Server 3_R Busy        .00774     (Insuf)    .00000     1.0000     .00000
Server 8_9_R Busy      .00000     (Insuf)    .00000     .00000     .00000
Server 6_7_R Available 1.0000     (Insuf)    1.0000     1.0000     1.0000
# in Server 15_R_Q     .00000     (Insuf)    .00000     .00000     .00000

COUNTERS

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<tr>
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<tr>
<td>floors 85 ft productio</td>
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<td>Infinite</td>
</tr>
<tr>
<td>floors 55 ft productio</td>
<td>8</td>
<td>Infinite</td>
</tr>
</tbody>
</table>

OUTPUTS

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>TAVG(FLOORS 65 FT CYCL)</td>
<td>297.39</td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL)</td>
<td>392.74</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL)</td>
<td>297.98</td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL)</td>
<td>281.32</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL)</td>
<td>386.82</td>
</tr>
</tbody>
</table>

ARENA Simulation Results
Ayman Abu Hammad - License #9400000

Output Summary for 100 Replications

Project: Simulation Model         Run execution date: 12/18/2002
Analyst: Ayman Abu Hammad         Model revision date: 11/24/2002

<table>
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<th>Minimum</th>
<th>Maximum</th>
<th># Replications</th>
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<td>1.2757E-13</td>
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<td>6.9584E-14</td>
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<td>392.74</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL)</td>
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<td>9.2779E-14</td>
<td>297.98</td>
<td>297.98</td>
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<td>100</td>
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</tbody>
</table>

Simulation run time: 0.03 minutes.
Simulation run complete.
### Appendix 9.3  Run Results for the Generic U-Shape Layout

Beginning replication 100 of 100

**ARENA Simulation Results**  
Ayman Abu Hammad - License #9400000

Summary for Replication 100 of 100

Project: Simulation Model  
Run execution date: 12/18/2002

Analyst: Ayman Abu Hammad  
Model revision date: 11/24/2002

Replication ended at time: 210000.0

<table>
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<tr>
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<tr>
<td><strong>Observations</strong></td>
<td></td>
<td></td>
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<td>(Insuf)</td>
<td>0.0000</td>
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<tr>
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<td>(Insuf)</td>
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<td>floors 55 ft cycle tim</td>
<td>6989.6</td>
<td>(Insuf)</td>
<td>1909.8</td>
<td>10761.</td>
</tr>
<tr>
<td>floors 65 ft cycle tim</td>
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<td>(Insuf)</td>
<td>4930.6</td>
<td>10872.</td>
</tr>
<tr>
<td>Server 4_5_R_Q Queue Ti</td>
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<td>(Insuf)</td>
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</tr>
<tr>
<td>floors 75 ft cycle time</td>
<td>9391.7</td>
<td>(Insuf)</td>
<td>5870.0</td>
<td>10845.</td>
</tr>
<tr>
<td>Server 10_11_R_Q Queue Ti</td>
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<td>(Insuf)</td>
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<tr>
<td>floors 85 ft cycle time</td>
<td>569.90</td>
<td>(Insuf)</td>
<td>0.0000</td>
<td>1251.4</td>
</tr>
<tr>
<td>Server 14_R_Q Queue Ti</td>
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<td>(Insuf)</td>
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<td>0.0000</td>
</tr>
<tr>
<td>Server 15_R_Q Queue Ti</td>
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<td>0.0000</td>
<td>138.52</td>
</tr>
<tr>
<td>floors 45 ft cycle time</td>
<td>7560.3</td>
<td>(Insuf)</td>
<td>1438.9</td>
<td>10755.</td>
</tr>
</tbody>
</table>

| **DISCRETE-CHANGE VARIABLES**     |         |            |         |         |
| **Identifier**                    | Average | Half Width | Minimum | Maximum |
| # in Server 10_11_R_Q             | 0.06513 | (Insuf)    | 0.0000  | 7.0000  | .00000  |
| # in Server 14_R_Q               | 1.4299  | (Insuf)    | 0.0000  | 39.000  | .00000  |
| # in Server 4_5_R_Q              | 0.09193 | (Insuf)    | 0.0000  | 11.000  | .00000  |
| Server 4_5_R Available           | 1.0000  | (Insuf)    | 1.0000  | 1.0000  | 1.0000  |
| Server 15_R Busy                 | 0.00493 | (Insuf)    | 0.0000  | 1.0000  | .00000  |
| # in Server 8_9_R_Q              | 3.8758E-04 | (Insuf) | 0.0000  | 1.0000  | .00000  |
| Server 10_11_R Availab           | 1.0000  | (Insuf)    | 1.0000  | 1.0000  | 1.0000  |
| Server 14_R Busy                 | 0.05706 | (Insuf)    | 0.0000  | 1.0000  | .00000  |
| # in Server 2_R_Q                | 0.00161 | (Insuf)    | 0.0000  | 2.0000  | .00000  |
| Server 4_5_R Busy                | 0.01663 | (Insuf)    | 0.0000  | 1.0000  | .00000  |
| # in Server 1_R_Q                | 0.01768 | (Insuf)    | 0.0000  | 5.0000  | .00000  |
| Server 10_11_R Busy              | 0.02293 | (Insuf)    | 0.0000  | 1.0000  | .00000  |
| Server 8_9_R Available           | 1.0000  | (Insuf)    | 1.0000  | 1.0000  | 1.0000  |
| Server 2_R Available             | 1.0000  | (Insuf)    | 1.0000  | 1.0000  | 1.0000  |
| Server 15_R Available            | 1.0000  | (Insuf)    | 1.0000  | 1.0000  | 1.0000  |
| Server 2_R Busy                  | 0.00771 | (Insuf)    | 0.0000  | 1.0000  | .00000  |
Server 14_R Available  1.0000     (Insuf)    1.0000     1.0000     1.0000
Server 1_R Available   1.0000     (Insuf)    1.0000     1.0000     1.0000
Server 1_R Busy        .00873     (Insuf)    .00000     1.0000     .00000
Server 8_9_R Busy      .01111     (Insuf)    .00000     1.0000     .00000
# in Server 15_R_Q     .00000     (Insuf)    .00000     .00000     .00000

COUNTERS

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<tr>
<th>Identifier</th>
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<th>Limit</th>
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<td>floors 65 ft productio</td>
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<tr>
<td>floors 75 ft productio</td>
<td>10</td>
<td>Infinite</td>
</tr>
<tr>
<td>floors 85 ft productio</td>
<td>6</td>
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</tr>
<tr>
<td>floors 45 ft productio</td>
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<tr>
<td>floors 55 ft productio</td>
<td>8</td>
<td>Infinite</td>
</tr>
</tbody>
</table>

OUTPUTS

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>TAVG(FLOORS 65 FT CYCL)</td>
<td>9016.4</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL)</td>
<td>7560.3</td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL)</td>
<td>6989.6</td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL)</td>
<td>8861.4</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL)</td>
<td>9391.7</td>
</tr>
</tbody>
</table>

ARENA Simulation Results
Ayman Abu Hammad - License #9400000

Output Summary for 100 Replications

<table>
<thead>
<tr>
<th>Identifier</th>
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<th>Half-width Minimum</th>
<th>Maximum</th>
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<td>2989.6</td>
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<td>TAVG(FLOORS 45 FT CYCL)</td>
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Simulation run time: 0.03 minutes.
Simulation run complete.
Appendix 9.4  Run Results for the Spine Layout

Beginning replication 20 of 20

ARENA Simulation Results
Systems Modeling <user unknown> - License #9400000

Summary for Replication 20 of 20

Project: Simulation Model Run execution date: 5/30/2003
Analyst: Ayman Abu Hammad Model revision date: 5/30/2003

Replication ended at time: 42000.0

TALLY VARIABLES

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<td>(Insuf)</td>
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</tr>
<tr>
<td>floors 55 ft cycle tim</td>
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<td>(Insuf)</td>
<td>21636.</td>
<td>20</td>
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<tr>
<td>floors 65 ft cycle tim</td>
<td>15055</td>
<td>(Insuf)</td>
<td>21644.</td>
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<td>196</td>
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<tr>
<td>floors 75 ft cycle tim</td>
<td>15472</td>
<td>(Insuf)</td>
<td>21479.</td>
<td>18</td>
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<tr>
<td>Server 10_11_R_Q Queue T</td>
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<td>(Insuf)</td>
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</tr>
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<td>(Insuf)</td>
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<tr>
<td>floors 85 ft cycle tim</td>
<td>16936</td>
<td>(Insuf)</td>
<td>21512.</td>
<td>22</td>
</tr>
<tr>
<td>floors 45 ft cycle tim</td>
<td>19508</td>
<td>(Insuf)</td>
<td>21371.</td>
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DISCRETE-CHANGE VARIABLES

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<td>(Insuf)</td>
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<tr>
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<td>1.0000</td>
<td>(Insuf)</td>
<td>1.0000</td>
<td>1.0000</td>
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Server 1_R Busy 0.04548  (Insuf) 0.00000 1.0000 0.00000
Server 8_9_R Busy 0.11685  (Insuf) 0.00000 1.0000 0.00000
# in Server 15_R_Q 0.00000  (Insuf) 0.00000 0.00000 0.00000

COUNTERS

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<th>Limit</th>
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</tr>
<tr>
<td>floors 75 ft productio</td>
<td>18</td>
<td>Infinite</td>
</tr>
<tr>
<td>floors 85 ft productio</td>
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</tr>
<tr>
<td>floors 55 ft productio</td>
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OUTPUTS

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<tr>
<th>Identifier</th>
<th>Value</th>
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<tr>
<td>TAVG(FLOORS 65 FT CYCL)</td>
<td>15055.</td>
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<tr>
<td>TAVG(FLOORS 85 FT CYCL)</td>
<td>16936.</td>
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<tr>
<td>TAVG(FLOORS 55 FT CYCL)</td>
<td>14441.</td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL)</td>
<td>19508.</td>
</tr>
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ARENA Simulation Results
Systems Modeling <user unknown> - License #9400000

Output Summary for 20 Replications

Project: Simulation Model           Run execution date: 5/30/2003
Analyst: Ayman Abu Hammad           Model revision date: 5/30/2003

OUTPUTS

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<td>TAVG(FLOORS 45 FT CYCL)</td>
<td>12922.</td>
<td>3838.5</td>
<td>19508.</td>
<td>20</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL)</td>
<td>10560.</td>
<td>2484.5</td>
<td>15472.</td>
<td>20</td>
</tr>
</tbody>
</table>

Simulation run time: 0.02 minutes.
Simulation run complete.
Appendix 9.5  Run Results for the Central Layout

Beginning replication 100 of 100

ARENA Simulation Results
Ayman Abu Hammad - License #9400000

Summary for Replication 100 of 100

Project: Simulation Model  Run execution date: 12/18/2002
Analyst: Ayman Abu Hammad  Model revision date: 11/24/2002

Replication ended at time: 240000.0

TALLY VARIABLES

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Average</th>
<th>Half Width</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>floors 55 ft cycle tim</td>
<td>735.71</td>
<td>110.00</td>
<td>1350.0</td>
<td>42</td>
</tr>
<tr>
<td>floors 65 ft cycle tim</td>
<td>763.63</td>
<td>120.00</td>
<td>1370.0</td>
<td>44</td>
</tr>
<tr>
<td>floors 75 ft cycle tie</td>
<td>783.93</td>
<td>130.00</td>
<td>1390.0</td>
<td>33</td>
</tr>
<tr>
<td>Assembly Stations R_Q</td>
<td>645.75</td>
<td>.00000</td>
<td>1260.0</td>
<td>200</td>
</tr>
<tr>
<td>floors 85 ft cycle tim</td>
<td>731.05</td>
<td>170.00</td>
<td>1360.0</td>
<td>38</td>
</tr>
<tr>
<td>floors 45 ft cycle tim</td>
<td>809.53</td>
<td>110.00</td>
<td>1360.0</td>
<td>43</td>
</tr>
</tbody>
</table>

DISCRETE-CHANGE VARIABLES

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Average</th>
<th>Half Width</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Final</th>
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</thead>
<tbody>
<tr>
<td># in Assembly Stations</td>
<td>.53812</td>
<td>.00000</td>
<td>36.00</td>
<td>.00000</td>
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</tbody>
</table>

COUNTERS

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<thead>
<tr>
<th>Identifier</th>
<th>Count</th>
<th>Limit</th>
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</thead>
<tbody>
<tr>
<td>House 65 ft production</td>
<td>44</td>
<td>Infinite</td>
</tr>
<tr>
<td>House 75 ft production</td>
<td>33</td>
<td>Infinite</td>
</tr>
<tr>
<td>House 85 ft production</td>
<td>38</td>
<td>Infinite</td>
</tr>
<tr>
<td>House 45 ft production</td>
<td>43</td>
<td>Infinite</td>
</tr>
<tr>
<td>House 55 ft production</td>
<td>42</td>
<td>Infinite</td>
</tr>
</tbody>
</table>

OUTPUTS

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAVG(FLOORS 65 FT CYCL)</td>
<td>763.63</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL)</td>
<td>731.05</td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL)</td>
<td>735.71</td>
</tr>
<tr>
<td>TAVG(FLOORS 45 FT CYCL)</td>
<td>809.53</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL)</td>
<td>783.93</td>
</tr>
</tbody>
</table>
### ARENA Simulation Results

Ayman Abu Hammad - License #9400000

Output Summary for 100 Replications

<table>
<thead>
<tr>
<th>Identifier Replications</th>
<th>Average</th>
<th>Half-width</th>
<th>Minimum</th>
<th>Maximum #</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAVG(FLOORS 65 FT CYCL 756.72)</td>
<td>10.479</td>
<td>285.00</td>
<td>763.63</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 85 FT CYCL 725.07)</td>
<td>8.8479</td>
<td>351.33</td>
<td>731.05</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 55 FT CYCL 728.96)</td>
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<td>735.71</td>
<td>100</td>
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<td>TAVG(FLOORS 45 FT CYCL 802.26)</td>
<td>10.657</td>
<td>333.00</td>
<td>809.53</td>
<td>100</td>
</tr>
<tr>
<td>TAVG(FLOORS 75 FT CYCL 777.15)</td>
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<td>783.93</td>
<td>100</td>
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<td>TAVG(ASSEMBLY STATIONS 639.15)</td>
<td>9.7266</td>
<td>212.30</td>
<td>645.75</td>
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</tr>
</tbody>
</table>

Simulation run time: 0.02 minutes.
Simulation run complete.
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