Development of a Manufacturing & Business Planning Tool to Aid in Forward Planning

by

Michael J. Chrzanowski

B.S. Mechanical Engineering, GMI Engineering & Management Institute, 1990

Submitted to the Sloan School of Management and
the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science in Mechanical Engineering

In Conjunction with the
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Signature of Author ______________________________
Sloan School of Management
Department of Mechanical Engineering
May 7, 1993

Certified by ______________________________
Stanley B. Gershwin
Senior Research Scientist
Department of Mechanical Engineering

Certified by ______________________________
Stephen C. Graves
Professor of Management

Certified by ______________________________
Ain Sonin
Chairman, Department Committee
Department of Mechanical Engineering

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ABSTRACT

Managing multiple manufacturing facilities that produce variations of the same product can be difficult. Management is further complicated when the facilities have different manufacturing equipment, production capabilities, process flows, and cost structures. To help effectively manage such facilities, a structured management process must exist to evaluate the effects of manufacturing and allocation decisions, while minimizing the associated costs. Lack of such a process will most likely result in an operational plan that is inefficient and uncompetitive.

This thesis uses the known methodology of mathematical modeling to help evaluate the effects of potential manufacturing and management decisions on multiple facilities. The mathematical model developed in this thesis simultaneously minimizes the operating and investment costs of multiple facilities while meeting production demands.

The effectiveness of the mathematical model is demonstrated through several examples. One example centers on the allocation of 1994 production volumes for the organization where the thesis research was conducted. Comparison of their 1994 allocation plan to the one generated by the mathematical model, reveals the latter plan resulting in a $480,000 savings in yearly investment and operating expenses.

However, use of the mathematical model alone to effectively manage multiple facilities is not possible. It will be demonstrated in the thesis that supporting organizational and management processes must exist for the full benefits of a mathematical model to be realized. As a result, a general management framework and decision process is created to ensure the effective evaluation of different manufacturing and planning decisions on the facilities' financial bottom line. The mathematical model is a central part of this process. A final discussion on the implementation and continued development of the framework and mathematical model is included.

Thesis Supervisors

Stanley B. Gershwin, Senior Research Scientist, Department of Mechanical Engineering
Stephen C. Graves, Professor of Management, Sloan School of Management

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Thanks are due to my advisors, Professors Steve Graves and Stan Gershwin. Without their patience, input and guidance I might still be trying to develop a mathematical model. They were helpful in guiding me down the right path before I went too far astray.

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Chapter 1: Introduction

1.1 Overview

Today's marketplace is more competitive than ever. As globalization of world markets occur, competition arises from countries and companies that many US based companies have never anticipated. In today's market, it does not matter where you are, because distribution systems now give everybody access to every market. As a result, production capacity can come from anywhere. With increased world capacity many companies have come to the realization that they can no longer build two factories to meet anticipated demand. They must meet demand with one factory that is efficient, flexible and productive. In essence, they must do more with less. As a result, the utilization of production capabilities and personnel has become a key driver in the decision making of many US based companies.

Many large US companies operate manufacturing facilities in multiple locations around the world. These facilities often make the same or similar products. With seemingly excess capacity in every market and increased competition, the management and utilization of these multiple facilities is extremely important to the financial health of an organization. Without proper management, money can be easily lost. In this thesis, the development of a management process to aid in making ongoing decisions with regard to the forward planning of a particular company's current and proposed manufacturing facilities worldwide is sought. It is anticipated that the process developed here will help in determining how to best utilize existing facilities to achieve profitable results and incorporate proposed new facilities into the process.

1.2 Company Background

The company at which the research for this thesis was performed is referred to as the MJC company in this thesis. MJC is responsible for supplying several different components and assemblies for applications in one customer's product. This customer represents approximately 90% of MJC's business. The product MJC produces for this customer is referred to as a widget in this thesis. Due to the sensitive nature of this thesis and other proprietary information, all capacity data, production rates, operation times, and costs have been disguised. In addition, it was felt that the name of the company, its products and the customer should be omitted. Although this makes describing and understanding MJC's production process and product attributes difficult, it is the management process that is the subject matter of the thesis. The processes developed can be applied to other companies and is not solely suited to application at MJC.

MJC's largest volume manufactured component is the widget with over 60,000 being produced on a daily basis in 1992. MJC currently operates five semi-independent manufacturing areas in North America. Of these five manufacturing areas, three have overlapping capabilities to produce the same widget models. Depending on volume requirements, investment and production capabilities, widget volumes and models will be shifted among these three areas to meet daily demand. The shifting and scheduling of these models is complicated because each manufacturing area has different process equipment, different production costs, as well as different investment drivers.

1.3 Statement of the Problem

Beside overlapping widget production capabilities, MJC currently has excess production capacity and uncertain future production demands. This excess capacity and unused manufacturing flexibility result in operating inefficiencies that cost MJC money. The inefficiencies are in part due to the lack of a structured process to effectively evaluate how manufacturing and allocation decisions effect the widget business's financial bottom line. A structured management process to evaluate such potential decisions and aid in the forward planning of MJC's facilities worldwide has not been developed due to the complexity of the evaluation process and that until recently, there has not been an urgent need. The lack of urgency is due to the fact that MJC has consistently made money and is regarded as a world class supplier of widgets. However, with increased competition, the need for the development of a manufacturing and business planning tool to aid in MJC's forward planning and management decisions has dramatically increased.

1.4 Thesis Objective

The objective of this thesis is to develop a management process to aid in the forward planning of MJC widget manufacturing facilities. This process would help facilitate the following decisions:

- Yearly shifts in model allocations between facilities based on customer requirements and volume changes.

- Decision of which widgets should be manufactured at each location to minimize costs.
- On the basis of forecasted demand indicate how MJC should best utilize existing equipment to minimize costs.

The thesis research ensures that the process developed allows what-if evaluations to analyze the effects of different management decisions on the business. This thesis also details the current processes used to allocate production and proposes the use of a mathematical model to better evaluate potential decisions. Other objectives are to identify the resources and actions needed to successfully implement the use of mathematical models in MJC's decision making process.

1.5 Scope and Limitations

Due to the many issues involved in the development of a manufacturing and business planning tool, the scope of this project was limited to investigating the three areas of MJC with overlapping production capabilities. The production operation of each area and how forward planning is performed was investigated and analyzed. A mathematical model to aid in this planning was then developed. Finally, the incorporation of this model into a larger management process is detailed. The information presented in this thesis does not directly apply to any other area of MJC or any of its other products. The methods and procedures used in this investigation may, however, be altered to apply to other areas of MJC that are encountering similar problems.

In addition, the mathematical model and management process created are not in their final states. This thesis demonstrates the first steps towards the development of a tool that MJC can use on a daily basis to aid in its management of manufacturing facilities worldwide. Only with continued development can a process be developed that MJC's management feels comfortable with to aid in making tactical decisions.

1.6 Specific Deliverables of the Thesis

The writing of this thesis was done with several specific deliverables in mind for MJC and the reader. This thesis was intended to provide MJC a map to help it understand the various procedures undertaken during this thesis and to help it with continued development of the management process. The deliverables of this thesis are:

- Description and development of an optimization model to minimize yearly investment and allocation decisions for widgets at MJC.
- Description of the inputs and processes used to gather the inputs for the mathematical model.
- Analysis of the mathematical process and outputs.
- Development and description of a general management framework and decision process.
- Recommendations regarding the use and continued development of the general management process.

This thesis also demonstrates that a process using mathematical models can aid in the forward management of MJC's widget facilities.

1.7 Methods

At the beginning of the thesis investigation, a plan of attack was written. Discussion of this plan of attack is necessary to enable the reader to understand the methodology used to attain the goals of this thesis.

The approach used in developing the desired management process at MJC was similar to the reactive approach for problem solving, which consists of the following four steps: Plan, Do, Check and Act. During the thesis research, the first step (Plan) focused on identifying problems and collecting facts pertaining to MJC and its forward planning process. The second step (Do) identified the planning and implementation steps required of any improved ideas or new process. The third step (Check) involved the confirmation of the desired effects after implementation of the process. The fourth step (Act) would involve the standardization of the solution process at MJC. Due to the nature of the project and the limited time, only the first two steps were completed. Some work was performed on the third step also. However, it is strongly felt that completion of the first two steps is the most important part to the successful correction of any problem. By identifying the problems and pertinent information in step 1, and outlining the planning and implementation steps needed to solve MJC's forward planning problem in step 2, a foundation for implementing the solution process has been created.

1.8 Preview of the Discussion

The body of this report is broken into five main sections. The first section consists of Chapter 2. This section is designed to familiarize the reader with a widget and the production operations and capabilities of the three manufacturing areas considered in this thesis. The analyses of these areas provide a basis for the information used in the mathematical model and general management process. The second section of the thesis consists of Chapter 3. This section discusses MJC's current forward planning and widget allocation process. Current allocation processes are summarized and analyzed. The third section of the thesis consists of Chapters 4 and 5. This section discusses in detail the steps taken to identify and formulate a mathematical model to aid in forward planning. In addition, the mathematical model is evaluated to demonstrate its analysis capabilities and potential drawbacks. The fourth section, Chapter 6, describes a general management framework and decision process in which the mathematical model is used. This section examines the benefits of the process as well as implementation and development issues. The final and fifth section, Chapter 7, provides recommendations regarding this thesis and the use of a manufacturing and business planning tool to aid in forward planning at MJC.

Chapter 2: MJC's Production Operations

The widget is MJC's largest volume manufactured component with over 60,000 being produced on a daily basis in 1992. To achieve this volume, MJC operates five semi-independent widget manufacturing areas. In this thesis, three of these five areas are studied and are referred to as locations A, B and C. Sections 2.1 and 2.2 of this Chapter provide a brief description of a widget and how it is manufactured. Sections 2.3 through 2.6 discuss the production processes and capacities of areas A, B, and C.

2.1 Description of a widget

The majority of widgets MJC produces are for one customer's products. Once installed in the product, the widget serves as part of a larger central system that is integral to the function of the product. The widget model used in a system is dependent on the customer's product specifications. Since MJC's main customer produces a wide array of product configurations, a variety of different widget models are required.

Exhibit 2.1 illustrates a widget and some of its associated characteristics. The characteristics are its height, width, and depth, plus the configuration of its two subassemblies. A widget is often referenced to by its height, width and depth dimensions. When subassemblies are added to form the final product, it is referenced by a model number.

2.1.1 Widget sizes

Exhibit 2.1 illustrates the three dimensions that determine a widget's size. Size is important because it is one factor used in determining where a widget is produced within MJC. Exhibit 2.2 lists the 21 different sizes produced in the A, B and C production areas. The sizes are listed by depth, height and width and represent current production models. In these areas, MJC produces widgets with four different depths that are referred to as D1 through D4 in this thesis. In addition, three different heights and seven different widths are manufactured at MJC. These heights and widths are represented by H1 through H3 and W1 through W7 respectively. In Exhibit 2.2, each row represents a different widget size.

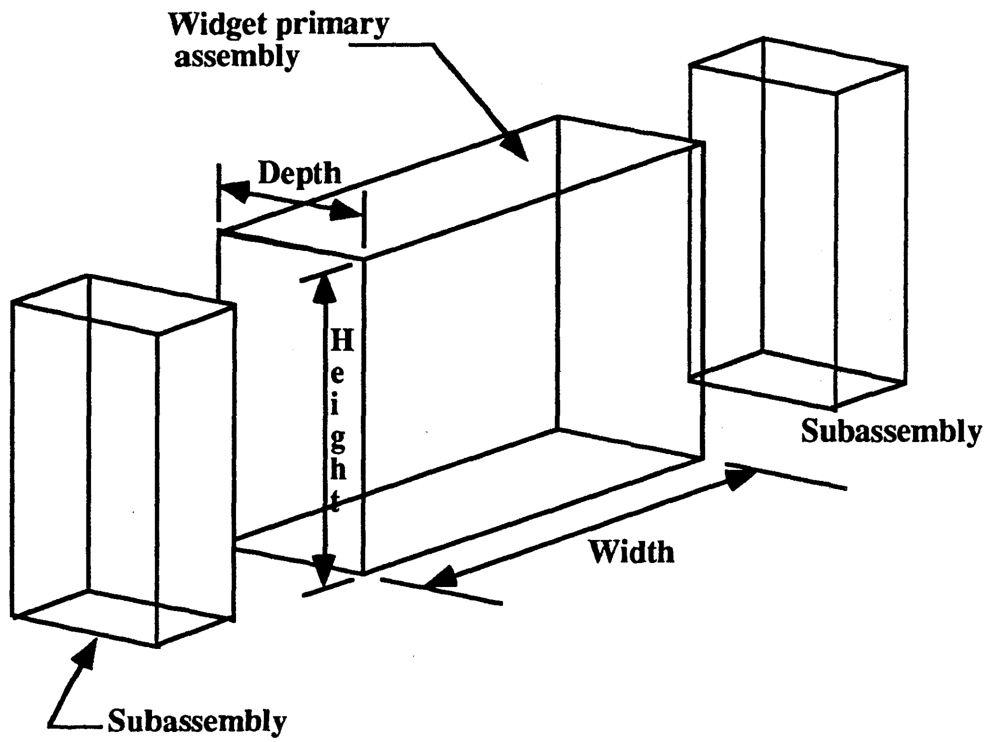

Exhibit 2.1 -- Widget primary assembly and subassemblies

Currently, MJC is trying to reduce the number of widget sizes produced. This is difficult to accomplish due to customer requirements, present capital equipment and product specifications. Additional sizes, called *service models*, are not listed in Exhibit 2.2. Service models are produced to replace previous model widgets sold to MJC's customer. Since MJC's customer produces a wide array of products, a proliferation of widget sizes is required.

Size #	Depth	Height	Width
1	D1	H2	W7
2	D2	H2	W2
3	D2	H2	W5
4	D2	H2	W6
5	D2	H3	W1
6	D2	H3	W2
7	D2	H3	W3
8	D2	H3	W5
9	D2	H3	W6
10	D2	H3	W7
11	D3	H2	W4
12	D4	H1	W2
13	D4	H2	W4
14	D4	H2	W5
15	D4	H2	W6
16	D4	H2	W7
17	D4	H3	W1
18	D4	H3	W2
19	D4	H3	W5
20	D4	H3	W6
21	D4	H3	W7

Exhibit 2.2 -- Widget Sizes Produced at MJC

2.1.2 Widget Subassemblies

All widget subassemblies possess similar features. However, the shape of the widget subassembly and the location of these features vary significantly. Changes in a widget's subassembly occur more frequently than changes in a widget's size. These subassembly changes are often driven by the customer's requirements. Although the manufacture of subassemblies is not dramatically affected by these changes, the alteration of a subassembly's characteristics can dramatically affect the final production process of a widget. If changes in a widget's subassembly are significant, then the final assembly equipment may not be able to process the new configuration. As a result, the production location of that widget model might have to be changed. Thus, besides widget size, subassembly configuration is another important factor in determining where a particular widget will be manufactured.

2.2 Overview of the widget production process

The manufacture of widgets at A, B and C occurs with different production equipment and assembly methods. Although the equipment and methods differ between areas, the basic principles used in the production of a widget are the same. Producing a widget consists of four stages: primary assembly, joining, final assembly and final testing.

2.2.1 Primary assembly of a widget

Primary assembly of a widget involves a series of manufacturing operations that assemble the widget's primary components into its desired dimensions. This assembly can be done manually, semi-automatically or fully automatically.

Manufacturing a widget with the desired dimensions is highly dependent on the primary assembly operation and the dimensional accuracy of the primary components. Assembling a widget that is perfectly rectangular in shape is very important to subsequent stages. Producing a widget that is out of square can result in a failed unit. Consequently, primary assembly is very important to the final quality of a widget.

2.2.2 Joining of the primary assembly

After primary assembly the widget is prepped for the joining operation. The joining operation's purpose is to form a permanent bond between the primary parts. Creation of these bonds is critical to the widget performing to the customer's application specifications.

The *manufacturing capacity* of each area studied is currently determined by the joining operation. Manufacturing capacity is defined as the number of widgets manufactured in an area during a production shift. Although the widget *model mix* can affect if the bottleneck is located at the joining operation or after it, production planning is based on the joining operation's capacity. Model mix refers to the number of different models scheduled to be produced in an area. An area with a high model mix will produce many different widget sizes every day.

2.2.3 Final assembly of the widget

After joining the widget is sent to final assembly. At the final assembly operation the proper subassemblies are attached to each widget. Since several different subassemblies are used for each widget size, the determination of which subassemblies to use depends on the daily production schedule. Properly attaching both subassemblies to a widget is important to achieve a perfect seal. If a perfect seal is not obtained, the unit will fail in the final testing operation.

As a note of reference, after the subassemblies have been added to the widget, the unit is referenced by its model number and no longer its size.

2.2.4 Final testing of the widget

Every widget at every manufacturing location is tested for an *Zeta defect.* A zeta defect is a defect that, if it goes undetected, will result in a failure. A zeta defect can be a result of several things. The most common reasons are problems due to improper primary assembly, lack of bonds formed between primary parts during joining or a poor seal between the subassemblies and the widget.

At MJC, several different final testing methods are used to perform the zeta test. Whether the final test can be performed on a widget or not depends on the shape of its subassemblies and the test equipment capabilities. Each area's final testing equipment processes a window of subassembly configurations. If a subassembly configuration falls outside this window, the unit must be manufactured elsewhere or investment made in the testing operation to enable it to process that configuration.

2.2.5 Restrictions on the widget manufacturing process

Each manufacturing area is capable of processing a number of widget models. These models are determined by the sizes and assembly configurations that the production equipment at each stage can process. Since each production operation is sensitive to different physical characteristics of the product, knowledge of these sensitivities is required to allocate production to the various manufacturing areas. For example, primary assembly equipment is capable of producing widgets with different heights and widths; however, it is limited to manufacturing one depth. To handle a second depth, other primary assembly equipment is required.

2.3 Area A's widget production process

The A production area consists of two nearly identical *manufacturing cells.* A manufacturing cell is a self contained production area that assembles and packs finished widgets. These cells utilize the latest automated assembly technology and operate using synchronous manufacturing principles. A's production process, capabilities and capacities are discussed below.

2.3.1 A's product process flow

Exhibit 2.3 presents A's widget manufacturing process flow for both cells. The product path flow is indicated by the arrows in the Exhibit.

Stage 1 consists of the automated assembly of the widget. The primary parts are assembled into the desired size through a series of automated operations. Stage 2 consists of two pre-joining operations. After the widget passes through the second pre-joining operation it proceeds to Stage 3. Stage 3, which is the joining operation, consists of five different stages. Once the widget enters this operation, operator intervention is impossible. After the widget has been joined, it is visually inspected and forwarded to the final assembly operation. Stage 4 consists of two separate activities. The first activity involves assembly operations on the subassemblies. The second activity is the attachment of the subassembly to the widget. After the subassembly has been attached, the widget passes directly to Stage 5, final testing. In each manufacturing cell there are four final testing stations. Each final testing station has been designed to process certain widget sizes and subassembly configurations. Any widget passing the test is sent to packaging. A widget that fails is sent to the repair station.

2.3.2 A's widget production sizes

Determining the manufacturing capabilities of each cell was done by analyzing the widget sizes (height, width, depth) that each cell could produce. The production cells are currently restricted to producing widgets with a D4 depth only.

Cell #1 manufactures widget with a height of H2 and H3. The different widths it currently processes are W3, W4, W5, W6, and W7. For 80% of the time, cell #1 processes widgets with a height of H3.

Cell #2 handles all D4 depth widgets with a height of H2 or H3, and a width of W2, W3, W4, W5, W6, or W7. Manufacturing a widget with a height of H1 in this cell requires equipment investment.

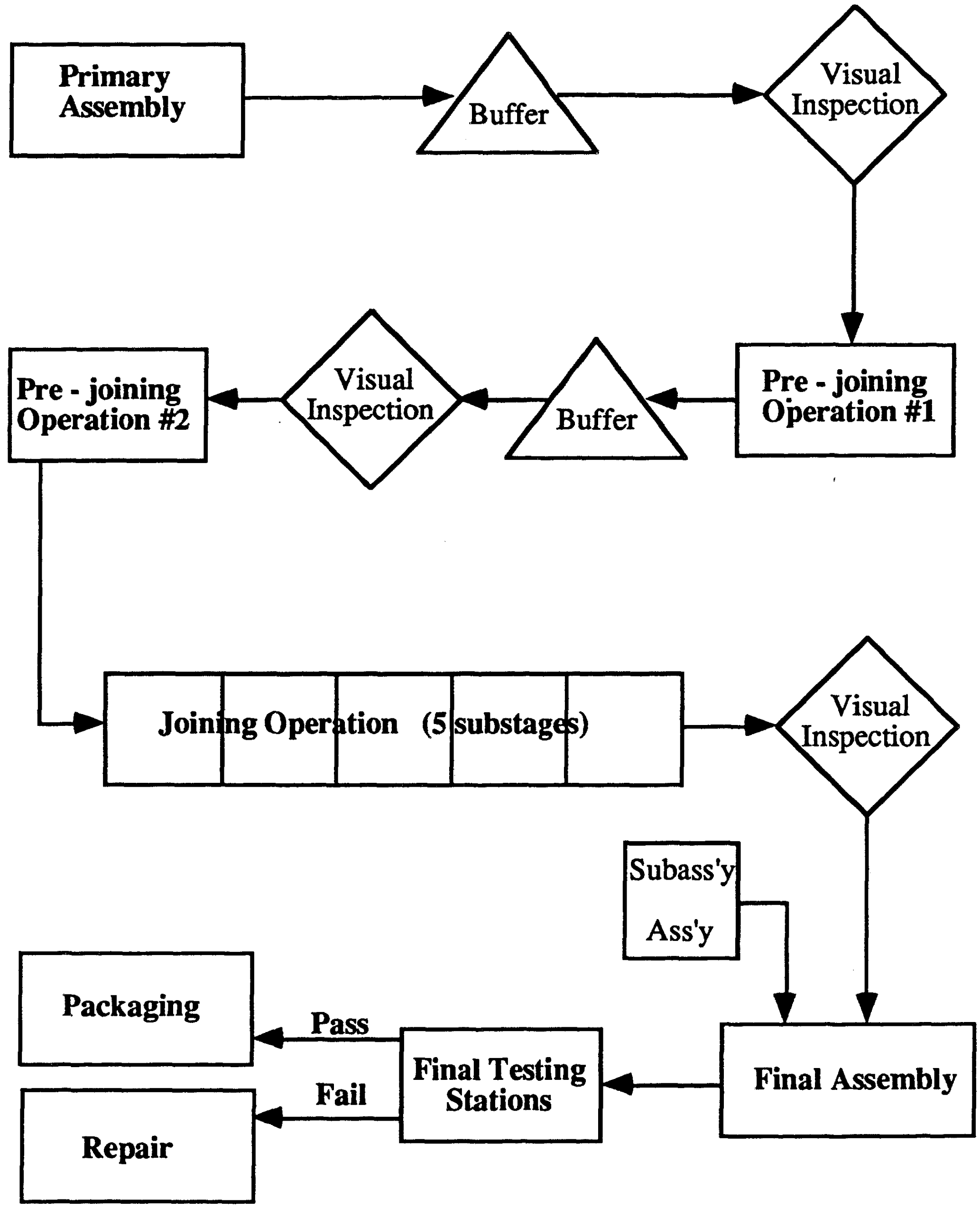

Exhibit 2.3 -- Product Process Flow of Area A

2.3.3 Throughput and bottleneck analysis of area A

At MJC, production is divided into three 8 hour shifts. The first shift starts at 10:30 PM, the second shift at 6:30 AM, and the third shift at 2:30 PM. Area A operates for two shifts, with each shift allotted a total lunch and break time of 48 minutes. Each cell's equipment is capable of operating three shifts; however, MJC's widget production capacity exceeds current market demand, thus eliminating the need for a third shift.

Both manufacturing cells were designed or rated to build a set capacity of widgets. Each cell is currently rated to produce 3,150 widgets per shift. On the basis of the current two shifts of operation for each department, total daily rated capacity is 12,600 widgets; 6,300 widgets per shift. These numbers were obtained from manufacturing engineering and are used for forward planning and volume allocation processes. To verify these figures, an analysis of current gross equipment production speeds for this thesis resulted in estimated gross capacities of:

Cell #2	3,336 widgets/shift
Cell #1	2,736 widgets/shift
Total Gross Capacity	6,072 widgets/shift

The calculated total gross capacity number differs from the rated capacity in that cell #2's calculated capacity is greater than cell #1. Total gross and rated capacity are almost identical (6,300 vs. 6,072) until *equipment uptime* and *first time through quality* are considered. Equipment uptime is the fraction of time that the equipment is up and running. First time through quality (FTTQ) is the yield obtained from the number of units entering a process and the number of units emerging with no defects. The ratio is expressed below:

FTTQ = (# units leaving process stage with no defects / # units entering process stage)

Factoring in 90% equipment uptime and 90% FTTQ, results in an adjustment to the calculated gross capacity. These adjusted figures are referred to as a cell's net capacity figure.

Cell #2	2,703 widgets/shift
Cell #1	2,217 widgets/shift
Total Net Capacity	4,920 widgets/shift

Based on two shifts of production, the difference between the calculated total net production (4,920) and the total rated capacity (6,300) is 22%. This significant capacity difference will affect the volume allocation of widgets to these areas. To determine which capacity number should be used for planning purposes, a comparison of these figures to actual production was performed. Actual build capacity for 50 two shifts of production from April 23 to July 6, 1993, is shown on the next page.

Average widgets built per shift

	Cell #2	Cell #1
* 50 day Average	2,780	2,520
High over 50 days	3,549	3,171
Low over 50 days	1,809	1,539

The calculated net capacity figures of 2,703 (cell #2) and 2,217 (cell #1) are within 12% of the 50 day build averages. Comparing the total of both cells (4,920) to the total 50 daily build average (5,300), the net capacities are within 7.2%. Even though the net capacity numbers represent averages and do not take into account production fluctuations, these numbers are more representative of the cells' actual production capacities than the rated capacities. Determination and verification of actual capacities are critical to the forward planning activities of MJC and subsequent analyses performed in this thesis.

The bottleneck operation of each cell is its joining operation. In both cells, the joining equipment is currently operating at its limit; whereas, the cells' other production equipment is not. For planning and capacity analysis, each manufacturing cell's capacity is determined by the joining operation's capacity.

For forward capacity planning it was noted that changes in a widget's width do not affect the net capacity of either cell after setup changes had been made. However, changes in a widget's height affects the capacity of cell #2 by a factor that is the ratio of H3 to H2.

2.3.4 Area A desires to produce the high volume D4 widgets

Due to the high level of automated assembly equipment in each cell, minimization of changeovers is highly desired. In producing a lower model mix, there are fewer changeovers, less downtime, and both cells can achieve targeted volumes faster. As a result, area A has traditionally produced the high volume D4 widget models.

2.4 Location B's widget production process

Although area B is located in the same plant as A, it uses different primary assembly, joining and final assembly equipment than A. A second significant difference between these areas is the multiple paths a widget can take during the primary assembly operation of area B. A third difference is area B manufactures widgets with depths of D2, D3, and D4. Its process flows, production capabilities and capacity are discussed below.

2.4.1 B's product process flow

Exhibit 2.4 depicts B's widget manufacture process flow. Stage 1 of this process flow is the primary assembly of the widget into its desired size. Primary assembly in area B, consists of three separate manufacturing stations. Stations #1 and #2 consist of multiple machines that are capable of processing only one widget depth each. However, each station has capabilities to process several different heights and widths for its depth. The only manufacturing station shared by the different depth widgets is station #3. It is flexible enough to process any size widget.

Unlike A, B has only one pre-joining operation. Stage 2, the joining operation, consists of three parallel joiners. These joiners use a different technology than area A, to form a permanent bond between the primary parts. Each joiner can process any size widget in batches of 105. The only restriction is that the widgets in a batch must all be the same depth. In addition, each joiner's cycle time is affected by the widget's depth.

Stages 3 and 4 involve the final assembly and final testing of the widget. Area B has four processing lines to accomplish these two operations. The equipment and processes used in each line are slightly different. Some lines automatically assemble and test the widget on one piece of equipment; others semi-automatically assemble and automatically test the widget on separate equipment. Like area A, each line is limited to processing a window of widget sizes and subassembly configurations.

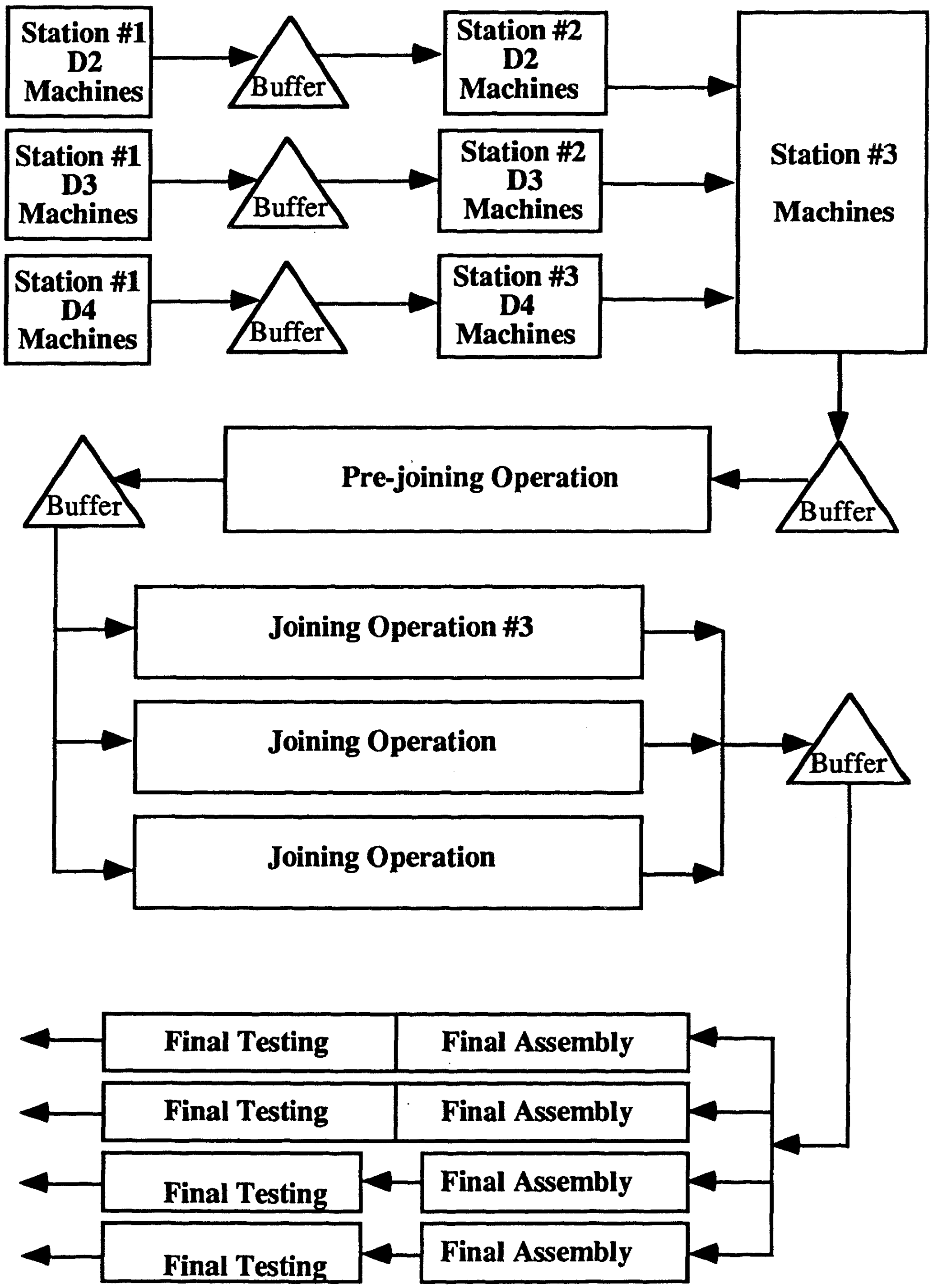

Exhibit 2.4 -- Product Process Flow of Area B

2.4.2 B's widget production sizes

Area B manufactures widgets with depths of D2, D3, and D4. Exhibit 2.5 lists the widget sizes produced at B in 1992. Area B also produces 19 of the 21 different sizes manufactured in the three areas studied in this thesis. The large combination of widget sizes and associated subassembly configurations result in a substantial model mix for B.

Size #	Depth	Height	Width
1	D2	H2	W8
2	D2	H2	W2
3	D2	H2	W5
4	D2	H2	W6
5	D2	H3	W1
6	D2	H3	W2
7	D2	H3	W5
8	D2	H3	W6
9	D2	H3	W7
10	D3	H2	W4
11	D4	H1	W2
12	D4	H2	W4
13	D4	H2	W5
14	D4	H2	W6
15	D4	H3	W1
16	D4	H3	W2
17	D4	H3	W5
18	D4	H3	W6
19	D4	H3	W7

Exhibit 2.5 -- Widget Sizes Produced in area B

2.4.3 Throughput analysis and bottleneck identification of B

Due to the complexity of multiple process flows and equipment capabilities, analyzing capacity at the same level of detail as was done for A was not possible. However, capacity and bottleneck analysis was accomplished by analyzing the gross capacity and production rates of the various stages of production, independent of the model mix. This analysis resulted in the following capacities (widget/shift) for each stage of production. It should be noted that this analysis did not take into account variations in the production process, downtime and first time through quality.

Stage 1	Stage 2	Stage 3	Stage 4
18,960	9,900	8,715	12,600

Like area A, the joining operation (Stage 3) limits the capacity of area B. Its capacity is set by the cycle time of each joiner. Comparing the production capacity of Stage 3 to the other stages, it is evident that excess capacity exists at the primary assembly (Stage 1) and final assembly/testing operations (Stage 4). This excess capacity is an indirect result of B's high model mix. Because its primary and final assembly operations require frequent changeovers and downtime to process the high model mix, extra equipment is used to minimize downtime. In contrast, the pre-joining and joining operations are relatively insensitive to model mix and widget size. Thus changeover time is minimal and extra equipment is not needed.

B's capacity is based on the cycle time of the joiners. In turn, the joiners' cycle times are determined by the depths of widgets they process. Depth D2 widgets have the shortest cycle time. D3 depth widget's cycle time is 30 seconds longer than D2's. D4 widget's cycle time is 90 seconds longer than D2's. These cycle time differences can dramatically affect the capacity of an area. Consequently, B's joining capacity is dependent on the number of widgets processed for each depth.

Based on proprietary cycle time analyses and historical information, it was determined that 8,715 widgets can be joined every shift. This results in a daily production capacity of 26,145 widgets based on all three joiners operating three shifts. For forward planning and volume allocation purposes this is the capacity number used to determine the widget volume that can be allocated to area B.

2.4.4 B's widget model mix philosophy

Due to B's flexible stage 1 operation and extra equipment, it produces a much higher product mix than A. B has the ability to produce almost any widget model that has a depth of D2, D3 or D4. In 1992, B produced 32 current models and 98 service models. The average daily volume for each current model was 597 widgets. The average daily volume for each service model was 12 widgets. In contrast, A's manufacturing cells produced 28 current models and 22 service models. B's large number of service models and associated low volumes result in frequent changeovers and scheduling problems.

2.5 Area C's widget production process

The C production area is located in another plant and for the most part operates independently of areas A and B. The production equipment it uses in the primary assembly, final assembly and final testing stages is different from the equipment and processes used in either A or B. C uses a mixture of automated assembly and manual assembly techniques to manufacture its widgets. It then uses a high level of automation to perform the final test and move the widgets to packaging. The only similarity C has with the other areas is that it uses the same joining equipment that B does.

C's production process was analyzed in the same manner as A and B; however, the detailed results of that analysis are not presented.

2.5.1 C's production process

C uses both automated and manual assembly equipment in the primary assembly of its widgets. It currently assembles widgets with a depth of D2 and D4. In 1993, it is scheduled to start production of D1 depth widgets. C's primary assembly area is divided into sub-areas based on depth. The D4 primary assembly sub-area uses both automated and manual assembly methods. The D2 sub-area uses automated assembly for 90% of its production. Finally, the D1 widgets will be assembled using only automated equipment.

The second stage of the production process, the pre-joining operation, is similar to the pre-joining operation of area B. After the widgets have been processed through the pre-joiner, they enter the joining operation. C uses two joiners whose operating cycle times depend on the widget depth being processed. The joining operation runs for three shifts. One difference in the way C operates its joining machines in comparison to B is that it restricts joiner #1 to processing only D2 or D4 widgets. It restricts joiner #2 to processing D1 or D2 depth widgets.

After joining, the widgets move to the fourth stage, final assembly. Final assembly uses both automated and manual methods to attach the subassemblies to the widget. After final assembly, the widgets are tested. C's final testing equipment is similar A's and B's, but is capable of processing a larger number of subassembly configurations.

2.5.2 C's widget production sizes

Exhibit 2.6 lists the nine different sizes produced at C in 1992. With minimum investment C could produce additional widths for its D2 and D4 depth widgets. C's model mix is greater than A's, but smaller than B's.

Size #	Depth	Height	Width
1	D2	H2	W6
2	D2	H3	W1
3	D2	H3	W2
4	D2	H3	W5
5	D2	H3	W6
6	D2	H3	W7
7	D4	H2	W7
8	D4	H3	W1
9	D4	H3	W6

Exhibit 2.6 -- Widget Sizes Produced at C in 1992

2.5.3 C's production capacity

C's current production capacity is limited by its joining capacity which is rated at 16,800 widgets per day. This number is based on three full shifts of production on the two joiners. Like B's, C's joiners' cycle times are sensitive to widget depth and they must process batches of widgets with the same depth. In January 1992, an analysis of the throughput rates for the different depth widgets was performed. The results of that analysis are:

Depth	Production Rate/Joiner	
D1	558 widgets/hour *	
D2	426 widgets/hour	
D4	303 widgets/hour	* - estimated

Based on 24 hours of production, the maximum capacity of C would be 26,784 widgets. That is for processing only D1 widgets in each joiner. The minimum capacity based on 24 hours of D4 processing would be 14,544 widgets. Obviously, rated capacity is dependent on the number of widgets processed for each depth. However, based on historical information and model mix, for forward planning purposes C's rated capacity is 16,800 widgets per day.

2.6 MJC's Production capabilities

Even though the three areas discussed have different production processes, each area manufactures similar widget sizes and models. A, B, and C have overlapping production capabilities. For MJC, maximizing the equipment and production capabilities of these areas is crucial. In the highly competitive market in which it competes, MJC can not afford to add new equipment without first maximizing its present capabilities. However, determining how to perform this maximization has been a problem for MJC.

Currently, MJC has five widget manufacturing areas in North America. Two of these areas serve niche customer markets. The remaining three manufacture widgets that any one of the three could manufacture. If a customer requests a particular type of widget, and it is a particular niche model, there is no question which niche manufacturing area will produce it. In contrast, if the customer requests a standard widget, it could be produced in one areas, A, B or C. The problem with this situation is determining which area to manufacture it in. Answer this question is difficult due to the large number of models and production possibilities. The answer is now more important than ever when future production forecasts are considered.

Forecasts for 1993 show daily production requirements of approximately 45,000 units per day. These are the widgets to be produced in A, B and C. Analysis of these areas resulted in the following daily capacity estimates.

Area	Capacity
A - cell #1	4,434 *
A - cell #2	5,406 *
B	26,145
C	16,800
Total Capacity	**52,785**

* - 2 shift capacity

Capacity exceeds demand by 7,785 units per day. This poses problems in determining how to best allocate the demand of 45,000 widgets to the different areas to minimize associated costs. Operating each area at 85% utilization is not very cost effective for MJC.

Chapter 3: MJC's Forward Planning and Allocation Process

MJC's excess capacity and high levels of unused flexibility create operating inefficiencies that cost money. These inefficiencies are a result of its lack of a structured process to effectively evaluate how potential manufacturing and allocation decisions effect the widget business's financial bottom line. This chapter summarizes MJC's current forward planning and widget allocation process for A, B and C. Section 3.1 examines the process of how new widget models are released into production. Section 3.2 reviews the process of how MJC allocates production volume between A, B, and C. Section 3.4. discusses problems with these processes.

3.1 How new widgets are incorporated into MJC's production plan

Approximately 80% of the widget models produced in locations A, B and C are *carry over* models. A carry over is a widget model whose design has not changed from the previous production year. The other 20% are widgets whose designs have changed. Design changes might be as simple as a slightly reconfigured subassembly or as complex as a new size and subassembly configuration. When a widget design changes, its manufacturing location must be re-examined. MJC's process for incorporating new and redesigned widget models into production is summarized in the following subsection. Highlighted are the factors that MJC considers in its allocation decisions and the complexities associated with making those decisions.

3.1.1 Incorporating new widget designs into production

New widget designs are driven by customers whose product applications have or will change. In turn, changes in the customer's product often require changes in the widget. MJC's Product Engineering department will work with a customer to develop a widget to meets its needs. After a suitable widget design has been completed, the decision of where it will be manufactured is made. In addition, probable associated investment cost is evaluated.

Determining where the new widget will be manufactured is performed by a member of forward planning. The following criteria are used to assign the new widgets to a manufacturing area.

1. Examination of the widget's size and which area can manufacture it.
2. Assessment of which area can perform final assembly and test for a widget's subassembly configuration.
3. Evaluation of projected production volume and available production capacity.
4. General feeling of which area can manufacture it with the least investment.

After a suitable manufacturing area is decided the widget model with its projected volume is entered into MJC's Five Year Manufacturing Plan.

To verify the designated area can build the widget model with minimal investment, the area's product manager will evaluate the new design to determine projected investment costs. To do this the area manager first notes which widget components have been redesigned or altered. The supervisor then asks the manufacturing engineers responsible for the parts and processes affected by the changes to determine the investment and tooling required to produce and assemble the new widget. In addition, the engineer will evaluate the labor hours needed to assemble the widget. All information gathered is fed into MJC's Estimating On-Line Computer System. This system will run a cost explosion to determine unit cost, unit cost change, and summarizes investment required for each widget.

The unit cost and investment information are then presented to the Widget Business Unit managers for their approval. Once approval is obtained, a quoted unit price can be provided to the customer. After the customer accepts the price and signs a contract, the required investment will be allocated to the manufacturing area.

Finally, the new widget is placed into MJC's Five Year Manufacturing Plan with its appropriate production volume. The area scheduled to manufacture the new widget will start planning for its manufacture.

3.1.2 Several factors that affect the production location decision

Determining where a new widget is to be manufactured and its associated cost is a complex process. It requires information from cost estimators, forward planners, purchasing agents and manufacturing engineers. As documented, the majority of the information is provided by the proposed production area. After examining the entire process, it has been concluded that two factors significantly drive the allocation decision. These are available production capacity and minimization of new investment.

Minimizing potential investment is important to MJC or any company. During the allocation decision process, the emphasis is on minimizing the capital needed to manufacture a new widget. As a result, a majority of the time is spent trying to use present capabilities to avoid spending capital funds. As a general rule, if a new widget can be readily manufactured in one area with much less investment than another, it will be allocated to that area. Production volume will be shifted to accommodate the new model, if necessary. This all occurs with the goal of minimizing unnecessary investment and using existing capabilities.

Available capacity, the other important factor considered in the allocation decision process, encompasses two items: equipment capacity and production capacity.

Equipment capacity is the volume an area possesses to produce or process a particular type of widget. It is considered when the volume of the new design and of the other widgets already allocated to that area might exceed the available equipment production capacity. An example, is if a new D4 design is placed into B, and the increased D4 volume requires additional D4 primary capacity. Consequently, equipment capacity is very dependent on the model mix and volume assigned to an area.

Production capacity is the number of widgets an area can produce on a daily basis. It is determined by the available production time at the joining operation. Available production time is also dependent on what other widgets have been allocated to an area.

The difference between equipment capacity and production capacity is that equipment capacity is considered for each stage of the production process. Whereas, production capacity is only considered and related to the joining operation of an area.

Both equipment and production capacity are dependent on what other widget models have been allocated to an area. Both capacities are considered in determining whether an area can produce a widget or not; however, knowledge of production capacity is more important than equipment capacity. The reason is investments in additional equipment capacity are avoided when MJC is currently overcapacitized.

3.2 MJC's widget model allocation process for A, B, and C

The process described in Section 3.1.1 is for the allocation and release of new widget models to the A, B, C manufacturing areas. Allocation of the remaining widget volume (carry over models) happens independently of this process. This allocation, which is summarized below, is overseen by a member of forward planning, who acts as a facilitator between the different production areas. The goal of the process is to equalize utilization of the areas. By doing this, disagreements between areas over budgeted volumes are eliminated.

The process starts by calculating each area's capacity as a percentage of MJC's total capacity, which is 52,785 widget per day. For example, area B's daily capacity is

26,145 widgets. This represents 49.7% of MJC's total capacity. Next, the forecast production volume is multiplied by these percentages. The multiplication of these percentages by total capacity results in the targeted production volume for each area.

Often the production volumes assigned to each area in MJC's Five Year Plan do not match the targeted production volumes calculated above. To rectify these differences, a proposed allocation plan is generated by the forward planning member monitoring this process. This plan is submitted to the area's assistant product managers. From this point on, negotiations occur as to which widget models each area will give up to attain the targeted volumes. The plan submitted by forward planning is used as a guideline. After several rounds of negotiations, the managers will have determined which models their area will produce. The Five Year Manufacturing Plan is updated to reflect any changes.

After the volume levels and models are set for a year they rarely change. However, additional shifting might occur midway through a year if a new model is being introduced or if the forecast production volumes have significantly changed and an area is running well below capacity. The goal of any additional shuffling is to try to ensure that each area is operating at an equal utilization level.

3.3 MJC's manufacturing plan

The design of a new widget and its incorporation into production takes time. For example, to produce a totally new widget in 1993, design and planning had to start in 1990. Since widget volumes and designs continually change, this information must be continually revised and incorporated into MJC's production planning process. The means to accomplish this is through MJC's Five Year Manufacturing Plan.

3.3.1 MJC's Five Year Manufacturing Plan

Information regarding current and future widget models is documented in MJC's Five Year Manufacturing Plan. The Five Year Plan allows each production area to know what widget models will be or are scheduled for production in the next several years. Exhibit 3.1 is an example of one page of this plan. This page contains the widget model, its physical dimensions and anticipated daily production volumes from 1992 to 1996. By looking at a widget model over a five year time frame, product managers can determine when it will be introduced and when it will be discontinued. It allows manager to know what they will have to be prepared to manufacture in future years. For example, by looking at widget #29, a manager knows he/she has to start producing it in 1993 and its production will cease after 1995.

Widget	Proposed	Physical	Size		Daily		Production	Volume	
#	Location	Height	Width	Depth	1992	1993	1994	1995	1996
1	j=1	H3	W7	D4	0	0	585	585	585
2	j=1	H3	W7	D4	0	0	1371	1371	1371
3	j=1	H3	W7	D4	0	0	174	174	174
4	j=1	H3	W7	D4	0	0	399	390	390
5	j=2	H3	W7	D4	0	0	393	393	393
6	j=6	H3	W7	D2	0	0	1539	1548	1524
7	j=4	H3	W7	D4	0	0	138	138	138
8	j=5	H3	W7	D2	0	0	42	30	30
9	j=1	H3	W7	D4	0	0	51	54	51
10	j=1	H3	W7	D4	0	0	450	483	456
11	j=1	H2	W7	D4	0	744	927	909	897
12	j=5	H3	W3	D2	0	180	183	198	207
13	j=5	H3	W3	D2	0	1260	1302	1362	1425
14	j=4	H3	W3	D4	0	192	195	177	162
15	j=4	H3	W3	D4	0	702	720	663	603
16	j=6	H3	W7	D2	0	0	6	0	0
17	j=6	H3	W7	D2	6	45	30	33	0
18	j=4	H3	W7	D4	0	3	3	3	0
19	j=4	H3	W7	D4	0	0	12	6	0
20	j=4	H3	W7	D4	0	36	27	24	0
21	j=4	H3	W7	D4	0	198	30	138	0
22	j=4	H3	W7	D4	0	0	33	27	0
23	j=4	H3	W7	D4	0	72	45	51	0
24	j=4	H3	W7	D4	0	57	45	42	0
25	j=4	H3	W7	D4	0	231	165	159	0
26	j=4	H3	W7	D4	0	273	267	189	0
27	j=5	H3	W1	D2	0	6	3	3	0
28	j=5	H3	W7	D2	0	0	6	9	0
29	j=5	H3	W7	D2	0	54	36	36	0
30	j=5	H3	W7	D2	156	183	45	126	0
31	j=5	H3	W7	D2	0	0	78	0	0
32	j=5	H3	W7	D2	564	645	96	411	0
33	j=5	H3	W7	D2	0	0	360	0	0
34	j=5	H3	W6	D2	0	249	249	249	249
35	j=5	H3	W5	D2	18	21	21	24	21
36	j=4	H3	W5	D4	0	0	945	945	993
37	j=4	H3	W6	D4	0	0	27	123	120

Exhibit 3.1 -- One page of MJC's Five Year Manufacturing Plan

The Plan is important because it provides a centralized database where changes with a widget and its associated information can be reflected. As volume changes occur or where a widget is to be manufactured, the plan is reviewed and updated. Placement of this information in a central database is critical for successful planning, because it is the best means to communicate changes to the different production areas. For the entire widget business there are over 40 pages similar to Exhibit 3.1.

The production volumes in the Five Year Plan are provided to MJC by its main customer. The accuracy of these volumes, especially future years are subject to debate at MJC. Errors and varying demand for the customer's product often make these forecasts unreliable and inaccurate. In addition, MJC will adjust volume forecasts for particular models if they feel they are unreasonable. These adjustments are based on historical data and past production trends. However, the manufacturing plan is still the best way to communicate production changes to each area, even if all data is not 100% accurate.

3.4 Problems with the current allocation process

The current allocation processes adequately distribute production volume among the three manufacturing locations. However, the processes are not optimal and money could be saved with the use and development of a better planning tool. It is felt by planners that the current allocation processes could be improved with documentation of investment information and interactions between areas and widget models. However, even with better information, fundamental problems exist with the current processes that prevent MJC from obtaining any measurable monetary savings. An examination of these problems is provided.

3.4.1 Minimizing investment decisions by hand is not possible

An important part of both processes discussed in this chapter is the decision of where a widget will be manufactured. The majority of these decisions are made by one person, whose goal is to minimize investment based on his/her knowledge of each manufacturing area. With approximately 50 new designs being incorporated into MJC's manufacturing plan every year, it is impossible for one person to minimize the investment required for all these designs one at a time and by hand. The best one can do is to minimize the investment associated with each design as it needs to be incorporated into production. However, doing this does not result in an optimal solution. The reason is the decision to allocate one model at say C, might eliminate the possibility to allocate a second model there. As a result, this second model must be allocated to area A or B, where the investment required is twice the amount that would be required at C. Thus, an allocation decision made for one model affects subsequent allocation decisions. To eliminate this problem, investment relationships between all new designs and areas would have to be known. Then minimization of the costs for all new designs could happen simultaneously to consider all investment scenarios. However, to effectively consider all possible scenarios a computer model would be needed. Minimizing these costs by hand would be very hard.

3.4.2 Catch-22: Investment determined by allocation. Allocation determined by investment.

The decision of where to manufacture a new widget is complicated. This is due to the fact that the allocation decision is dependent on investment and determining investment is dependent on allocation. The catch-22 situation leads to the conclusion that investment is closely tied to an area and its proposed model mix. The only way to effectively determine where to produce each model is to simultaneously consider the investment required for every model at every possible location. The problem is that with the current estimating process, determining this information would be cumbersome and very time consuming.

Investment estimates are further complicated when other widget models scheduled to be manufactured in an area are considered. For example, if two models, both requiring investments, are produced in the same location, then the total investment might be less than if the models were produced in separate areas. Such relationships would have to be determined, documented and simultaneously considered as well. The problem is that determination and documentation of these relationships does not occur at MJC.

Thus as expected, investment estimates at MJC are very sensitive to each production area's capabilities, current and proposed model mix.

3.4.3 Lack of documentation of interactions and inputs

The current allocation processes are hampered by lack of documented information regarding investments, production capabilities and interactions between and within production areas. Without such information, planners rely on their own knowledge or information supplied by each area. The inevitable result of decisions made on limited information is that they are not optimal.

One area where lack of documentation adversely affects decisions is interactions between and within production areas. For example, MJC lacks a process to identify which widget models can be produced in multiple areas without investment. In addition, if interactions within an area are known, often they are not communicated to the other production areas or the planners. Without documentation of these interactions and others, proper allocation of widget models is impossible.

Lack of documentation also occurs with the inputs used in MJC's past allocation decisions. These decisions were subjective and affected by the personalities of area managers. Therefore, the inputs used to decide where a widget is produced and their relative importance is unclear. By not identifying what inputs are used and why, improvements to these processes are prevented. The lack of documentation needs to be addressed in any proposed improvements to MJC's planning and allocation processes.

3.4.4 Process is adversely affected by equalization of underutilization

MJC's policy of equalizing utilization rates among the three areas significantly affects the allocation process. This policy forces widget models to be moved from one production area to another to achieve desired utilization levels. This contributes to the sub-optimization of the entire widget business, costs MJC money, and forces areas to juggle production volumes.

3.4.5 Processes lacks robustness and prevent systems analysis

Another problem with MJC's current processes is that they result in a short term manufacturing plan. MJC tries to create an allocation plan that minimizes investment over a five year period, but in reality the plan is good for only one year. The reason is that trying to obtain relevant information for next year's plan is difficult enough, let alone for the next four. MJC needs robust processes to help it minimize costs over a multi-year time frame.

This lack of robustness is also a problem in that evaluations can not be readily performed. As soon as one part of the allocation plan changes the current analysis is obsolete. Hence, performing any type of what-if analysis based on a current formulation is not possible. New analyses must be performed every time.

Finally, the current processes do not encourage a system evaluation of the widget business. The shortcomings in the processes and information provided prevent forward planners from examining what is best for the entire widget business. Consequently forward planning and allocation decisions are made with the goal of optimizing each area separately. Managers and planners will not be able to evaluate manufacturing and allocation decisions until a system viewpoint and structure analysis method is developed.

3.4.6 Current processes cost MJC money

As demonstrated, the current processes MJC uses are slightly unstructured. Although they are adequate to get the job done, they can be improved on. The main problem is that they result in sub-optimal decisions. The monetary loss due to these sub-optimal decisions could not be determined. But, based on an analysis presented in Chapter 5, it is safe to estimate MJC could save approximately $500,00 dollars a year with better processes.

In addition to the monetary loss, MJC loses valuable personnel time due to its current processes. The production plan must be re-evaluated whenever something changes at MJC. This requires engineer's time, manager's time, and planner's time. In lieu of its current processes, MJC needs a process it can build on, learn form and indicate where better and more detailed information is needed.

Chapter 4: Mathematical Model to Allocate Widget Production

Based on the analysis of MJC's widget forward planning process, it is evident that a tool to assist MJC in its forward planning and widget allocation process is needed. Pursuit of such a tool to facilitate this process and help evaluate potential allocation decisions started with structured interviews to obtain the Voice of the Customer. Section 4.1 presents results of these interviews. Section 4.2 relates how the interviews led to the decision to pursue the creation of a mathematical model. Derivation of this mathematical model is provided in Sections 4.3 through 4.5. Analysis of the model occurs in Chapter 5.

4.1 Obtaining the Voice of the Customer

While pursuing the development of a tool to assist MJC in its widget forward planning process, many different issues regarding forward planning and the answers that any tool should provide were raised. Because widget allocation decisions involve a group of people, all the parties involved in the process were interviewed. Their concerns regarding two issues were gathered:

- How forward widget and planning and allocation is done today.
- What questions and concerns should be addressed by a tool used in the forward planning process.

The people chosen for the interviews were involved in the current decision process or would use whatever tool was developed. The concerns and questions raised during the interviews were recorded and compiled. The data was broken into five categories and subcategories that were formed based on the information gathered. Two of these five categories pertained to desired system outputs and system requirements. The three remaining categories were useful in defining a management system that would effectively use any tool created. The interview raw data and subsequent breakdown into categories and subcategories is provided in Appendix A. The system outputs and system requirements derived from the interviews are discussed.

4.1.1 Desired system outputs

From the six interviews, 42 responses were obtained. These responses were grouped into categories based on the nature of the response. One category, reflecting desired system outputs, was titled "Questions/issues to be answered or captured by a tool used in forward planning." Of the 42 responses, 19 fell into this category. Since many of these responses were similar, subgroupings and subtitles were formed. The subtitles are prefaced by a capital letter and shown below the category title.

I. Questions/issues to be answered or captured by a tool used in forward planning.

A. Are we currently manufacturing the right type of widgets? Are we manufacturing widgets in the right area?
B. What is the proliferation of widget models costing us?
C. Tool should be able to assign all future model widgets to specific areas assuming we are currently building the right widgets in each area.
D. Tool should answer general manufacturing capacity, capabilities and labor questions.
E. Tool should detail the effect of utilization and volume levels on production and investment costs.
F. What is the impact of widget design changes on widget unit costs?

From the category sub titles and responses, it was concluded that whatever tool is developed must be able to assign all future widget models to specific areas. In performing this assignment, it should analyze and consider the effects of operating each area at different utilization levels. The different utilization levels should be reflected in each area's production and investment costs. Lastly, the tool should provide an output listing the manufacturing capacity and capabilities of each area.

4.1.2 Desired system requirements

The second category created from the interview responses focused on the process requirements of any planning tool. These requirements indicated how MJC's managers desired the tool to work and how it should generate the desired outputs discussed above. Ten responses created the category. These responses were broken down into three subcategories. The category and subcategories are shown on the following page.

II. What would be required of any tool used in the forward planning process?

A. The tool must be capable of adapting to changes in the production and planning processes at MJC. Tool must not be static. It must avoid evaluation methods that are only good for a point in time.

B. The planning tool must perform evaluations with a systems standpoint to avoid sub-optimal solutions. What-if evaluations must look at the financial bottom line of the entire widget business.

C. Discrepancies in information between various areas must be resolved before system evaluations can be conducted.

Examining the category sub titles, it is concluded the tool must be capable of doing two things. The first is the tool must be capable of adapting to changes in the production and planning processes at MJC. As a result, the tool and its generated outputs must be dynamic in nature. MJC wishes to avoid tools that are static, because as processes change, they become obsolete. Therefore, MJC desires that any new planning tool be flexible enough to reflect changes that occur in its processes. The second item, requires the tool to perform evaluations from a systems standpoint. No longer can investments and allocation decisions be based solely on the cost of each manufacturing area. The tool must evaluate the effect of decisions on financial bottom line of the entire widget business. By pursuing evaluations in this manner sub-optimal decisions will be avoided.

4.2 Use of mathematical modeling to create a planning tool

MJC needs a tool or method to help it assign future widget models to production locations. This has to be accomplished by avoiding static evaluation methods and using methods that perform a system evaluation. In addition, the tool should have the capabilities to do sensitivity analyses for what-if evaluations. One known method that would allow such allocation and analysis is mathematical programming. By representing the different manufacturing areas in a logical manner, a mathematical program to minimize investment for new widget models could be created.

The type of mathematical modeling and software package to use in MJC's situation was not clear. After several experimental mathematical formulations and evaluations, it was decided a form of mixed-integer mathematical programming would best accomplish the above objectives. The choice of mixed-integer programming was based on the nature of the production system and the choices to be made. This choice is significant because it affects the derivation of the mathematical model. In addition, the decision was made to use Hyper LINDO (a linear, interactive, discrete optimizer package) to analyze the mathematical model.

4.3 Formulation of a forward planning model

The final formulation of the mathematical model used in this thesis is the result of several development iterations. During these iterations the model's objective function and associated constraints continuously changed. The iteration process started with the first efforts focused on describing the following:

- Purpose of formulation
- Ideal deliverable product
- Required inputs to model
- Outputs of model
- Objective function
- Decision variables
- Constraints

The purpose of the problem formulation was to develop a tool or method that optimizes the allocation of widgets to the various locations of MJC. It would accomplish this over a multi-year period while minimizing costs. The ideal deliverable product would be a tool that assigns future widget production to the different locations to meet expected future demand. In addition, the product would be able to perform quick analyses that indicated how assignments would differ due to changes in production capabilities, costs or demand. Development of the rest of the formulation was highly dependent on the data to be used in the formulation. Therefore, first formulation efforts were also focused on determining what data should be used in the model.

The following subsections present the components of the mathematical model used in the thesis research. Also provided are definitions of the data variables and associated subscripts.

4.3.1 Written statements of the objective function and constraints

Any linear mathematical model is composed of three sections: decision variables, objective function, and constraints. Creation of the mathematical model began with written statements of these sections. From these written statements, the mathematical notation was developed and subsequent mathematical model created.

Decision Variables

Mathematical models are created to obtain a desired answer. For example, in this thesis the answer will be where to produce a particular widget when faced with several choices. This decision is represented in the mathematical model by a decision variable. In MJC's formulation we use the following two sets of binary decision variables.

- Whether to produce all or none of a particular widget at a specific location during a specific time period.
- Whether or not to make a specific investment in a location to produce a particular widget during a specific time period.

Objective Function

In any optimization problem, the decision maker wants to maximize (usually revenue or profit) or minimize (usually costs) some function of the decision variables. The function to be maximized or minimized is called the objective function. For MJC, several possible objective functions were considered for the model formulation. Each objective function represented a different goal and thus a different mathematical formulation. The objective function currently being used is:

- Minimize the total annualized manufacturing and investment cost for meeting daily product demand, while using existing manufacturing capabilities.

Constraints

Essential to any mathematical program problem is the constraints. Constraints restrict the mathematical model and must be adhered to in solving the problem formulation. In addition, the number of constraints in a formulation will affect the region of possible solutions and the optimal solution. In MJC's problem formulation three kinds of constraints were used. Additional constraints were considered and could be added in future formulations. The constraints are as follows.

- Each widget must be manufactured at one and only one location.
- The production hours needed to manufacture the widgets assigned to a location can not exceed that location's available production hours.
- If a widget is assigned to a location and a specific investment is required, then the decision to make the investment must be made.

4.3.2 Definition of subscripts, data variables and decision variables

Before presenting the mathematical model, definitions of the subscripts, data variables and decision variables are included. Knowledge of these definitions is required to understand the mathematical representations.

Definition of subscripts

- ***i* refers to a specific widget model**

In the mathematical model there are 91 different products or values of i. These products were obtained from MJC's Five Year Manufacturing Plan for areas A, B, and C.

- ***j* refers to a specific manufacturing location**

Manufacturing locations were determined by the widget depth that each area manufactures. Consequently, B is separated into three production locations since it produces three different depth widgets. In the model there are 8 manufacturing locations.

- ***k* refers to a specific capital investment**

Producing product i at a specific location often requires capital investment. Each investment in an area is referred to as k. For example, producing product #81 (size dimensions: D4 depth, H2 height, W5 width) in location C, requires investments in its primary and final assembly areas. The investments are as follows: k1 = $50,000 to add W5 capabilities. k2 = $100,000 to handle the subassembly configuration at the final assembly area. Hence, manufacturing this model at C requires two different investments.

Definition of Data Variables

- **I_{jk} is the amount of investment *k* at location *j***

As mentioned above, investments will often have to be made to produce a particular widget at a location. I_{jk} is the dollar amount of a specific k at a j location. In the example above there are two separate investments. One investment is $50,000. The second investment is $100,000.

- **M_{ij} is the manufacturing cost of producing product *i* at *j***

Manufacturing cost is the daily production cost to produce product i at location j. The manufacturing cost used in the model is composed of variable costs that differ between areas and affect the decision of where a widget would be built. Section 4.4.3 discusses how manufacturing costs were calculated.

- ***R_{ij}* is the daily production hours needed to produce *i* at location *j***

By analyzing the throughput rate of each product i at location j's bottleneck, R_{ij} was calculated. In area A, production rates are affected by widget height and in areas B and C by widget depth.

- ***C_j* is the available daily production hours of location *j***

Available production hours are dependent on the number of shifts an area's bottleneck is in operation and its production hours per shift. Because area B is modeled as three locations (B produces three different depths) an additional capacity constraint is added. This capacity constraint ensures that the assigned volumes to B's sub-locations do not exceed their primary assembly capacities.

The units of each data variable are the following:

I_{jk}	- Investment cost ($) amortized to a daily rate.
M_{ij}	- Daily manufacturing cost ($) to produce all of i at j.
R_{ij}	- Daily production hours required to produce all of i at j.
C_j	- Available daily production hours of location j.

Definition of Decision Variables

- ***X_{ij}* refers to the decision of whether or not to produce product *i* at *j***

X_{ij} is an integer decision variable that can only have a value of 0 or 1. It represents the decision of whether or not to produce all of product i at location j for a time horizon. A 1 indicates the decision to produce all of i at j has been made. A 0 indicates it has been decided not to produce i at j.

- ***Y_{jk}* refers to the decision of making an investment of type *k* at location *j***

Y_{jk} is an integer decision variable that can only have a value of 0 or 1. It represents the decision of whether or not to make an investment of type k at location j. A 1 indicates the decision to make a type k investment at j has been made. A 0 indicates the decision not to make a type k investment at j has been made.

4.3.3 Mathematical representation

Presented below is an integer model formulation to allocate widgets to a production location, while minimizing associated manufacturing and investment costs. Listed after the written objective function and constraints are their equivalent mathematical notation.

Objective Function

- Minimize the total annualized manufacturing and investment cost for meeting daily product demand, while using existing manufacturing capabilities.

$$\text{minimize} \quad \sum_{j}\sum_{i} M_{ij}X_{ij} + \sum_{j}\sum_{i} I_{jk}Y_{jk}$$

Constraints

1. Product i must be assigned to one and only one manufacturing location j.

$$\sum_{j} X_{ij} = 1 \qquad \text{for all i}$$

2. The production hours needed to produce assigned product i's to location j can not exceed location j's available production hours.

$$\sum_{i} R_{ij}X_{ij} \leq C_j \quad \text{for all j}$$

3. If widget i is assigned to location j and investment k is required, then the decision to make the investment must be made.

$$X_{ij} \leq Y_{jk} \qquad \text{for all i, j, k}$$

4.4 Gathering of the input data to generate the model

The mathematical model formulation minimizes both manufacturing and investment costs. Critical to this model are the inputs and data used in the formulation. How the data and inputs were obtained and analyzed is described in this section. This section should serve as a guide for MJC personnel on how to obtain and analyze the data needed to create similar model formulations in the future.

4.4.1 Widget models used in the formulation

An analysis of the Five Year Manufacturing Plan indicates that from 1993 to 1996, an average of 205 different model combinations are scheduled to be built. Incorporating 205 different widgets, each with multiple possible production locations, into a model results in a very large, cumbersome formulation. As a rule, the complexity and solution time of a model increases with the number of product variables. Reducing the number of product variables is desirable, if it does not adversely affect the solution output. Examining the widget models scheduled to be manufactured, reveals that 57% of them are *service models*. Service models are widgets produced for a customer's discontinued product application. Since it is not uncommon for the customer's product to last longer than the widget, replacement models are needed. Exhibit 4.1 breaks the scheduled widget production into current and service models. Exhibit 4.2 provides the production volumes associated with these models.

	1993	**1994**	**1995**	**1996**
# Current Models	95	91	95	71
# Service Models	121	117	116	114
TOTAL	**216**	**208**	**211**	**185**

Exhibit 4.1 -- Breakdown of Number of Current and Service Models

	1993	**1994**	**1995**	**1996**
Daily Volume -- Current	43,250	47,721	52,638	52,425
Daily Volume -- Service	1,750	1,647	1,470	1,407
TOTAL VOLUME	**45,000**	**49,368**	**54,108**	**53,832**

Exhibit 4.2 -- Daily production volumes for Current and Service Models

Service volume as a percentage of total daily volume is only 2.85% over these four years. However, these models represent over 57% of the model mix. Due to the complexity associated with mathematically representing both current and service models, and because service models represent a small percentage of the production volume, they were eliminated from the formulation. It was felt their elimination would not significantly alter the model output.

4.4.2 Determination of possible build locations for product i's

In the mathematical model formulation, j refers to a specific manufacturing location. These locations were determined by the widget depths manufactured in each area. The following mathematical notation is used to represent each production location.

Manufacturing Location	Widget Depth Produced	Mathematical Notation
A1	D4	$j = 1$
A2	D4	$j = 2$
C	D4	$j = 3$
B	D4	$j = 4$
C	D2	$j = 5$
B	D2	$j = 6$
C	D1	$j = 7$
B	D3	$j = 8$

Exhibit 4.3 -- Mathematical Notation of Production Locations

Using the guidelines listed below we determined where each widget model could be manufactured.

Possible Production Location Guidelines

1. Consider only a widget's size in determining a possible build location. Ignore subassembly configuration for now.

2. A widget can only be produced in a location whose present equipment capabilities can process its depth.

3. Any height or width widget can be manufactured at a location. The only exception is that widgets with a D4 depth and H1 height can not be manufactured at $j=2$.

A database listing all widgets and their possible build locations was created. Exhibit 4.4 presents one page from this data base. Listed by each widget number is the models associated size and daily production volume. At the far right of the exhibit is a matrix to indicate where each product could be built. A 1 in a matrix cell indicates that product i could be manufactured at that j location. A 0 indicates that manufacturing the widget at that j location is not possible. It should be realized a 1 does not necessarily mean the associated product is currently manufactured at that location. A 1 indicates the product is either currently manufactured there or that with minor additional investment it could be.

4.4.3 Identification of manufacturing costs - M_{ij}

One of the most critical variables to the model, manufacturing cost, is often calculated in different ways by various personnel at MJC. Because of this, much time was spent analyzing MJC's manufacturing costs and how they should be determined and used in the mathematical model. A brief overview of this analysis is included. A detailed analysis of MJC's costs and how they were determined can not be included due to proprietary information.

Overview

The reason a manufacturing cost analysis was conducted is that MJC currently accounts for every expense from sundry expenses to direct material expenses in its operating costs. Not all these expenses are relevant in deciding where a widget should be manufactured. MJC will routinely evaluate where widgets should be produced based on areas' operating expenses and potential investments. Hence, these evaluations could be improved by redefining which components of the operating cost really matter when deciding where a widget should be manufactured.

The goal of this analysis was to establish a method that uniformly accounts for relevant costs used in the decision of where a widget should be produced. The methods used in the analysis examine costs in a uniform manner to prevent skewing of any evaluations. Trying to determine the costs associated with producing each widget size in an area was not possible. In addition, this analysis showed there is a consistent lack of uniformity in level and detail of information available for each of MJC's production areas.

On the basis of the analysis the following recommendations were made regarding how MJC should calculate the manufacturing cost of a widget. Also provided are the reasons for these recommendations.

							Possible		Build		Locations		
Widget	Proposed	Physical		Size	Volume	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
#	Mnfg. Loctn.	Height	Width	Depth	1994	A1	A2	C	B	C	B	C	B
1	j=1	H3	W7	D4	585	1	1	1	1	0	0	0	0
2	j=1	H3	W7	D4	1371	1	1	1	1	0	0	0	0
3	j=1	H3	W7	D4	174	1	1	1	1	0	0	0	0
4	j=1	H3	W7	D4	399	1	1	1	1	0	0	0	0
5	j=2	H3	W7	D4	393	1	1	1	1	0	0	0	0
6	j=6	H3	W7	D2	1539	0	0	0	0	1	1	0	0
7	j=4	H3	W7	D4	138	1	1	1	1	0	0	0	0
8	j=5	H3	W7	D2	42	0	0	0	0	1	1	0	0
9	j=1	H3	W7	D4	51	1	1	1	1	0	0	0	0
10	j=1	H3	W7	D4	450	1	1	1	1	0	0	0	0
11	j=1	H2	W7	D4	927	1	1	1	1	0	0	0	0
12	j=5	H3	W3	D2	183	0	0	0	0	1	1	0	0
13	j=5	H3	W3	D2	1302	0	0	0	0	1	1	0	0
14	j=4	H3	W3	D4	195	1	1	1	1	0	0	0	0
15	j=4	H3	W3	D4	720	1	1	1	1	0	0	0	0
16	j=6	H3	W7	D2	6	0	0	0	0	1	1	0	0
17	j=6	H3	W7	D2	30	0	0	0	0	1	1	0	0
18	j=4	H3	W7	D4	3	1	1	1	1	0	0	0	0
19	j=4	H3	W7	D4	12	1	1	1	1	0	0	0	0
20	j=4	H3	W7	D4	27	1	1	1	1	0	0	0	0
21	j=4	H3	W7	D4	30	1	1	1	1	0	0	0	0
22	j=4	H3	W7	D4	33	1	1	1	1	0	0	0	0
23	j=4	H3	W7	D4	45	1	1	1	1	0	0	0	0

Exhibit 4.4 -- Data Base Page Indicating Possible Build Locations

Recommendations:

1. Consider only variable costs in determining manufacturing costs.
2. Determine what comprises variable costs.
3. Determine which variable costs are significantly different between manufacturing areas.

It is recommended for two reasons that only MJC's variable costs be considered in the planning model. First, 90% of areas A and B's operating costs are represented by the following categories: material, burden, fringe and premiums, and direct labor. Approximately 70% of operating cost could be classified as variable costs. These variable costs are composed of material cost, direct labor cost and variable portions of burden and fringe & premiums. Using just variable costs would account for the majority of the cost associated with producing a widget. Fixed costs could then be ignored.

Second, and perhaps more important, is that if a widget could be produced in multiple locations, the only costs that should be considered are those that are relevant to the decision. Those are its variable costs. To include present fixed costs in the model, may result in non-optimal allocations. Finally, fixed costs exist whether an area is in operation or not. Hence, for these reasons only variable costs were considered in the mathematical model.

Identifying which costs are truly variable and which ones are not is not always easy. Determining which variable costs to use was based on the philosophy that only the costs that significantly differ between manufacturing areas should be considered in the mathematical model. Because the model keys on relative cost differences, only the costs that differ between areas are important. This philosophy was applied to the following accounts: direct labor, direct material, burden, fringe and premiums. From this analysis, representative unit costs for each account above were determined in every area.

4.4.4 Determination of investment relationships - I_{jk}

Obtaining the necessary investment costs and relationship information for use in the mathematical model was very difficult. Investment information is not easy to calculate because it falls into two categories at MJC. The first category is investment due to capacity constraints. The second category is investment due to widget model proliferation. Because of MJC's excess production capacity, emphasis was placed on determining investment due to widget model proliferation. Investment required to increase capacity was ignored.

Widget model proliferation occurs when new widget configurations are added to MJC's product mix. Proliferation also occurs when a current widget model is moved to an area that does not have the current capabilities to process it. In both cases, investment must be made in the existing production equipment.

In general, for any manufacturing are the parts of the production process most affected by widget proliferation is its primary assembly, final assembly and test areas. Recall from Chapter 2, that the pre-joining and joining operations are relatively insensitive to changes in a widget. To determine the investment needed for a multitude of different widget sizes, area investment sheets were created. By documenting each area's primary assembly, final assembly and test capabilities (in terms of widget sizes), the investment for adding additional capabilities can be easily calculated. Exhibit 4.5 is the investment sheet for A2. Looking at this sheet, if a widget with a W9 height is to be added to this area, an investment of $17,000 would be needed in primary assembly, as well as an investment of $1,200 in final assembly. The investment amounts on these sheets were provided by the manufacturing engineers responsible for re-configuring the production equipment to handle the new widget sizes.

Investment is due to changes in a widget's basic dimensions or subassembly configuration. The general framework in Exhibit 4.5 is based on engineers' estimates and can only be used to determine investments caused by changes in a widget's size. The framework can not be applied to investments caused by subassembly changes because calculating this investment is a more complex process. Depending on which features of the subassembly change, the investment required to perform final assembly and test can range from $13,500 to $220,000. For the mathematical model, potential investment due to subassembly configuration was obtained by having engineers examine each model's subassembly and evaluate how much, if any, investment would be required to alter the final assembly and test equipment. At the same time, relationships between particular widget models and subassembly configurations were noted. If an investment to process one model's subassembly allowed an area to process others, then this relationship was documented.

Exhibit 4.6 illustrates the documentation of these relationships. This exhibit lists area A2's investment relationships for several models. Across the top of the page, the different specific investments (k) required to produce different models are listed. For product #15, a 1 in the k3 column indicates producing product #15 requires an investment of $80,000. Note that each k investment needs to be made only once in an area. For example, if the k3 investment is made, then all other models requiring that investment

Part of Process Affected	Widget Feature To be Changed	Possible Equipment Capabilities MIN	MAX	Sizes Currently Processed	Desired Change	Investment to make desired Change
Primary Assy	WIDTH	W2	W7	W2,W3,W4,	Within W2 - W7	$17,000
				W5, W6, W7		
Primary Assy	HEIGHT	H1	H3	H2 and H3	Add H1	$71,000
Primary Assy	DEPTH	D2	D4	D4	Add D2	$400,000
Final Assy	WIDTH	W2	W7	W2,W3,W4,	Within W2 - W7	$1,200
				W5, W6, W7		
Final Assy	HEIGHT	H1	H3	H2 and H3	Add H1	$168,000
Final Assy	DEPTH	D1	D4	D4	Add D1	$0
					Add D2	$0
					Add D3	$0
Test	WIDTH	W2	W7	W2,W3,W4,	Within W2 - W7	$0
				W5, W6, W7		
Test	HEIGHT	H1	H3	H2 and H3	Add H1	$400,000
Test	DEPTH	D1	D4	D4	Add D1	$1,200
					Add D2	$1,200
					Add D3	$1,200

Exhibit 4.5 -- Investments Required to Alter A2's Production Capabilities

Widget #	Proposed Mnfg. Location	1994 Volume	Physical Size: Height	Physical Size: Width	Physical Size: Depth	k = 1 Subassy Invstmnt 0$'s	k = 2 Subassy Invstmnt $18,000	k = 3 Subassy Invstmnt $80,000	k = 4 Subassy Invstmnt $639,000	k = 5 Subassy Invstmnt $218,000	k = 6 H1 Invstmnt $639,000
1	j=1	585	H3	W7	D4	0	1	0	0	0	0
2	j=1	1371	H3	W7	D4	0	1	0	0	0	0
3	j=1	174	H3	W7	D4	0	1	0	0	0	0
4	j=1	399	H3	W7	D4	0	1	0	0	0	0
5	j=2	393	H3	W7	D4	1	0	0	0	0	0
7	j=4	138	H3	W7	D4	1	0	0	0	0	0
9	j=1	51	H3	W7	D4	0	1	0	0	0	0
10	j=1	450	H3	W7	D4	0	1	0	0	0	0
11	j=1	927	H2	W7	D4	1	0	0	0	0	0
14	j=4	195	H3	W3	D4	0	0	1	0	0	0
15	j=4	720	H3	W3	D4	0	0	1	0	0	0
18	j=4	3	H3	W7	D4	1	0	0	0	0	0
19	j=4	12	H3	W7	D4	1	0	0	0	0	0
20	j=4	27	H3	W7	D4	1	0	0	0	0	0
25	j=4	165	H3	W7	D4	1	0	0	0	0	0
26	j=4	267	H3	W7	D4	1	0	0	0	0	0
36	j=4	945	H3	W5	D4	1	0	0	0	0	0
37	j=4	27	H3	W6	D4	1	0	0	0	0	0
38	j=4	984	H3	W6	D4	1	0	0	0	0	0
49	j=3	1209	H3	W6	D4	1	0	0	0	0	0
50	j=3	1389	H3	W6	D4	1	0	0	0	0	0
51	j=1	231	H3	W7	D4	1	0	0	0	0	0
52	j=1	282	H3	W7	D4	1	0	0	0	0	0
53	j=2	846	H3	W7	D4	1	0	0	0	0	0
55	j=4	378	H3	W7	D4	1	0	0	0	0	0

Exhibit 4.6 -- An Example of an Investment Relationship Sheet

can be produced at no additional cost. However, to produce a model there means all needed investments must be made.

4.4.5 Capacity of bottleneck operations - C_j

An area's available production hours and various production rates determine its production volume and model mix. In locations A1 and A2, only the joining operations production hours and production rates were considered. In areas B and C, primary assembly production hours for each depth were considered in addition to the joining operations' hours.

Exhibit 4.7 lists each area's available joining production hours. Exhibit 4.8 lists B's and C's available primary assembly hours. The hours in both exhibits are dependent on available equipment, changeover time, and scheduled downtime.

Location	Available Production Hours	Hours based on
A1	11.4 hours	2 shifts of production
A2	14.4 hours	2 shifts of production
B	72 hours	3 shifts of production
C	48 hours	2 shifts of production

Exhibit 4.7 -- Joining Operations available production hours

Location	Available Production Hours	Hours based on
j=4	153.12 hours	3 shifts of production
j=8	76.56 hours	3 shifts of production
j=6	191.4 hours	3 shifts of production
j=3	24 hours	3 shifts of production
j=5	24 hours	3 shifts of production
j=7	24 hours	3 shifts of production

Exhibit 4.8 -- Primary Assembly's available production hours

Also considered in addition to available production hours are production rates. By knowing these rates, the hours required to process all of product i at each location can be calculated. The joining operations' rates are affected by widget depth. The rates of the primary assembly operations are affected by widget depth, height and width. Both rates are contained in Exhibits 4.9 and 4.10.

Area	Widget Characteristics	Hours / Widget
A1	H3 height - any width	.002333333
	H2 height - any width	.002298841
	H1 height - any width	.002298841
A2	H3 height - any width	.002624672
	H2 height - any width	.002298841
	H1 height - any width	.002298841
B	D4 depth - any height, width	.002898551
	D3 depth - any height, width	.002710027
	D2 depth - any height, width	.002666667
C	D4 depth - any height, width	.003300330
	D2 depth - any height, width	.002347418
	D1 depth - any height, width	.001792115

Exhibit 4.9 -- Joining Operations' production rates

Area	Widget Characteristics	Hours / Widget
j=4	H3 height - any width	.007407407
	H2 height - any width	.006289308
	H1 height - any width	.006289308
j=6	H3 height, width >= W6	.006944444
	H3 height, width < W6	.006172840
	H2 height - any width	.006060606
j =8	H3 height, width >= W6	.006944444
	H3 height, width < W6	.006172840
	H2 mm height - any width	.006060606
j=3	Any width, height	.002057613
j=5	Any width, height	.001572329
j=7	Any width, height	.002732240

Exhibit 4.10 --Primary assembly production rates

4.5 Outputs of the mathematical model

All of the data discussed in Section 4.4 was formulated into a mathematical model and run through an optimization program called Hyper LINDO. Generated outputs are the daily investment and manufacturing cost, the allocation of widgets to specific areas and required investments. Other data generated was used to analyze utilization levels and remaining production capacity.

4.6 Review of the formation of the mathematical model

This chapter illustrates how the voice of the customer was used in determining the desired system outputs and system requirements for a planning tool. From these outputs and requirements written objectives were formulated. In turn, a mathematical model was derived to minimize costs. The different variables and subscripts of the mathematical model were defined and explained. Although this mathematical model does not incorporate every desired output it is a good first step in meeting MJC's needs.

This chapter also thoroughly discusses how the information used in the mathematical model was gathered and analyzed. Documenting these procedures is essential to continue development of the mathematical model.

Chapter 5 provides a detailed look of how this model can be used at MJC. The result is a clear indication of how the model works, what its outputs are, and what type of decisions it can aid MJC in making.

Chapter 5: Mathematical Model Analysis

An analysis of the mathematical and its capabilities are provided in this chapter. Section 5.1 illustrates its capabilities through a simple example, providing the reader with a manageable view of how larger problem formulations will be solved. In Section 5.2, a problem formulation that allocates MJC's forecasted 1994 production is reviewed. Finally, Section 5.3 is a critique of the mathematical model and solution technique.

5.1 Demonstration of the mathematical model

A demonstration of how the mathematical model works occurs through a simple allocation example. Using the information provided, the example is first solved by hand and then by the mathematical model. Solving the example by hand helps demonstrate the large number of interactions that must be considered to arrive at the correct solution. Solving the example with the mathematical model verifies the solution and ensures the correct mathematical formulation has been developed.

5.1.1 MJC allocation example -- Allocation of four products to four locations

A simplified business situation regularly faced by widget production managers at MJC is described below. The situation is typically solved by manual methods that focus only on the minimization of investment costs.

Situation:
You have just been notified that four 1994 widget model designs have changed. These changes require new investment in existing production equipment and force you to reconsider where these models should be manufactured. They could conceivably be produced in the following areas: A1, A2, B or C. Each area has a different manufacturing cost structure and each widget model requires different investments in each area. To further complicate matters, each area has limits on available capacity.

Question:
Where should these widgets be produced to minimize the total cost associated with meeting production demands?

Data to aid in the decision process:

- Daily production volumes
- Investments information
- Required joining hours
- Available production hours
- Manufacturing costs

This data is contained on the following pages.

- **Daily Volume**

Widget Number	Daily Demand
82	2,088
5	393
47	396
48	459

Exhibit 5.1 -- Daily Widget Volume

- **Investments Required**

Widget Number	Location j=1	Location j=2	Location j=3	Location j=4
82	$57,000	$20,000	$100,000	$100,000
5	$0	$0	$0	$0
47	$20,000	$20,000	$0	$0
48	$20,000	$20,000	$0	$0

Exhibit 5.2 -- Investment required to build the different models

The investment required to build a widget in each possible production area is contained in Exhibit 5.2. For example, producing product #82 in j=1 costs $57,000. These investment amounts were obtained from investment sheets similar to Exhibit 4.5.

- **Required joining hours**

Widget Number	Joining Hours needed at j = 1	Joining Hours needed at j = 2	Joining Hours needed at j = 3	Joining Hours needed at j = 4
82	4.80	4.80	6.89	6.05
5	0.94	1.03	1.30	1.14
47	0.94	1.04	1.31	1.15
48	1.09	1.21	1.52	1.33
Total Hours	7.77	8.08	11.02	9.67

Exhibit 5.3 -- Required joining hours for each widget and available joining

The joining hours are the hours needed to process a widget's total volume at a location. A widget can not be allocated to a location unless there is available joining hours.

- **Available Joining Hours**

Available Joining Hours	j = 1	j = 2	j = 3	j = 4
	7.77	8.08	11.02	9.67

Exhibit 5.4 -- Available Joining Hours for each Location

- **Manufacturing Costs**

Widget Number	Location j=1	Location j=2	Location j=3	Location j=4
82	$17,525.28	$17,323.44	$19,286.16	$17,922.00
5	$3,872.36	$3,834.37	$4,202.48	$3,945.72
47	$3,686.76	$3,648.48	$4,014.12	$3,755.40
48	$4,189.14	$4,144.77	$4,571.64	$4,271.76

Exhibit 5.5 -- Manufacturing cost to produce all of model i in an area

The manufacturing costs associated with producing the total volume of a widget in each area is listed above. Notice that location j=2 has the lowest manufacturing costs and location j=3 the highest.

5.1.2 Analysis by conventional methods

Analyzing the data above by hand can be time consuming and tedious. However, the answer to the question posed can be obtained in the following manner. First, examining Exhibits 5.3 and 5.4, consider that only widgets #5 and #47 can be assigned to j=1, based on required and available joining hours. The decision to allocate product #5 to j=1 is made when costs (Exhibits 5.2 and 5.5) are considered. Product #5 does not require investment in any location and can be manufactured for the lowest cost at j=1. Subsequently, for product #82, j=2 has low manufacturing costs and investments relative to j=3 and j=4. In addition, there are available joining hours to produce all of product #82 there. Hence, product #82 is allocated to j=2. For products # 47 and #48, there are available joining hours at j=2; however, producing there requires investment. Analyzing the manufacturing cost differences between j=2, 3, and 4 for products #47 and #48, the manufacturing cost saving's j=2 offers, does not offset its required investment. Further examination shows no investments are required in j=3 and j=4 for these products. Both j=3 and j=4 have available capacity; however, j=4 has lower manufacturing costs. Therefore, to minimize costs products #47 and #48 are allocated to j=4. A summary of the allocation decisions and their effects are below:

1. **Minimum cost to meet daily demand:**
   $49,222.96

2. **Allocation:**

Product #	Assigned to
82	j = 2
5	j = 1
47	j = 4
48	j = 4

3. **Investments Required:**
   $20,000 to j=2

4. **Remaining joining hours after allocation:**

Area	Hours
j = 1	0.06
j = 2	0.20
j = 3	8.00
j = 4	1.72

Arriving at the answer above required simultaneously examining several variables. The example involved only the allocation of four products to a possible four locations. The example was further simplified by considering only the joining capacity of each area. As demonstrated, solving this relatively small scale problem required a fair amount of information and the simultaneous evaluation of several variables and interactions. As can be easily imagined, when the possible number of products and locations increases, the information and interactions that must be considered becomes overwhelming. Consequently, the only efficient method for solving larger scale problems is to use a computer.

5.1.3 Analysis by mathematical modeling

The mathematical model developed to solve this typical problem follows. Included is the mathematical code executed by Hyper LINDO.

- **Objective Function:**

Minimize the total manufacturing and investment cost required to meet demand for the four products while utilizing the existing manufacturing locations.

$$\text{MIN} \quad \sum_{j}\sum_{i} M_{ij}X_{ij} + \sum_{j}\sum_{i} I_{jk}Y_{jk} \qquad \text{for all i, j and k}$$

MIN 17525.28 X821 + 3872.36 X51 + 3686.76 X471 + 4189.14 X481 + 17323.44 X822 + 3834.37 X52 + 3648.48 X472 + 4144.77 X482 + 19286.16 X823 + 4202.48 X53 + 4014.12 X473 + 4571.64 X483 + 17922.00 X824 + 3945.72 X54 + 3755.40 X474 + 4271.76 X484 + 20000 Y11 + 20000 Y12 + 37000 Y13 + 20000 Y21 + 20000 Y22 + 100000 Y31 + 100000 Y41

Constraints:

1. Product i must be assigned to one and only one manufacturing location.

$$\sum_{j} X_{ij} = 1 \qquad \text{for all i}$$

X821 + X822 + X823 + X824 = 1
X51 + X52 + X53 + X54 = 1
X471 + X472 + X473 + X474 = 1
X481 + X482 + X483 + X484 = 1

2. The joining hours required to produce the assigned product i's to an area can not exceed that area's available capacity.

$$\sum_{i} R_{ij}X_{ij} \leq C_j \qquad \text{for all } j$$

4.80 X821 + 0.94 X51 + 0.94 X471+ 1.09 X481 <= 1
4.80 X822 + 1.03 X52 + 1.30 X472+ 1.14 X482 <= 5
6.89 X823 + 1.30 X53 + 1.31 X473+ 1.52 X483 <= 8
6.05 X824 + 1.14 X54 + 1.15 X474+ 1.33 X484 <= 4

3. If a widget is assigned to location j and investment k is required, then the decision to make the investment must be "1".

$X_{ij} \leq Y_{jk}$ for all i, j

X821 - Y11 <= 0	X822 - Y21 <= 0	X824 - Y41 <= 0
X481 - Y11 <= 0	X482 - Y21 <= 0	X821 - Y13 <= 0
X471 - Y12 <= 0	X472 - Y22 <= 0	X823 - Y31 <= 0

4. All X_{ij}'s and Y_{jk}'s must be integer values.

Exhibit 5.6 is the formulation entered into Hyper LINDO. The output generated after execution of the formulation is Exhibit 5.7. At the top of Exhibit 5.7 is the objection function value of $49,222.96. Listed below the objective function value are the decision variables and their assumed values after optimization. A 1 in the value column indicates the widget has been allocated to the location. For example, $X_{51} = 1$ signifies that widget #5 has been allocated to j = 1. Examining the Y_{jk} investment variables reveals the only investment required was Y_{21}. That was for producing widget #82 at j=2. Below the decision variables are the slack or surplus values of each constraint. From these variables, we determine each location's remaining joining capacity after allocation. In this formulation, rows 6 through 9 correspond to the joining capacity of j=1 through j=4. After analyzing the Hyper LINDO output, it is concluded that the mathematical model provides the same results that were calculated by hand.

The program arrived at its answer by simultaneously trading off the investment and manufacturing cost to produce a widget. Before making the allocation, it ensured there was available joining hours. This is the same analytical procedure used to solve the problem by hand.

```
MIN    17525.28 X821 + 3872.36 X51 + 3686.76 X471 + 4189.14 X481
   + 17323.44 X822 + 3834.37 X52 + 3648.48 X472 + 4144.77 X482
   + 19286.16 X823 + 4202.48 X53 + 4014.12 X473 + 4571.64 X483 + 17922 X824
   + 3945.72 X54 + 3755.4 X474 + 4271.76 X484 + 20000 Y11 + 20000 Y12
   + 37000 Y13 + 20000 Y21 + 20000 Y22 + 100000 Y31 + 100000 Y41
SUBJECT TO
     2)  X821 + X822 + X823 + X824 =   1
     3)  X51 + X52 + X53 + X54 =   1
     4)  X471 + X472 + X473 + X474 =   1
     5)  X481 + X482 + X483 + X484 =   1
     6)  4.8 X821 + 0.94 X51 + 0.94 X471 + 1.09 X481 <=  1
     7)  4.8 X822 + 1.03 X52 + 1.3 X472 + 1.14 X482 <=  5
     8)  6.89 X823 + 1.3 X53 + 1.31 X473 + 1.52 X483 <=  8
     9)  6.05 X824 + 1.14 X54 + 1.15 X474 + 1.33 X484 <=  4
    10)  X821 - Y11 <=  0
    11)  X481 - Y11 <=  0
    12)  X471 - Y12 <=  0
    13)  X821 - Y13 <=  0
    14)  X822 - Y21 <=  0
    15)  X482 - Y21 <=  0
    16)  X472 - Y22 <=  0
    17)  X823 - Y31 <=  0
    18)  X824 - Y41 <=  0
END
INTE   23
```

Exhibit 5.6 -- Hyper LINDO code for allocation example

OBJECTIVE FUNCTION VALUE

1) 49222.960

DECISION VARIABLE	VALUE
X821	.000000
X51	1.000000
X471	.000000
X481	.000000
X822	1.000000
X52	.000000
X472	.000000
X482	.000000
X823	.000000
X53	.000000
X473	.000000
X483	.000000
X824	.000000
X54	.000000
X474	1.000000
X484	1.000000
Y11	.000000
Y12	.000000
Y13	.000000
Y21	1.000000
Y22	.000000
Y31	.000000
Y41	.000000

ROW	SLACK OR SURPLUS
2)	.000000
3)	.000000
4)	.000000
5)	.000000
6)	.060000
7)	.200000
8)	8.000000
9)	1.520000
10)	.000000
11)	.000000
12)	.000000
13)	.000000
14)	.000000
15)	1.000000
16)	.000000
17)	.000000
18)	.000000

Exhibit 5.7-- Hyper LINDO output of allocation example

5.1.4 "What-if" analysis capabilities

One advantage of doing analyses with mathematical models over conventional methods is it allows what-if analyses to be performed quickly and easily. These analyses are performed in response to additional questions posed by management or engineers. The questions are based on an original evaluation scenario. What-if analysis questions for the example situation would be:

- What-if j=2 has only 5 available joining hours? How does the analysis change?
- What-if j=1 manufacturing cost structure changes? Do the allocation scheme and objective function value change?

What-if analyses are evaluated by altering input information used in the original mathematical formulation. The advantage of mathematical models is that once the model has been created, making minor changes to perform additional analyses are easy. However, there are limits to a mathematical model's what-if capabilities. Some questions might cause the actual formulation to change. An example is:

- What-if j=2 has 12 available joining hours but can only process two models?

The phrase "but can only process two models" indicates another constraint. Adding this constraint changes the existing mathematical model. As more and more changes are made to the mathematical model, you are no longer capitalizing on its what-if capabilities but creating new models. This limitation should be considered when deriving a mathematical formulation and performing subsequent analyses.

5.2 Full Scale 1994 allocation mathematical model

The simplified example demonstrates the feasibility and accuracy of the mathematical model. Additional tests of the model and its capabilities were performed by creating and analyzing successively larger formulations. The last formulation created was to allocate MJC's 1994 production to the various areas. In this formulation eight possible locations and 91 different products were considered. Over 350 decision variables were represented in the model.

A temporary 1994 allocation plan had already been created by forward planners. It was desired to compare the cost of MJC's allocation plan to the optimal allocation plan generated by the mathematical model. To accomplish this two problem formulations were created. Both formulations used the same manufacturing costs, investment costs, capacity rates and production data. The first formulation was based on their plan. The second formulation reflected the different possible production locations for each model. The second formulation and its Hyper LINDO output are included in Appendix B.

5.2.1 1994 mathematical model analysis

A detailed analysis of the Hyper-LINDO results could not be provided due to proprietary restrictions. However, a comparison of the formulations' outputs are provided.

The first problem formulation, which reflects MJC's plan, resulted in an objective function value of $466,847.90. This is the daily manufacturing and investment cost to produce MJC's 1994 daily widgets in areas A, B and C. Running the second formulation through Hyper LINDO, and minimizing the costs, resulted in an objective function value of $464,845.90. The difference of $2,002 between the two plans equates to a yearly difference of approximately $480,000. Therefore, if MJC altered their 1994 proposed production plan to reflect the optimal plan, it should result in a savings of approximately $480,000.

To determine why the objective values differed, the widgets allocated under both plans was analyzed. Exhibits 5.8 and 5.9 lists the proposed daily volume allocation for each area under both plans.

Location	MJC's Plan	Mathematical Plan
j =1	4,715	4,856
j = 2	6,222	5,569
j = 3	6,418	10,347
j =4	5,507	2,092
j = 5	6,271	6
j = 6	7,206	13,467
j = 7	3,387	3,388
j = 8	7,995	7,996

Exhibit 5.8 -- Volume allocation by j location

Location	MJC's Plan	Mathematical Plan
A	10,937	10,425
B	20,708	23,555
C	16,076	14,118

Exhibit 5.9 -- Volume allocation by area

Comparing MJC's plan to the mathematical plan reveals the following about the mathematical plan.

- For B, a significantly lower volume of D4 (j=4) widgets is produced on a daily basis.
- B essentially produces all of MJC's D2 depth widgets (j=6 vs. j=5).
- B's total daily volume increases by 13.7%.
- C essentially no longer produces any D2 depth widgets (j=5).
- C produces a significantly larger volume of D4 depth widgets (j=3). C's D4 volume increases by 61%.
- C's total daily volume decreases by 1,958 widgets, a decrease of 12%.
- The daily production volume of A1 and A2 remains essentially the same.

Summarizing the above results, volume was removed from C to fully use A and B's production capacity. This was driven by these areas lower manufacturing and investment costs. As a result, dramatic shifts in the production location of D2 and D4 widgets occurred. With the new plan, B would essentially produce all of MJC's D2 depth widgets and C would produce the majority of the D4 widgets not produced in A.

Comparison of the widget models allocated to each location was feasible for only j=1 and j=2. The comparison showed the widget models allocated to these locations were essentially the same ones allocated by the MJC plan. For both plans the widgets were high volume models. The reason MJC's plan allocated these models is that A's manufacturing philosophy is to minimize changeovers. To minimize changeovers requires high volume models. The reason the mathematical formulation allocated them was to capitalize on A's low manufacturing cost structure relative to the other areas. Further determination of why these particular models were allocated is not possible due to the complex and numerous interactions involved in obtaining the answer.

5.3 Critique of Model

The mathematical model and its formulation process has its strengths and weaknesses. The weaknesses are discussed in this section; while, the strengths of the model are emphasized in Chapter 6.

5.3.1 Weaknesses of the mathematical model and the formulation process

As the mathematical formulation and what-if analyses were being performed limitations of the mathematical model and its formulation were discovered. Fortunately these limitations were circumvented during the thesis and analysis work; however, these limitations need to be addressed in future development work.

<u>Weaknesses of the mathematical model</u>

- **Pure Integer vs. Mixed Integer**

A pure integer mathematical model is one where all decision variables must take on integer values. For the same number of variables, a pure integer model is harder to solve than a mixed integer problem; while, a mixed integer model is harder to solve than a linear program. The mathematical model derived in this thesis was a pure integer type. Although the example problem was solved as a pure integer formulation, trying to solve the 1994 allocation model this way was impractical. Running as a pure integer formulation, Hyper LINDO executed the optimization process for over 10 hours, reached its pivot limit, and still produced no solution. With 267 X_{ij} and 90 Y_{jk} integer variables, the problem formulation was too tight to solve in an acceptable time frame. To relax the formulation, the X_{ij} variables were run as continuous. By doing this, the mathematical formulation now a mixed integer type, was solved in approximately one minute. The implication of continuous X_{ij} variables is that a widget could be allocated to more than one location. However, examination of the output revealed this happened infrequently. Of the 91 widget models, only three were allocated to more than one location. This discrepancy was handled by allocating the entire production of these models to the areas that had sufficient capacity.

- **Scaling of the model**

A second problem with the mathematical formulation was the scaling of the model. When running the problem formulation through Hyper LINDO, it indicated the problem was poorly scaled. A poorly scaled problem occurs when the spread between variable coefficients is too large. One example is the variable X194, which has a coefficient of 117.48 in the objective function and a coefficient of 0.049 in a constraint. The 2,397 ratio between these coefficients is too large. To solve this problem a scaling factor converting hours to seconds was used on the production rate coefficients. Since, MJC prefers to represent the production rate in hours this is a minor problem.

- **Time Frame of Model**

The current mathematical formulation is for a one year time frame. To effectively minimize costs a three year time frame should be developed into the model. Accomplishing this would mean rewriting the mathematical derivation to incorporate multiple time periods.

- **System Failures**

Another problem experienced with the model was it crashing. Crashing refers to the event that happens when a particular formulation can not be solved due to a constraint that can not be met. Crashing was often experienced during what-if analyses. Although this problem is more inherent of mathematical programming than the actual model formulation it still remains a problem.

- **Model Sensitivity Analysis**

A problem with the model is that it is difficult to analyze how sensitive the solution is to bad data or changes in the data. For example, if the data in the model is wrong, it is difficult to predict what will happen to the solution and how bad it will be. Measuring the robustness of the system to variations in the input data was not possible in the available time.

The limitations below deal with the processes used to create the mathematical model and analyze its outputs.

<u>Weaknesses of the formulation process</u>

- **What-if analysis involves altering model and information**

A problem with performing what-if analyses are that it requires continuous alterations of the mathematical model and information used in the model. This poses a problem in that continual changes can result in an incorrect formulation or a correct formulation with incorrect information. Output from either formulation will be incorrect. The current processes have no error proofing mechanisms to prevent this from happening.

- **Lack of user interface between the data and the mathematical model**

Another problem with the current process is that it is not user friendly. The current process requires a person who is familiar with mathematical modeling to alter and input information to perform analyses. If a person is not familiar with mathematical modeling the process can not be used. The model needs a user interface that allows a person to input new information and automatically generate an updated formulation. Making the entire process more user friendly is important to get MJC to use it on a regular basis for forward planning.

5.3.2 Verification of mathematical techniques and solution path

Of the drawbacks discussed, it is felt the lack of a user interface will seriously impede implementation of a mathematical model. Since internal capabilities were not possible to develop such an interface, outside consultants were contacted. The consultants were asked to quote on the development of a user interface to automatically generate model formulations and perform the subsequent analyses. One consultant has developed a modeling system used for business planning called PLANETS. PLANETS is a system that interprets a database and model specifications for a business scenario. It then builds a mixed-integer programming model to solve that scenario. In addition PLANETS contains a mandatory building block category called *Timestage*. This block defines the financial and production planning horizon of the model. Up to a 10 year time horizon can be built into the model.

On the basis of discussions with this consultant and others, it appears the exact solution techniques pursued in this thesis are not uncommon and are the correct ones to be pursued. Knowledge of PLANETS is helpful in that it provides a measure of confidence in the work performed and that continued development through outside consultants is possible.

5.3.3 Benefits of the mathematical formulation and process

There are tangible benefits to be derived from the use and continue development of this mathematical model. One benefit is that it is the start of a structured process to effectively evaluate how potential manufacturing and allocation decisions affect the widget business's bottom line.

The current model provides for the allocation of yearly widget volumes between areas A, B and C. In addition, it allows analysis of where widget production can be shifted to reduce costs. Finally, it can be used to determine the effect of changing volume levels and manufacturing costs on the widget business. However, as Chapter 6 will illustrate, the benefits derived for the mathematical model are small compared to the benefits derived for the application of an entire planning process.

Chapter 6: General Management Framework and Decision Process

The use and development of a mathematical model to evaluate the effect of potential manufacturing is beneficial to MJC. However, the full benefits of the mathematical model will not be derived from its independent use, but from its application in a general management process. This process, referred to as the General Management Framework and Decision Process, is detailed in Section 6.1. Section 6.2 lists the benefits of the process and decisions that could be made with its application. Section 6.3 highlights implementation issues. Section 6.4 discusses future development concerns.

6.1 General Management Framework and Decision Process (GMFDP)

The proposed general management framework and decision process to aid MJC in its forward planning decisions is illustrated in Exhibit 6.1. Up to this point, this thesis has focused on the development of the mathematical model and its evaluation capabilities; however, it will really be the application of the GMFDP that allows MJC to evaluate the effects of different manufacturing and allocation decisions. Hence, although the mathematical model is central to this process, it will be the GMFDP that provides the real benefits.

6.1.1 Description of General Management Framework / Decision Process

The GMFDP diagram was developed after re-examining the steps used to formulate the original mathematical model and gather the information used in it. The GMFDP consists of the following six distinct stages.

- **Stage 1 -- Analysis by the Main Players**

Although forward planning and allocation decisions involve many different people at MJC, this GMFDP is carried out by five main players. These players represent manufacturing areas A, B, and C, Finance and Product Engineering. Stage 1 focuses on each player obtaining and analyzing the basic information needed from their area to use in any mathematical model or decision process. Basic information supplied by each manufacturing area would be its capacity, production rates, possible production

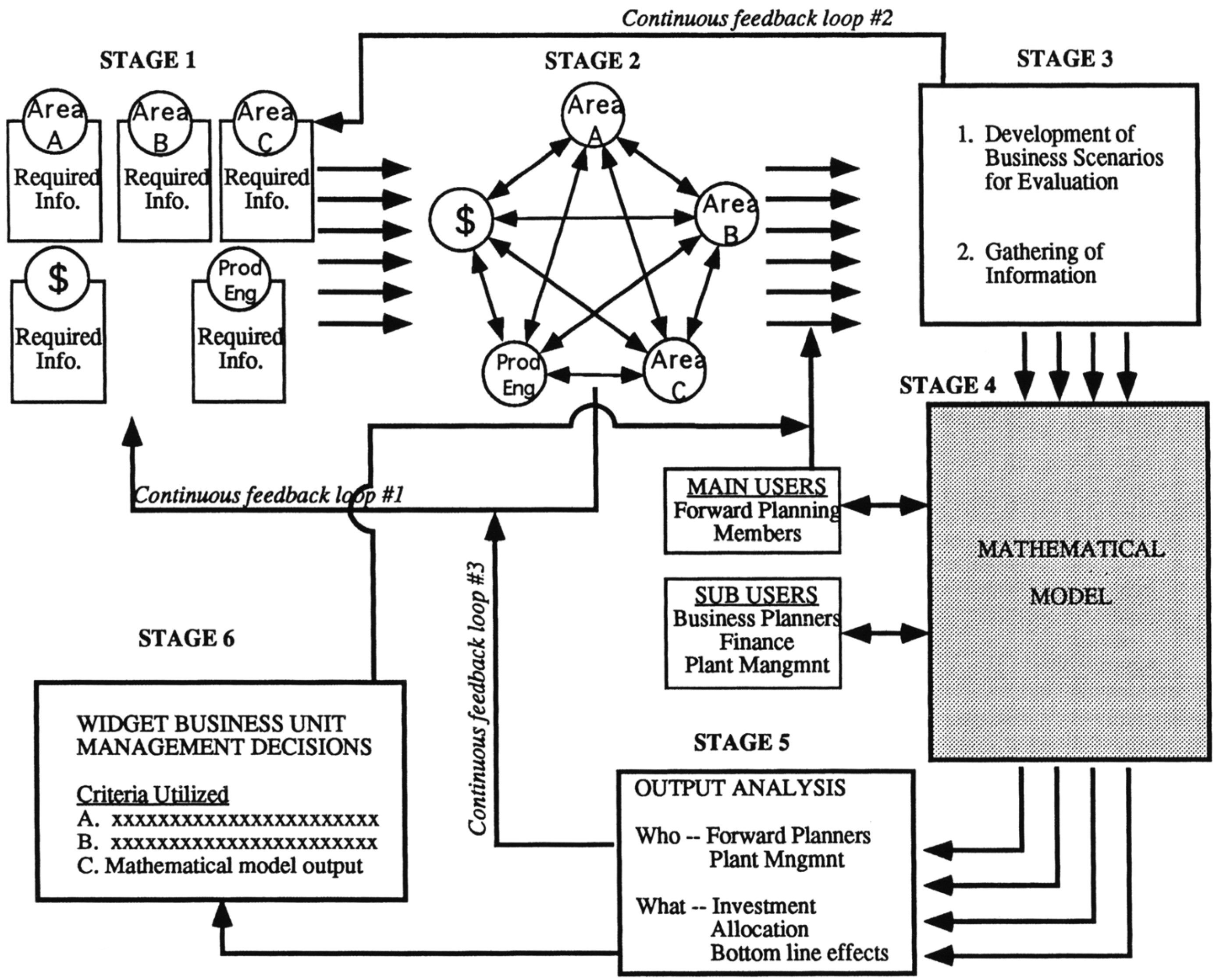

Exhibit 6.1 -- General Management Framework and Decision Process

capabilities and investment cost relationships. Information required from the finance player would be the manufacturing costs of each area. The product engineering player would provide subassembly design information, production volumes, and information on new widgets. Elaboration of the information required by these players is provided in Appendix C.

- **Stage 2 -- Exchange of Information**

In stage 2, the five players exchange the information collected in stage 1. This exchange should be free flowing and characterized by open and direct comments on each area's information. The purpose of this stage is three fold. The first is to get the players communicating with each other to develop a better understanding of each area's production capabilities and investment relationships. Since this process advocates system thinking and optimization, knowledge of each area's capabilities is required for every player. The second purpose is to identify information required from every player and to reach an agreement on how it should be analyzed and documented. It is envisioned that a centralized database will be formed to record this information. Thus, as an area changes, associated information can be automatically changed as well. The third purpose is to gather information for use in the evaluation of a particular business scenario. Most of the information needed for any scenario should be readily accessible from the centralized database.

A mathematical formulation could be created without this stage; consequently, it could be eliminated from the GMFDP. However, it will be from the successful completion of this stage that the players gather the most benefits. Only through the exchange of information at this stage, can each player learn and document the interactions that exist between widget models in each area. This information should make an area's forward planning easier and allow systems optimization. In addition, with the exchange of information and methods used to gather it, refinement of these processes can occur. This feedback and refinement is represented by continuous feedback loop #1.

Besides being the stage where the most benefits can be gained, it is the most critical stage of the GMFDP. If stage 2 were to falter, then the ability of the GMFDP to continue and generate useful answers would cease. Successful completion of this stage is dependent on three factors. The first is the ability of all five players to exchange information freely and work together. Teamwork is essential to the process and this stage. The second factor is the weight given to the mathematical model output as a decision criterion in stage 6. To further explain this second factor, if the result of the GMFDP carries little weight in upper management decisions, then the players will perceive the execution of stages 1 and 2 to be useless. However, if the results of the GMFDP are an important decision criterion, it will be in the best interest of all players to obtain the most accurate information for use in the process. The third factor needed for this stage to be a success, is for upper level management to communicate its support of the GMFDP to each player. They must also point out the benefits each player will gain by supporting the process.

- **Stage 3 -- The Model Formulation**

Stage 3 revolves around the formulation of the mathematical model, which consists of two main activities. One is developing and specifying a business scenario for evaluation. Two is compiling the information to solve the scenario.

Developing a specific business scenario for evaluation should be completed by the Widget Business Unit Managers and members of forward planning. Their job will be to specify the problem they desire to have analyzed. They will also be responsible for providing guidelines on the type of information they wish to use in the scenario. In addition, they should indicate how the results of the output analysis (stage 5) will be included in their final decision (stage 6).

The second activity involves compiling the information to solve the specified business scenario. We anticipate that the majority of information needed to evaluate the scenario will have already been documented in stages 1 and 2. However, with increased use of the GMFDP, it is expected that other required standard information will become apparent. Through continuous feedback loop #2, the gathering of this other information can be incorporated back into the activities of stage 1.

- **Stage 4 -- The Mathematical Model**

Stage 4 is the development of the mathematical model. The model developed will depend on the evaluation scenario and might require altering of the current or previous formulations. Alterations would ideally be performed by a person familiar with forward planning and mathematical modeling. It is hoped that the mathematical model can be automatically generated from the centralized database developed in stage 2, if a suitable user interface is developed. Consequently, this would eliminate the requirement of a person who is familiar with mathematical modeling.

At first the main users of the mathematical model will be forward planning members. If a user interface is developed, it is expected that the number of people using the model will increase. Possible subusers would be plant managers, financial personnel, business planners and product engineers. The more people who are familiar with the system the greater its benefits to MJC.

- **Stage 5 -- Output Analysis**

The output generated from Hyper LINDO model will be analyzed in stage 5. Since the model currently indicates what investments should be made, what products should be produced where and the effect on the financial bottom line, it would seem the analyses would be straightforward. However, they are not. The personnel performing these analyses must be able to interpret the output to ensure that it can be done and makes good business sense. If the generated output does not make sense, the mathematical formulation must be re-examined. More often than not, it will be discovered that some information or interaction was ignored. The ability to interpret the output and arrive at this conclusion is very important. To correct any discovered problem, feedback loop #3 should be used to bring it to the attention of the players.

The output should be analyzed by forward planning members and plant management. The culmination of their analysis should be an answer or recommended plan of action for the specific business scenario. This answer or recommendation will then be forwarded to the widget business managers.

It is important to note that the old adage "garbage in equals garbage out" holds true in the GMFDP. The mathematical model output is only as good as the model formulation and the information used in the formulation. Therefore, anyone using this model must interpret the output sensibly and not accept it blindly. The model in this thesis should be used to point MJC in the right direction and to indicate where further analysis might be conducted.

- **Stage 6 -- Final Decision**

Stage 6 represents the final decision of the widget business managers on the evaluation scenario analyzed by the GMFDP. Their decision will be made based on selected criteria, one of which will be the recommendations generated in stage 5. Depending on the business scenario, the criteria used to make a decision may vary. In some cases the only criteria used might be the recommendations.

It is anticipated that for many of the scenarios that the final decision can be made without the use of stage 6. Involvement of the top managers will vary. However, their involvement is important because they drive the requests for evaluations. Furthermore, it is important for them to participate in the process since extensive work will have been undertaken by the players in stages 1 and 2. If top management ignores the process and recommendations provided, the process will degenerate and be of little benefit to MJC.

6.2 Benefits of the General Management Framework Decision Process

The decisions and benefits to be derived from the successful execution of the GMFDP are provided in Sections 6.2.1 and 6.2.2. Section 6.2.3 is a summary of the GMFDP process.

6.2.1 Benefits of the GMFDP stages

Each stage of the GMFDP is meant to accomplish several different things that will benefit MJC. MJC will only gain these benefits when it successfully completes each stage.

Benefits of Stage 1

- Allows MJC to determine and document the information it needs to analyze potential business situations and update it on a regular basis for future analyses.
- Once the characterization of an area is complete it provides an easy way to understand the interactions between models and the effects of possible allocation decisions.
- Creation of investment sheets will facilitate easy analysis of investment relationships.
- Allows each player to self-examine their processes and highlight areas for improvement.

Benefits of Stage 2

- Facilitates teamwork and communication between the players. This has not always existed at MJC.
- Open and regular lines of communication that do not currently exist will be created.
- This stage provides a forum for players to standardize how information will be gathered and analyzed. In addition, each player will be able to examine other's information to ensure that no games are being played.
- Allows for easy determination of interactions between areas.
- Provides Product Engineering with better design guidelines on what can be built in each area and how design changes will impact investment cost, production rates and capacity.
- Provides each player with a better understanding of how manufacturing costs change in response to changes in their volume and product mix.

- Facilitates the beginning of systems thinking and will bring about systems planning.

- Provides each area with documentation of what the other areas can and can not do.

<u>**Benefits of Stage 3**</u>

- The development of a business scenario (problem statement) and relevant pertinent information is an important first step in any problem solving exercise.

- This stage specifies how the output of stage 5 will be used.

- Clarifies for MJC and its management what problem or situation is to be evaluated. Removes ambiguity and confusion.

<u>**Benefits of Stage 4**</u>

- The use of mathematical modeling allows what-if analyses to be performed rapidly.

- The mathematical model performs a system evaluation. Its objective is to optimize the entire widget business of MJC, which is in contrast to the current sub-optimization.

- The development of a user friendly system allows multiple users. Thus, the benefits from a mathematical model can be provided to multiple people versus a small group.

- The mathematical model performs complex evaluations of a large number of interactions and data that manual methods can not.

<u>**Benefits of Stage 5**</u>

- By having the output analyzed by forward planners and plant management it is ensured that the output is not accepted blindly without it making good business sense.

- The output is analyzed by a group, rather than one individual. Biases are eliminated.

<u>**Benefits of Stage 6**</u>

- Involves top management in the decision process and definition of the business scenario. Gathering their active involvement is important to the success of the GMFDP and sets a good example for all players participating.

Realizing these benefits depends upon the proper execution of each stage. Proper execution requires MJC to constantly evaluate different business scenarios and to improve on the GMFDP through its feedback loops. Since this process is new and dynamic, all the benefits will not be realized until the process has been applied several times. A summary of the process is provided in Section 6.2.3.

6.2.2 Decisions that can be made with the GMFDP

Examination of the GMFDP reveals several different decisions can be made with the process in its current state. Those decisions are:

1. Allocation of yearly widget volumes between A, B and C.
2. Analysis of where production can be shifted to reduce the total manufacturing cost.
3. Analysis of the effects due to changes in volumes and cost structures.

We expect that continued development of the mathematical model and the GMFDP will help in making the following types of decisions in the future:

1. Help make tactical decisions regarding the direction the widget business and manufacturing areas should be moving.
2. Indicate how to best deploy existing facilities and resources over a medium time frame (3 years) to meet anticipated demand.
3. Analyze the effect of varying demand on production costs, investment and widget assignments.

With refinement of the GMFDP, MJC will have a structured process to evaluate the effects of potential manufacturing and allocation decisions on the entire widget business. Development of such a structured process will benefit MJC and provide it a distinct competitive advantage.

6.2.3 Overview of the GMFDP

The GMFDP described in this chapter is not solidified in stone. If this was true then the feedback and continuous improvement loops would not exist. The GMFDP is meant to be dynamic and ever-changing. It was developed this way for two reasons. The first reason is due to expectations that a dynamic process with feedback mechanisms can only get better with time and use. The second reason is that point in time evaluation models are not desired by MJC. Only with a dynamic management process can point in time evaluations be avoided. Hence, as MJC's production capabilities change, a dynamic process can respond and adapt to these changes.

As demonstrated in this chapter, the full benefits derived from the use of the mathematical model can not be realized until the supporting processes are in place (stages 1, 2, 3, 5 and 6). These supporting processes and procedures themselves bring about many benefits to MJC. Thus, in retrospect, trying to implement the use of a mathematical modeling system to aid in forward planning without the development of the supporting processes would fail. The process developed in this chapter and throughout this thesis is not a mathematical model to aid in forward planning, but a manufacturing and business planning process to aid in forward planning.

Development of this process offers MJC a structured method to evaluate potential widget and manufacturing decisions. It is accomplished through a system view of the entire business. This process has also focused on identifying and defining the information to be used in forward planning decisions. Identification of this information does not always occur at MJC. Consequently, the development of a structured process offers many benefits to MJC.

However, it must be remembered that the output of the process is not intended to provide an absolute correct answer. It is only intended to point MJC in the right direction. Once pointed in the right direction, further analysis using the GMFDP can be performed.

In reading this Chapter, the reader might have raised other issues that were not touched upon in this thesis. Although it is impossible to address or anticipate all of them, the author expects that with the continuous improvement loops, the GMFDP can be adapted to address all issues raised.

6.3 Implementation of the GMFDP

To implement the GMFDP at MJC two things must be done. The first is educating the players about the process and the second is committing personnel to perform the process.

6.3.1 Educating the members

The education process would focus on communicating to the personnel involved what the GMFDP is about, what their role would be and why MJC is pursuing it. To help sell this process, the benefits to be gained by each member's support would be highlighted. Time would also be spent reviewing the process and its procedures. Educating and informing each member is important for successful implementation. Unless each member has a clear understanding of what the process is about, how it will work, what their role will be and what benefits they can expect, implementation will fail.

6.3.2 Human Resources to implement the GMFDP

One potential problem with obtaining the information listed in stage 1 and Appendix C is the time and resources required to do it. Although monetary sources will be required to develop the database and mathematical formulations, the greatest expense to MJC will be the dedication of personnel to the project. There are two estimates of human resource requirements for the GMFDP. The first estimate is the human resource time required during implementation of the process. More time will be needed during implementation than any other time. As the process is further refined and developed, it is estimated that the required personnel to continue the process will decrease. This estimate is the second human resource figure.

Human Resource Estimates for Implementation

Facilitator/Developer -- Member of forward planning

- 1 to 1.5 years of full time work on implementing the process, developing mathematical model and incorporating improvements.
- 1 day per week per year after implementation.

Manufacturing Engineering -- Each area

- 2 months of full time work determining and documenting how and what information will be gathered.
- 1 day per week per year after implementation.

Product Engineering

- 1 to 2 days per week during the initial development.
- 1 day per week per year after implementation.

Finance

- 2 to 3 months of full time work in developing and analyzing the cost drivers to be used in the process.
- 1/2 to 1 day per week per year after implementation.

Technical Support -- Performed internally or by consultants

- 3 to 5 months to develop a user interface.
- 3 to 5 months to overcome additional technical concerns.
- 1 to 2 months to develop the data base structure.
- 1 day per week per year after implementation.

6.4 Continued Development of model and process

The benefits of the mathematical model and the GMFDP have been thoroughly detailed in this thesis. However, to achieve these benefits continued development work must be done before the process can be readily accepted and implemented. Several concerns must be addressed during continued development. These concerns are both technical and organizational in nature and are listed below:

Technological Concerns

- Simultaneously minimizing costs over a three year period as opposed to one.
- Development of a user friendly interface.
- Representation of sub-level bottlenecks and process flows.

Organizational Concerns

- Dedicating personnel to update model and develop it on an ongoing basis.
- Determining whether the process is to be used and developed as a strategic or an operational tool.
- Formalizing the use of the decision process within MJC.

These concerns are valid but should not stop continued development. Based on consultations with mathematical programmers, it is agreed that the technological concerns can be resolved in a reasonable time frame. In addition, it is the opinion of the author that the organizational concerns would be overcome with continued development and support from MJC's management. Being able to overcome these concerns, combined with the benefits offered by implementation of the GMFDP, indicate that continued development is in the best interests of MJC.

6.5 Summary

The GMFDP described in this chapter provides the first steps in the creation of a tool to aid in forward planning. It must be stressed that this tool is not to be considered a cure all or final solution for forward planning. With any continuous improvement process, there must be a foundation upon which the improvement is based. It is hoped that continued development of this foundation will result in a process that MJC's management feels comfortable with and is confident in.

Chapter 7: Conclusions and Recommendations

7.1 Accomplishing the thesis objectives

The thesis objectives were to develop a manufacturing planning and business tool to aid in forward planning. This tool would help facilitate decisions such as:

- Which widgets should be manufactured where to minimize costs.
- How MJC should best utilize existing equipment to minimize costs.
- How MJC should handle yearly shifts in model allocation between facilities based on customer requirements and volume changes.

The tool developed also had to perform what-if evaluations to analyze the effect of different management decisions on the widget business, while avoiding static evaluations. Another objective was to identify the resources and actions needed to successfully implement the use of any tool in MJC's decision making process.

The result of the thesis research is the development of a mathematical model and a management process to accomplish the objectives above. Chapters 5 and 6 demonstrate that the mathematical model and the GMFDP provide MJC with a manufacturing and planning tool to aid in its manufacturing and allocation planning process. The tool developed also possesses the following attributes:

- Capabilities to analyze the effect of different evaluation scenarios.
- Dynamic nature to avoid point in time evaluations.

This thesis also illustrates a structured process using mathematical modeling can aid in the forward management of MJC's widget facilities. It indicates that a mathematical model can decide where widgets should be produced, what investments should be made, and how to best use existing equipment to minimize a total manufacturing and investment cost.

7.2 Meeting the desired thesis deliverables

The written thesis was intended to not only help MJC understand the procedures undertaken during the thesis research but to help it with the continued development of the mathematical model and management process. The overall deliverable of this thesis was to develop a process that aids in the forward planning of widget production and allows the effective evaluation of different management decisions. This deliverable was accomplished by providing the following to MJC:

- Description and development of a mathematical model to aid in MJC's allocation decisions.
- Description of the inputs and processes needed to gather the inputs used in the mathematical model.
- Development of a general management framework and decision making process.
- Recommendations regarding the use and continued development of the general management process.

The work detailed in this thesis provides a structured process and associated methodologies to aid in forward planning. In addition, the thesis work should be regarded as the foundation upon which continued development work can be added. Developing the tool to its desired final format in the available time frame was not possible due to the scope and nature of the problem. However, a more refined tool can be developed and would be extremely useful to MJC.

7.3 Recommendations

Throughout the thesis various recommendations have been made ranging from how costs should be considered to how investments should be analyzed. These recommendations and others are based on different issues and different levels of analysis. It is felt that listing, categorizing and analyzing all of the recommendations made in the thesis would prove time consuming and provide little benefit to the reader. There are two reasons for this thought. The first is the reader by now should have formed a distinct opinion regarding the manufacturing and business planning tool presented in this thesis. Additional review of these recommendations would do little to sway the reader's opinion. Second, and what is more important, all of these recommendations can be synthesized into four general recommendations for MJC.

These four recommendations are broad and do not directly take into account such details of how costs should be calculated and what type of centralized database should be created. However, if these recommendations are followed, these other details will ultimately be addressed and resolved. Implementation of these recommendations should result in the development and use of a structured process to aid in the forward planning of MJC's widget manufacturing facilities. These recommendations are provided and explained below.

RECOMMENDATIONS

1. **MJC should continue with development of the mathematical model and management process.**

2. **Continued development of the tool has to occur as a team based activity, with direct input from manufacturing, finance and product engineering.**

3. **MJC should use the tool and processes developed in their current state. Learning comes from people using the tool and processes over time.**

4. **MJC should pursue outside consultants to aid in the continued development of this tool.**

The first recommendation is based on the following items that were detailed in this thesis.

- The model's current ability to do a system evaluation of a multitude of interactions.
- The model's ability to do what-if analyses.
- The model and process helps MJC quantify and identify the inputs and relationships required in its decision making processes.
- The model and process can be applied to other product areas of MJC.
- The model's technical concerns can be overcome by utilizing the proper resources.

The second recommendation is based on the fact that the tool (mathematical model and GMFDP) can only be effectively developed as a team based activity. Development of the tool by one functional area would result in biases that adversely affect the use of the tool in other functional areas of MJC. In addition, development of the tool by a team will help break down some of the functional walls that exist at MJC.

Currently, MJC should try to use the tool in its present state. Many people at MJC are unaware or unfamiliar with the benefits offered by mathematical modeling. It is anticipated that as forward planning members and managers use the tool and processes developed, many of the benefits listed in Chapter 6 will be realized. Each process developed offers its own benefits. As each process is used, it will be refined to best help

MJC. By using the current processes MJC will learn, and be in a better position to articulate what they desire in the continued development of this management tool.

At this time, MJC lacks the internal technical resources to develop an interactive business system similar to PLANETS. Development of such a system would require people familiar with mathematical programming, relational databases and user interfaces. MJC could hire people to develop it into a practical working tool; however, the time required to hire and assemble the people would be too long. To complete the tool in an acceptable time frame to start reaping its benefits, it is recommended that MJC pursue continued development with the help of consultants. MJC has worked with several consultants who are familiar with MJC and could prove to be of great help in completing any desired system. Developing the system quickly and implementing it into MJC's decision process is important because of the competitive environment in which MJC competes.

Implementing these four recommendations are steps MJC needs to take if it desires to fully develop a tool to aid it in making tactical decision regarding the forward planning of widget manufacturing facilities.

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Appendix A: Obtaining the Voice of the Customer

In the pursuit of a tool to assist MJC in its widget forward planning process many different issues regarding forward planning were raised. Since forward widget allocation decisions involve a group of people, all parties involved in the decision making process were interviewed. Their concerns with regard to two issues were gathered:

- How forward widget planning and allocation is done today
- What questions and concerns should be addressed by a tool used in the forward planning process.

Six people were interviewed. The concerns and questions raised during the interviews are listed under Raw Data. The interviewee's responses are numbered from 1 to 42. The breakdown of these responses into categories and subcategories follows as well.

RAW DATA

1. Where and what widget models should be built to minimize costs?
   Is it easier to build certain model widgets in particular areas?
   Can area A manufacture widgets at a lower cost than B?

2. What are the cost drivers and/or manufacturing constraints of the various production areas?
   What factors drive the manufacturing philosophy in each area?

3. Forward planning should determine the type and level of equipment flexibility required to produce future widget models.

4. What are the benefits of deproliferation. Example, "If I decrease the number of widget models by a certain percentage what does that do to my capacity, investment cost, etc.?"

5. Is forward planning being done by the right part of the organization - product engineering?

6. Does MJC have the correct organizational structure to making forward planning decisions and effectively implement any recommendations?

7. Any evaluation tool must avoid point in time evaluations. Tool must characterize the relationships between the inputs so what-if decisions can be evaluated.

8. Is the current process to make forward planning decisions adequate? What information should we be examining to make better decisions?

9. Currently, there is an inability to allocate future widget to manufacturing areas early enough to gather their input on the widget designs.

10. Any evaluation tool must use systems thinking by considering all inter-relationships.

11. Tool should be able to generate proposals for where new widget models should be produced, thus eliminating the need for constant mediation.

12. Is MJC's current manufacturing model allocation correct? What should be built in each area?

13. Tool should indicate where widgets should be manufactured based on anticipated changes in current and future volumes.

14. Tool should answer general questions about manufacturing capacities and capabilities of product areas. Example, "What is the capacity for widget X in C?"

15. Is forward widget allocation being done by the right people?

16. Is it correct to equalize utilization across all the areas? What are the problems of running all areas at only 80% utilization?

17. To drive home allocation decisions do we not need someone who all the product managers report to and are evaluated by? This would avoid the problem of sub-optimization.

18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.

19. Production areas should have a greater influence in the design of a widget. We are forced to react to systems engineering. The reason this occurs is that forward planning doesn't happen early enough.

20. Forward planning should eliminate the need of single tooling for a specific model. An example is widget N.

21. Forward planning should be influencing product designs. Product Engineering doesn't ensure that future widget designs match the capabilities of current manufacturing equipment.

22. Any tool used for forward planning should evaluate manufacturing from a systems standpoint. Decisions can't be made at a level of A vs. B. Decisions must be evaluated at the level of how that decision impacts the bottom line of MJC's entire widget business.

23. Tool should indicate where and what models should be built to minimize costs.

24. Issue of what production capacity number should be used in planning needs to be answered. Rated capacity vs. real average production capacity.

25. Tool must account for the relationship between model mix and volume. If future volume drops, it doesn't mean that the model mix drops the same amount.

26. Evaluation of where to build a model can't just look at scrap cost per unit. The primary part production area's scrap all goes against area B, when these areas produce parts for A too.

27. Have to evaluate the impact of a decision on the entire widget business.

28. Is forward planning being done by the right part of the organization?

29. Is the correct organizational structure in place to evaluate and implement forward planning decisions?

30. What is the effect of the decision to utilize and invest for 3 shifts in B, and for a possible 4 shifts in A?

31. When you make a change in a widget design, what does it cost you in the different manufacturing areas?
    What does the design change do to the material and process costs?
    What are the inputs needed to make this evaluation?

32. What effect does different volume levels impact the burden costs in the different areas?

33. What effect does it have on your burden, if you run at 88% capacity in all production areas?

34. What is the cost/savings for proliferation/deproliferation in each product area?

35. How many changeovers can a department effectively do in a shift before it becomes a penalty?

36. If you were to move a widget from C to B would there be a reduction in the number of people to produce it?

37. Tool should avoid point in time evaluations. Relationships between the inputs needed to make these decisions must be characterized.

38. The tool should assign widget production to different areas based on the lowest overall investment.

39. Tool should maintain information on areas production capabilities.

40. Tool should provide a framework to which additional capabilities and evaluation scenarios could be added,

41. Tool should help minimize future investment in MJC's production equipment.

42. Tool should be able to do what-if decisions on investment and production capabilities.

Analysis of the raw data resulted in it being segmented into five categories. These categories and the responses that comprise them are shown below:

SEGMENTATION INTO CATEGORIES

I. Questions/issues to be answered or captured by a tool used in forward planning.

1. Where and what widget models should be built to minimize costs?
   Is it easier to build certain model widgets in particular areas?
   Can area A manufacture widgets at a lower cost than B?
2. What are the cost drivers and/or manufacturing constraints of the various production areas?
   What factors drive the manufacturing philosophy in each area?
4. What are the benefits of deproliferation. Example, "If I decrease the number of widget models by a certain percentage what does that do to my capacity, investment cost, etc.?"
9. Currently, there is an inability to allocate future widget to manufacturing areas early enough to gather their input on the widget designs.
11. Tool should be able to generate proposals for where new widget models should be produced, thus eliminating the need for constant mediation.
13. Tool should indicate where widgets should be manufactured based on anticipated changes in current and future volumes.
14. Tool should answer general questions about manufacturing capacities and capabilities of product areas. Example, "What is the capacity for widget X in C?"
16. Is it correct to equalize utilization across all the areas? What are the problems of running all areas at only 80% utilization?
23. Tool should indicate where and what models should be built to minimize costs.
25. Tool must account for the relationship between model mix and volume. If future volume drops, it doesn't mean that the model mix drops the same amount.
30. What is the effect of the decision to utilize and invest for 3 shifts in B, and for a possible 4 shifts in A?
31. When you make a change in a widget design, what does it cost you in the different manufacturing areas?
    What does the design change do to the material and process costs?
    What are the inputs needed to make this evaluation?
32. What effect does different volume levels impact the burden costs in the different areas?
33. What effect does it have on your burden, if you run at 88% capacity in all production areas?
34. What is the cost/savings for proliferation/deproliferation in each product area?
35. How many changeovers can a department effectively do in a shift before it becomes a penalty?
36. If you were to move a widget from C to B would there be a reduction in the number of people to produce it?
38. The tool should assign widget production to different areas based on the lowest overall investment.
39. Tool should maintain information on areas production capabilities.
41. Tool should help minimize future investment in MJC's production equipment.

II. What would be required of any tool used in the forward planning process?

7. Any evaluation tool must avoid point in time evaluations. Tool must characterize the relationships between the inputs so what-if decisions can be evaluated.
10. Any evaluation tool must use systems thinking by considering all inter-relationships.
18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.
22. Any tool used for forward planning should evaluate manufacturing from a systems standpoint. Decisions can't be made at a level of A vs. B. Decisions must be evaluated at the level of how that decision impacts the bottom line of MJC's entire widget business.
26. Evaluation of where to build a model can't just look at scrap cost per unit. The primary part production area's scrap all goes against area B, when these areas produce parts for A too.
27. Have to evaluate the impact of a decision on the entire widget business. What are the inputs needed to make this evaluation?
37. Tool should avoid point in time evaluations. Relationships between the inputs needed to make these decisions must be characterized.
40. Tool should provide a framework to which additional capabilities and evaluation scenarios could be added,
42. Tool should be able to do what-if decisions on investment and production capabilities.

III. What are some of the problems/concerns with the way forward planning is done today?

5. Is forward planning being done by the right part of the organization - product engineering?
8. Is the current process to make forward planning decisions adequate? What information should we be examining to make better decisions?
9. Currently, there is an inability to allocate future widget to manufacturing areas early enough to gather their input on the widget designs.
11. Tool should be able to generate proposals for where new widget models should be produced, thus eliminating the need for constant mediation.
12. Is MJC's current manufacturing model allocation correct? What should be built in each area?
15. Is forward widget allocation being done by the right people?
18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.
19. Production areas should have a greater influence in the design of a widget. We are forced to react to systems engineering. The reason this occurs is that forward planning doesn't happen early enough.
20. Forward planning should eliminate the need of single tooling for a specific model. An example is widget N.
21. Forward planning should be influencing product designs. Product Engineering doesn't ensure that future widget designs match the capabilities of current manufacturing equipment.
24. Issue of what production capacity number should be used in planning needs to be answered. Rated capacity vs. real average production capacity.
28. Is forward planning being done by the right part of the organization?

IV. What other issues/concerns should forward planning be addressing that a planning tool might not?

3. Forward planning should determine the type and level of equipment flexibility required to produce future widget models.
4. What are the benefits of deproliferation. Example, "If I decrease the number of widget models by a certain percentage what does that do to my capacity, investment cost, etc.?"
16. Is it correct to equalize utilization across all the areas? What are the problems of running all areas at only 80% utilization?
18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.
19. Production areas should have a greater influence in the design of a widget. We are forced to react to systems engineering. The reason this occurs is that forward planning doesn't happen early enough.
20. Forward planning should eliminate the need of single tooling for a specific model. An example is widget N.
21. Forward planning should be influencing product designs. Product Engineering doesn't ensure that future widget designs match the capabilities of current manufacturing equipment.
24. Issue of what production capacity number should be used in planning needs to be answered. Rated capacity vs. real average production capacity.

V. What concerns are there about successful implementation of forward planning decisions?

6. Does MJC have the correct organizational structure to making forward planning decisions and effectively implement any recommendations?
15. Is forward widget allocation being done by the right people?
17. To drive home allocation decisions do we not need someone who all the product managers report to and are evaluated by? This would avoid the problem of sub-optimization.
28. Is forward planning being done by the right part of the organization?
29. Is the correct organizational structure in place to evaluate and implement forward planning decisions?

Further analysis of each category resulted in the creation of subcategories. Based on these categories and subcategories, requirements of any tool to aid in forward planning could be readily determined. The breakdown of the categories is shown below:

SEGMENTATION INTO SUBCATEGORIES

I. Questions/issues to be answered or captured by a tool used in forward planning.

A. Are we currently manufacturing the right type of widgets? Are manufacturing widgets in the right area?

1. Where and what widget models should be built to minimize costs?
   Is it easier to build certain model widgets in particular areas?
   Can area A manufacture widgets at a lower cost than B?
2. What are the cost drivers and/or manufacturing constraints of the various production areas?
   What factors drive the manufacturing philosophy in each area?

B. What is the proliferation or widget models costing us?

4. What are the benefits of deproliferation. Example, "If I decrease the number of widget models by a certain percentage what does that do to my capacity, investment cost, etc.?"
34. What is the cost/savings for proliferation/deproliferation in each product area?

C. Tool should be able to assign all future model widgets to specific areas assuming we are currently building the right widgets in each area.

9. Currently, there is an inability to allocate future widget to manufacturing areas early enough to gather their input on the widget designs.
11. Tool should be able to generate proposals for where new widget models should be produced, thus eliminating the need for constant mediation.
13. Tool should indicate where widgets should be manufactured based on anticipated changes in current and future volumes.
23. Tool should indicate where and what models should be built to minimize costs.
38. The tool should assign widget production to different areas based on the lowest overall investment.

D. Tool should answer general manufacturing capacity, capabilities and labor questions.

14. Tool should answer general questions about manufacturing capacities and capabilities of product areas. Example "What is the capacity for widget X in C?"
35. How many changeovers can a department effectively do in a shift before it becomes a penalty?
36. If you were to move a widget from C to B would there be a reduction in the number of people to produce it?
39. Tool should maintain information on areas production capabilities.

E. Tool should detail the effect of utilization and volume levels on production and investment costs.

16. Is it correct to equalize utilization across all the areas? What are the problems of running all areas at only 80% utilization?
30. What is the effect of the decision to utilize and invest for 3 shifts in B, and for a possible 4 shifts in A?

32. What effect does different volume levels impact the burden costs in the different areas?
33. What effect does it have on your burden, if you run at 88% capacity in all production areas?
41. Tool should help minimize future investment in MJC's production equipment.

F. What are the impact of widget design changes on widget unit costs?

31. When you make a change in a widget design, what does it cost you in the different manufacturing areas?
    What does the design change do to the material and process costs?
    What are the inputs needed to make this evaluation?

II. What would be required of any tool used in the forward planning process?

A. The tool must be capable of adapting to changes in the production and planning processes at MJC. Tool must avoid point in time evaluations.

7. Any evaluation tool must avoid point in time evaluations. Tool must characterize the relationships between the inputs so what-if decisions can be evaluated.
37. Tool should avoid point in time evaluations. Relationships between the inputs needed to make these decisions must be characterized.
40. Tool should provide a framework to which additional capabilities and evaluation scenarios could be added,

B. Planning tool must perform evaluations with a systems standpoint to avoid suboptimal solutions. What-if evaluations must look at the financial bottom line of the entire widget business.

10. Any evaluation tool must use systems thinking by considering all inter-relationships.
18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.
22. Any tool used for forward planning should evaluate manufacturing from a systems standpoint. Decisions can't be made at a level of A vs. B. Decisions must be evaluated at the level of how that decision impacts the bottom line of MJC's entire widget business.
27. Have to evaluate the impact of a decision on the entire widget business.
    What are the inputs needed to make this evaluation?
42. Tool should be able to do what-if decisions on investment and production capabilities.

C. Discrepancies in information between various areas must be resolved before system evaluations can be conducted.

26. Evaluation of where to build a model can't just look at scrap cost per unit. The primary part production area's scrap all goes against area B, when these areas produce parts for A too.

III. What are some of the problems/concerns with the way forward planning is done today?

A. Who should be doing forward planning?

5. Is forward planning being done by the right part of the organization - product engineering?
15. Is forward widget allocation being done by the right people?

28. Is forward planning being done by the right part of the organization?

B. Is the right information and processes being used to do forward planning?

8. Is the current process to make forward planning decisions adequate? What information should we be examining to make better decisions?
12. Is MJC's current manufacturing model allocation correct? What should be built in each area?
24. Issue of what production capacity number should be used in planning needs to be answered. Rated capacity vs. real average production capacity.

C. Product Engineering isn't aware of the financial impact their design decisions have on the manufacturing areas.

18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.
19. Production areas should have a greater influence in the design of a widget. We are forced to react to systems engineering. The reason this occurs is that forward planning doesn't happen early enough.
20. Forward planning should eliminate the need of single tooling for a specific model. An example is widget N.
21. Forward planning should be influencing product designs. Product Engineering doesn't ensure that future widget designs match the capabilities of current manufacturing equipment.

D. Forward planning doesn't happen early enough

9. Currently, there is an inability to allocate future widget to manufacturing areas early enough to gather their input on the widget designs.

IV. What other issues/concerns should forward planning be addressing that a planning tool might not?

A. Forward planners should work to determine the amount of flexibility that future manufacturing equipment will require.

3. Forward planning should determine the type and level of equipment flexibility required to produce future widget models.

B. Forward planners should analyze the benefits of reduced widget models/

4. What are the benefits of deproliferation. Example, "If I decrease the number of widget models by a certain percentage what does that do to my capacity, investment cost, etc.?"

C. Forward planning should be influencing future widget designs.

18. Any tool used should indicate the impact of widget design decisions on product and tooling cost.
19. Production areas should have a greater influence in the design of a widget. We are forced to react to systems engineering. The reason this occurs is that forward planning doesn't happen early enough.
21. Forward planning should be influencing product designs. Product Engineering doesn't ensure that future widget designs match the capabilities of current manufacturing equipment.

D. Examination of the proper utilization level for each area is needed.

16. Is it correct to equalize utilization across all the areas? What are the problems of running all areas at only 80% utilization?

V. What concerns are there about successful implementation of forward planning decisions?

A. MJC's present organizational structure might not allow the successful implementation of forward planning recommendations.

6. Does MJC have the correct organizational structure to making forward planning decisions and effectively implement any recommendations?
15. Is forward widget allocation being done by the right people?
17. To drive home allocation decisions do we not need someone who all the product managers report to and are evaluated by? This would avoid the problem of sub-optimization.
28. Is forward planning being done by the right part of the organization?
29. Is the correct organizational structure in place to evaluate and implement forward planning decisions?

Appendix B: Mathematical Model for MJC's 1994 Widget Allocation

The mathematical formulation and output used to optimize MJC's 1994 widget allocation are contained on the following pages. The model has been segmented into its objective function and constraints. The Hyper LINDO output has been analyzed to show where each model has been allocated. The volume and cost data for each widget could not be included due to proprietary restrictions. Only the objective value could be retained.

- **Objective Function**

$$\text{MIN} \quad \sum_j \sum_i M_{ij} X_{ij} + \sum_j \sum_i I_{jk} Y_{jk}$$

MIN 75 Y12 + 333.33 Y13 + 2787.5 Y14 + 908.33 Y15 + 2787.5 Y16
+ 83.33 Y17 + 83.33 Y18 + 154.17 Y19 + 75 Y22 + 333.33 Y23 + 2662.5 Y24
+ 908.33 Y25 + 2662.5 Y26 + 83.33 Y27 + 83.33 Y28 + 166.67 Y32
+ 916.67 Y33 + 416.67 Y34 + 1250 Y35 + 250 Y36 + 208.33 Y37 + 208.33 Y38
+ 166.67 Y42 + 916.67 Y43 + 1666.67 Y44 + 416.67 Y45 + 1250 Y46
+ 1666.67 Y52 + 1666.67 Y53 + 250 Y54 + 1666.67 Y55 + 416.67 Y56
+ 1666.67 Y62 + 416.67 Y63 + 58.33 Y64 + 1250 Y71 + 633.33 Y81
+ 5762.78 X11 + 13505.59 X21 + 1714.06 X31 + 3930.51 X41 + 3871.4 X51
+ 1359.42 X71 + 502.4 X91 + 4432.91 X101 + 8201.7 X111 + 1755.18 X141
+ 6480.65 X151 + 29.55 X181 + 115.45 X191 + 265.97 X201 + 295.53 X211
+ 317.49 X221 + 443.29 X231 + 443.29 X241 + 1625.4 X251 + 2630.19 X261
+ 8735.8 X361 + 257.87 X371 + 9398.09 X381 + 1204.4 X391 + 218.98 X441
+ 1117.46 X451 + 2052.95 X461 + 3685.8 X471 + 4188.02 X481
+ 11252.85 X491 + 13266.2 X501 + 2222.43 X511 + 2713.09 X521
+ 8333.861 X531 + 3723.64 X551 + 2119.28 X571 + 6694.99 X581
+ 6476.42 X591 + 5888.81 X661 + 8357.34 X781 + 2617.96 X811
+ 17520.2 X821 + 345.06 X831 + 1978.25 X841 + 20284.05 X851
+ 30453.94 X861 + 371.6 X901 + 530.85 X911 + 5707.13 X12 + 13375.18 X22
+ 1697.51 X32 + 3892.56 X42 + 3834.02 X52 + 1346.3 X72 + 497.54 X92
+ 4390.1 X102 + 8113.52 X112 + 1736.63 X142 + 6412.16 X152 + 29.27 X182
+ 114.31 X192 + 263.41 X202 + 292.67 X212 + 314.35 X222 + 439.01 X232
+ 439.01 X242 + 1609.7 X252 + 2604.79 X262 + 8645.92 X362 + 255.31 X372
+ 9304.49 X382 + 1191.84 X392 + 216.7 X442 + 1106.33 X452 + 2031.55 X462
+ 3648.13 X472 + 4144.36 X482 + 11137.85 X492 + 13134.08 X502
+ 2200.46 X512 + 2686.27 X522 + 8253.39 X532 + 3687.69 X552
+ 2094.17 X572 + 6615.66 X582 + 6406.79 X592 + 5822.9 X662 + 8262.6 X782
+ 2588.28 X812 + 17321.6 X822 + 341.35 X832 + 1957.99 X842
+ 20076.31 X852 + 30142.05 X862 + 367.6 X902 + 525.15 X912 + 6263.39 X13
+ 14678.82 X23 + 1862.96 X33 + 4271.95 X43 + 4207.71 X53 + 1477.52 X73

+ 546.04 X93 + 4817.99 X103 + 8985.7 X113 + 1924.65 X143 + 7106.39 X153
+ 32.12 X183 + 125.48 X193 + 289.08 X203 + 321.2 X213 + 345.07 X223
+ 481.8 X233 + 481.8 X243 + 1766.6 X253 + 2858.68 X263 + 9531.88 X363
+ 280.35 X373 + 10217.18 X383 + 1316.48 X393 + 239.36 X443
+ 1214.85 X453 + 2244 X463 + 4019.39 X473 + 4577.75 X483 + 12271.33 X493
+ 14422.43 X503 + 2415.49 X513 + 2948.78 X523 + 9057.83 X533
+ 4047.11 X553 + 7095.51 X593 + 6486.47 X663 + 9212.981 X783
+ 2885.99 X813 + 19313.96 X823 + 378.04 X833 + 2156.27 X843
+ 22109.32 X853 + 33194.35 X863 + 407.26 X903 + 581.8 X913 + 5873.3 X14
+ 13764.6 X24 + 1746.93 X34 + 4005.89 X44 + 3945.65 X54 + 1385.5 X74
+ 512.03 X94 + 4517.92 X104 + 8367.56 X114 + 1794.62 X144 + 6626.28 X154
+ 30.12 X184 + 117.48 X194 + 271.08 X204 + 301.19 X214 + 323.06 X224
+ 451.79 X234 + 451.79 X244 + 1656.57 X254 + 2680.63 X264 + 8901.74 X364
+ 262.35 X374 + 9561.03 X384 + 1228.46 X394 + 223.36 X444 + 1136.83 X454
+ 2093.96 X464 + 3755.33 X474 + 4271.68 X484 + 11465.14 X494
+ 13496.21 X504 + 2261.45 X514 + 2760.73 X524 + 8493.691 X534
+ 3795.05 X554 + 2170.91 X574 + 6858.12 X584 + 6607.39 X594
+ 6024.36 X664 + 8548.83 X784 + 2677.95 X814 + 17921.64 X824
+ 352.03 X834 + 2014.23 X844 + 20652.98 X854 + 31007.85 X864
+ 379.25 X904 + 541.79 X914 + 14389.62 X65 + 392.7 X85 + 1603.69 X125
+ 11409.84 X135 + 54.32 X165 + 271.6 X175 + 24.7 X275 + 54.32 X285
+ 330.6 X295 + 413.25 X305 + 716.3 X315 + 897.6 X325 + 3365.99 X335
+ 2202.82 X345 + 182 X355 + 780.1 X405 + 1452.6 X415 + 3025.55 X425
+ 8917.42 X435 + 15792.12 X545 + 15483.57 X565 + 6199.04 X605
+ 6199.04 X615 + 1089.06 X675 + 12420.44 X685 + 27.38 X725 + 27.38 X735
+ 1823.25 X745 + 1187.69 X755 + 2023.38 X765 + 11422.02 X775
+ 2072.14 X795 + 6140.6 X805 + 1711.38 X895 + 13363.39 X66 + 364.69 X86
+ 1481.66 X126 + 10541.64 X136 + 50.32 X166 + 251.59 X176 + 22.7 X276
+ 50.32 X286 + 306.59 X296 + 383.24 X306 + 664.29 X316 + 833.58 X326
+ 3125.94 X336 + 2036.78 X346 + 168 X356 + 722.09 X406 + 1344.57 X416
+ 2797.5 X426 + 8245.27 X436 + 14665.86 X546 + 14379.32 X566
+ 5756.94 X606 + 5756.94 X616 + 1005.04 X676 + 11462.22 X686
+ 25.38 X726 + 25.38 X736 + 1673.21 X746 + 1093.67 X756 + 1861.34 X766
+ 10517.81 X776 + 1908.1 X796 + 5654.48 X806 + 1579.35 X896
+ 3324.15 X877 + 17960.58 X887 + 23.94 X628 + 2394.7 X638 + 4069.71 X648
+ 16470.36 X658 + 4835.89 X698 + 10533.37 X708 + 32366.18 X718

- <u>Constraints</u>

1. Product i must be assigned to only one manufacturing location.

$$\sum_j Xij = 1 \qquad \text{for all i}$$

2) X11 + X12 + X13 + X14 = 1
3) X21 + X22 + X23 + X24 = 1
4) X31 + X32 + X33 + X34 = 1
5) X41 + X42 + X43 + X44 = 1
6) X51 + X52 + X53 + X54 = 1
7) X65 + X66 = 1
8) X71 + X72 + X73 + X74 = 1
9) X85 + X86 = 1

10) $X91 + X92 + X93 + X94 = 1$
11) $X101 + X102 + X103 + X104 = 1$
12) $X111 + X112 + X113 + X114 = 1$
13) $X125 + X126 = 1$
14) $X135 + X136 = 1$
15) $X141 + X142 + X143 + X144 = 1$
16) $X151 + X152 + X153 + X154 = 1$
17) $X165 + X166 = 1$
18) $X175 + X176 = 1$
19) $X181 + X182 + X183 + X184 = 1$
20) $X191 + X192 + X193 + X194 = 1$
21) $X201 + X202 + X203 + X204 = 1$
22) $X211 + X212 + X213 + X214 = 1$
23) $X221 + X222 + X223 + X224 = 1$
24) $X231 + X232 + X233 + X234 = 1$
25) $X241 + X242 + X243 + X244 = 1$
26) $X251 + X252 + X253 + X254 = 1$
27) $X261 + X262 + X263 + X264 = 1$
28) $X275 + X276 = 1$
29) $X285 + X286 = 1$
30) $X295 + X296 = 1$
31) $X305 + X306 = 1$
32) $X315 + X316 = 1$
33) $X325 + X326 = 1$
34) $X335 + X336 = 1$
35) $X345 + X346 = 1$
36) $X355 + X356 = 1$
37) $X361 + X362 + X363 + X364 = 1$
38) $X371 + X372 + X373 + X374 = 1$
39) $X381 + X382 + X383 + X384 = 1$
40) $X391 + X392 + X393 + X394 = 1$
41) $X405 + X406 = 1$
42) $X415 + X416 = 1$
43) $X425 + X426 = 1$
44) $X435 + X436 = 1$
45) $X441 + X442 + X443 + X444 = 1$
46) $X451 + X452 + X453 + X454 = 1$
47) $X461 + X462 + X463 + X464 = 1$
48) $X471 + X472 + X473 + X474 = 1$
49) $X481 + X482 + X483 + X484 = 1$
50) $X491 + X492 + X493 + X494 = 1$
51) $X501 + X502 + X503 + X504 = 1$
52) $X511 + X512 + X513 + X514 = 1$
53) $X521 + X522 + X523 + X524 = 1$
54) $X531 + X532 + X533 + X534 = 1$
55) $X545 + X546 = 1$
56) $X551 + X552 + X553 + X554 = 1$
57) $X565 + X566 = 1$
58) $X571 + X572 + X574 = 1$
59) $X581 + X582 + X584 = 1$
60) $X591 + X592 + X593 + X594 = 1$
61) $X605 + X606 = 1$
62) $X615 + X616 = 1$
63) $X628 = 1$

64) X638 = 1
65) X648 = 1
66) X658 = 1
67) X661 + X662 + X663 + X664 = 1
68) X675 + X676 = 1
69) X685 + X686 = 1
70) X698 = 1
71) X708 = 1
72) X718 = 1
73) X725 + X726 = 1
74) X735 + X736 = 1
75) X745 + X746 = 1
76) X755 + X756 = 1
77) X765 + X766 = 1
78) X775 + X776 = 1
79) X781 + X782 + X783 + X784 = 1
80) X795 + X796 = 1
81) X805 + X806 = 1
82) X811 + X812 + X813 + X814 = 1
83) X821 + X822 + X823 + X824 = 1
84) X831 + X832 + X833 + X834 = 1
85) X841 + X842 + X843 + X844 = 1
86) X851 + X852 + X853 + X854 = 1
87) X861 + X862 + X863 + X864 = 1
88) X877 = 1
89) X887 = 1
90) X895 + X896 = 1
91) X901 + X902 + X903 + X904 = 1
92) X911 + X912 + X913 + X914 = 1

2. The production hours needed to produce assigned product i's to location j can not exceed location j's available production hours.

$$\sum_{i} R_{ij} X_{ij} \leq C_j \quad \text{for all j}$$

j=3 primary assembly

93) 1.204 X13 + 2.821 X23 + 0.358 X33 + 0.821 X43 + 0.809 X53
+ 0.284 X73 + 0.105 X93 + 0.926 X103 + 1.907 X113 + 0.401 X143
+ 1.481 X153 + 0.006 X183 + 0.025 X193 + 0.056 X203 + 0.062 X213
+ 0.068 X223 + 0.093 X233 + 0.093 X243 + 0.34 X253 + 0.549 X263
+ 1.944 X363 + 0.056 X373 + 2.025 X383 + 0.272 X393 + 0.049 X443
+ 0.241 X453 + 0.463 X463 + 0.815 X473 + 0.944 X483 + 2.488 X493
+ 2.858 X503 + 0.475 X513 + 0.58 X523 + 1.741 X533 + 0.778 X553
+ 1.506 X593 + 1.426 X663 + 2.049 X783 + 0.642 X813 + 4.296 X823
+ 0.08 X833 + 0.438 X843 + 4.494 X853 + 6.747 X863 + 0.086 X903
+ 0.123 X913 <= 24

j=4 primary assembly

94) 4.333 X14 + 10.156 X24 + 1.289 X34 + 2.956 X44 + 2.911 X54
+ 1.022 X74 + 0.378 X94 + 3.333 X104 + 5.83 X114 + 1.444 X144

+ 5.333 X154 + 0.022 X184 + 0.089 X194 + 0.2 X204 + 0.222 X214
+ 0.244 X224 + 0.333 X234 + 0.333 X244 + 1.222 X254 + 1.978 X264
+ 7 X364 + 0.2 X374 + 7.289 X384 + 0.978 X394 + 0.178 X444 + 0.867 X454
+ 1.667 X464 + 2.933 X474 + 3.4 X484 + 8.956 X494 + 10.289 X504
+ 1.711 X514 + 2.089 X524 + 6.267 X534 + 2.8 X554 + 1.66 X574
+ 5.245 X584 + 4.604 X594 + 5.133 X664 + 6.264 X784 + 1.962 X814
+ 13.132 X824 + 0.245 X834 + 1.34 X844 + 13.736 X854 + 20.623 X864
+ 0.311 X904 + 0.444 X914 <= 153.12

j=5 primary assembly

95) 2.42 X65 + 0.066 X85 + 0.288 X125 + 2.047 X135 + 0.009 X165
+ 0.047 X175 + 0.005 X275 + 0.009 X285 + 0.057 X295 + 0.071 X305
+ 0.123 X315 + 0.151 X325 + 0.566 X335 + 0.392 X345 + 0.033 X355
+ 0.137 X405 + 0.255 X415 + 0.538 X425 + 1.585 X435 + 2.656 X545
+ 2.604 X565 + 1.042 X605 + 1.042 X615 + 0.198 X675 + 2.259 X685
+ 0.005 X725 + 0.005 X735 + 0.354 X745 + 0.222 X755 + 0.382 X765
+ 2.132 X775 + 0.387 X795 + 1.146 X805 + 0.311 X895 <= 24

j=6 primary assembly

96) 10.688 X66 + 0.292 X86 + 1.13 X126 + 8.037 X136 + 0.042 X166
+ 0.208 X176 + 0.019 X276 + 0.042 X286 + 0.25 X296 + 0.313 X306
+ 0.542 X316 + 0.667 X326 + 2.5 X336 + 1.729 X346 + 0.13 X356
+ 0.6039999 X406 + 1.125 X416 + 2.375 X426 + 7 X436 + 11.729 X546
+ 11.5 X566 + 4.604 X606 + 4.604 X616 + 0.778 X676 + 8.87 X686
+ 0.021 X726 + 0.021 X736 + 1.364 X746 + 0.855 X756 + 1.473 X766
+ 8.218 X776 + 1.491 X796 + 4.418 X806 + 1.222 X896 <= 191.4

j=7 primary assembly

97) 1.607 X877 + 8.68 X887 <= 24

j=8 primary assembly

98) 0.018 X628 + 1.873 X638 + 3.091 X648 + 12.509 X658 + 3.782 X698
+ 8 X708 + 24.582 X718 <= 76.56

A1's joining operation

99) 1.393 X11 + 3.264 X21 + 0.414 X31 + 0.95 X41 + 0.936 X51
+ 0.329 X71 + 0.121 X91 + 1.071 X101 + 2.131 X111 + 0.464 X141
+ 1.714 X151 + 0.007 X181 + 0.029 X191 + 0.064 X201 + 0.071 X211
+ 0.079 X221 + 0.107 X231 + 0.107 X241 + 0.393 X251 + 0.6359999 X261
+ 2.25 X361 + 0.064 X371 + 2.343 X381 + 0.314 X391 + 0.057 X441
+ 0.279 X451 + 0.536 X461 + 0.943 X471 + 1.093 X481 + 2.879 X491
+ 3.307 X501 + 0.55 X511 + 0.671 X521 + 2.014 X531 + 0.9 X551
+ 0.607 X571 + 1.917 X581 + 1.683 X591 + 1.65 X661 + 2.29 X781
+ 0.717 X811 + 4.8 X821 + 0.09 X831 + 0.49 X841 + 5.021 X851
+ 7.538 X861 + 0.1 X901 + 0.143 X911 <= 11.4

A2's joining operation

100) 1.535 X12 + 3.598 X22 + 0.457 X32 + 1.047 X42 + 1.031 X52
+ 0.362 X72 + 0.134 X92 + 1.181 X102 + 2.131 X112 + 0.512 X142
+ 1.89 X152 + 0.008 X182 + 0.031 X192 + 0.071 X202 + 0.079 X212
+ 0.087 X222 + 0.118 X232 + 0.118 X242 + 0.433 X252 + 0.701 X262
+ 2.48 X362 + 0.071 X372 + 2.583 X382 + 0.346 X392 + 0.063 X442
+ 0.307 X452 + 0.591 X462 + 1.039 X472 + 1.205 X482 + 3.173 X492
+ 3.646 X502 + 0.606 X512 + 0.74 X522 + 2.22 X532 + 0.992 X552

+ 0.607 X572 + 1.917 X582 + 1.683 X592 + 1.819 X662 + 2.29 X782
+ 0.717 X812 + 4.8 X822 + 0.09 X832 + 0.49 X842 + 5.021 X852
+ 7.538 X862 + 0.11 X902 + 0.157 X912 <= 14.4

C's joining operation

101) 1.931 X13 + 4.525 X23 + 0.574 X33 + 1.317 X43 + 1.297 X53
+ 0.455 X73 + 0.168 X93 + 1.485 X103 + 3.059 X113 + 0.644 X143
+ 2.376 X153 + 0.01 X183 + 0.04 X193 + 0.089 X203 + 0.099 X213
+ 0.109 X223 + 0.149 X233 + 0.149 X243 + 0.545 X253 + 0.881 X263
+ 3.119 X363 + 0.089 X373 + 3.248 X383 + 0.436 X393 + 0.079 X443
+ 0.386 X453 + 0.743 X463 + 1.307 X473 + 1.515 X483 + 3.99 X493
+ 4.584 X503 + 0.762 X513 + 0.931 X523 + 2.792 X533 + 1.248 X553
+ 2.416 X593 + 2.287 X663 + 3.287 X783 + 1.03 X813 + 6.891 X823
+ 0.129 X833 + 0.703 X843 + 7.208 X853 + 10.822 X863 + 0.139 X903
+ 0.198 X913 + 3.613 X65 + 0.099 X85 + 0.43 X125 + 3.056 X135
+ 0.014 X165 + 0.07 X175 + 0.007 X275 + 0.014 X285 + 0.085 X295
+ 0.106 X305 + 0.183 X315 + 0.225 X325 + 0.845 X335 + 0.5849999 X345
+ 0.049 X355 + 0.204 X405 + 0.38 X415 + 0.803 X425 + 2.366 X435
+ 3.965 X545 + 3.887 X565 + 1.556 X605 + 1.556 X615 + 0.296 X675
+ 3.373 X685 + 0.007 X725 + 0.007 X735 + 0.528 X745 + 0.331 X755
+ 0.57 X765 + 3.183 X775 + 0.577 X795 + 1.711 X805 + 0.465 X895
+ 1.054 X877 + 5.694 X887 <= 48

B's joining operation

102) 1.696 X14 + 3.974 X24 + 0.504 X34 + 1.157 X44 + 1.139 X54
+ 0.4 X74 + 0.148 X94 + 1.304 X104 + 2.687 X114 + 0.565 X144
+ 2.087 X154 + 0.009 X184 + 0.035 X194 + 0.078 X204 + 0.087 X214
+ 0.096 X224 + 0.13 X234 + 0.13 X244 + 0.478 X254 + 0.774 X264
+ 2.739 X364 + 0.078 X374 + 2.852 X384 + 0.383 X394 + 0.07 X444
+ 0.339 X454 + 0.652 X464 + 1.148 X474 + 1.33 X484 + 3.504 X494
+ 4.026 X504 + 0.67 X514 + 0.817 X524 + 2.452 X534 + 1.096 X554
+ 0.765 X574 + 2.417 X584 + 2.122 X594 + 2.009 X664 + 2.887 X784
+ 0.904 X814 + 6.052 X824 + 0.113 X834 + 0.617 X844 + 6.33 X854
+ 9.504 X864 + 0.122 X904 + 0.174 X914 + 4.104 X66 + 0.112 X86
+ 0.488 X126 + 3.472 X136 + 0.016 X166 + 0.08 X176 + 0.008 X276
+ 0.016 X286 + 0.096 X296 + 0.12 X306 + 0.208 X316 + 0.256 X326
+ 0.96 X336 + 0.6639999 X346 + 0.056 X356 + 0.232 X406 + 0.432 X416
+ 0.912 X426 + 2.688 X436 + 4.504 X546 + 4.416 X566 + 1.768 X606
+ 1.768 X616 + 0.336 X676 + 3.832 X686 + 0.008 X726 + 0.008 X736
+ 0.6 X746 + 0.376 X756 + 0.648 X766 + 3.616 X776 + 0.656 X796
+ 1.944 X806 + 0.528 X896 + 0.008 X628 + 0.837 X638 + 1.382 X648
+ 5.593 X658 + 1.691 X698 + 3.577 X708 + 10.992 X718 <= 72

3. **If widget i is assigned to location j and investment k is required, then the decision to make the investment must be yes or 1.**

$X_{ij} \leq Y_{jk}$ for all i, j, k

103) - Y12 + X11 <= 0
104) - Y12 + X21 <= 0
105) - Y12 + X31 <= 0

106) - Y12 + X41 <= 0
107) - Y12 + X91 <= 0
108) - Y12 + X101 <= 0
109) - Y13 + X141 <= 0
110) - Y13 + X151 <= 0
111) - Y14 + X571 <= 0
112) - Y14 + X581 <= 0
113) - Y15 + X841 <= 0
114) - Y15 + X851 <= 0
115) - Y15 + X861 <= 0
116) - Y16 + X571 <= 0
117) - Y16 + X581 <= 0
118) - Y17 + X391 <= 0
119) - Y17 + X441 <= 0
120) - Y17 + X461 <= 0
121) - Y17 + X481 <= 0
122) - Y17 + X661 <= 0
123) - Y17 + X781 <= 0
124) - Y17 + X811 <= 0
125) - Y17 + X821 <= 0
126) - Y18 + X111 <= 0
127) - Y18 + X191 <= 0
128) - Y18 + X221 <= 0
129) - Y18 + X471 <= 0
130) - Y18 + X491 <= 0
131) - Y18 + X51 <= 0
132) - Y18 + X521 <= 0
133) - Y18 + X571 <= 0
134) - Y18 + X581 <= 0
135) - Y18 + X591 <= 0
136) - Y18 + X831 <= 0
137) - Y19 + X111 <= 0
138) - Y19 + X591 <= 0
139) - Y19 + X781 <= 0
140) - Y19 + X811 <= 0
141) - Y19 + X821 <= 0
142) - Y19 + X831 <= 0
143) - Y19 + X841 <= 0
144) - Y19 + X851 <= 0
145) - Y19 + X861 <= 0
146) - Y22 + X12 <= 0
147) - Y22 + X22 <= 0
148) - Y22 + X32 <= 0
149) - Y22 + X42 <= 0
150) - Y22 + X92 <= 0
151) - Y22 + X102 <= 0
152) - Y23 + X142 <= 0
153) - Y23 + X152 <= 0
154) - Y24 + X572 <= 0
155) - Y24 + X582 <= 0
156) - Y25 + X842 <= 0
157) - Y25 + X852 <= 0
158) - Y25 + X862 <= 0
159) - Y26 + X572 <= 0

160) - Y26 + X582 <= 0
161) - Y27 + X392 <= 0
162) - Y27 + X662 <= 0
163) - Y27 + X782 <= 0
164) - Y27 + X442 <= 0
165) - Y27 + X462 <= 0
166) - Y27 + X482 <= 0
167) - Y27 + X812 <= 0
168) - Y27 + X822 <= 0
169) - Y28 + X112 <= 0
170) - Y28 + X512 <= 0
171) - Y28 + X522 <= 0
172) - Y28 + X592 <= 0
173) - Y28 + X832 <= 0
174) - Y28 + X192 <= 0
175) - Y28 + X222 <= 0
176) - Y28 + X572 <= 0
177) - Y28 + X582 <= 0
178) - Y28 + X472 <= 0
179) - Y28 + X492 <= 0
180) - Y32 + X13 <= 0
181) - Y32 + X23 <= 0
182) - Y32 + X33 <= 0
183) - Y32 + X43 <= 0
184) - Y32 + X93 <= 0
185) - Y32 + X103 <= 0
186) - Y33 + X113 <= 0
187) - Y33 + X593 <= 0
188) - Y33 + X833 <= 0
189) - Y34 + X813 <= 0
190) - Y34 + X823 <= 0
191) - Y35 + X843 <= 0
192) - Y35 + X853 <= 0
193) - Y35 + X863 <= 0
194) - Y36 + X903 <= 0
195) - Y36 + X913 <= 0
196) - Y37 + X663 <= 0
197) - Y37 + X903 <= 0
198) - Y37 + X913 <= 0
199) - Y38 + X363 <= 0
200) - Y38 + X783 <= 0
201) - Y38 + X813 <= 0
202) - Y38 + X823 <= 0
203) - Y42 + X14 <= 0
204) - Y42 + X24 <= 0
205) - Y42 + X34 <= 0
206) - Y42 + X44 <= 0
207) - Y42 + X94 <= 0
208) - Y42 + X104 <= 0
209) - Y43 + X114 <= 0
210) - Y43 + X594 <= 0
211) - Y43 + X834 <= 0
212) - Y44 + X144 <= 0
213) - Y44 + X154 <= 0

```
214) - Y45 + X814 <=  0
215) - Y45 + X824 <=  0
216) - Y46 + X844 <=  0
217) - Y46 + X854 <=  0
218) - Y46 + X864 <=  0
219) - Y52 + X125 <=  0
220) - Y52 + X135 <=  0
221) - Y53 + X345 <=  0
222) - Y54 + X895 <=  0
223) - Y55 + X745 <=  0
224) - Y55 + X755 <=  0
225) - Y55 + X765 <=  0
226) - Y55 + X775 <=  0
227) - Y56 + X795 <=  0
228) - Y56 + X805 <=  0
229) - Y62 + X126 <=  0
230) - Y62 + X136 <=  0
231) - Y63 + X796 <=  0
232) - Y63 + X806 <=  0
233) - Y64 + X726 <=  0
234) - Y64 + X736 <=  0
235) - Y71 + X877 <=  0
236) - Y71 + X887 <=  0
237) - Y81 + X628 <=  0
238) - Y81 + X638 <=  0
239) - Y81 + X648 <=  0
240) - Y81 + X658 <=  0
241) - Y81 + X698 <=  0
242) - Y81 + X708 <=  0
243) - Y81 + X718 <=  0
```

4. All Y_{jk} variables must be integers.

```
INTE   37

END
```

The output generated by running the above formulation in Hyper LINDO is contained on the following pages.

```
LP OPTIMUM FOUND AT STEP   1275
OBJECTIVE VALUE =  464686.700
 FIX ALL VARS.(  18)  WITH RC >  88.4881
 SET     Y15 TO <=   0 AT   1, BND= -0.4648E+06 TWIN=-0.4649E+06  1387
 SET     Y32 TO >=   1 AT   2, BND= -0.4648E+06 TWIN=-0.4648E+06  1420
 SET     Y19 TO >=   1 AT   3, BND= -0.4648E+06 TWIN=-0.4650E+06  1561
 SET     Y27 TO <=   0 AT   4, BND= -0.4648E+06 TWIN=-0.4649E+06  1606
 SET     Y18 TO >=   1 AT   5, BND= -0.4648E+06 TWIN=-0.4649E+06  1703
 SET     Y28 TO <=   0 AT   6, BND= -0.4648E+06 TWIN=-0.4649E+06  1744

 NEW INTEGER SOLUTION OF    464845.900     AT BRANCH      13 PIVOT   1744
 BOUND ON OPTIMUM: 464775.2
 DELETE      Y28 AT LEVEL    6
 DELETE      Y18 AT LEVEL    5
 DELETE      Y27 AT LEVEL    4
 DELETE      Y19 AT LEVEL    3
 FLIP    Y32 TO <=         0 AT    2 WITH BND=   -464785.84
 SET     Y35 TO <=   0 AT   3, BND= -0.4649E+06 TWIN=-0.4650E+06  1952
 DELETE      Y35 AT LEVEL    3
 DELETE      Y32 AT LEVEL    2
 DELETE      Y15 AT LEVEL    1
 RELEASE FIXED VARIABLES
 ENUMERATION COMPLETE. BRANCHES=    14 PIVOTS=    2124

 LAST INTEGER SOLUTION IS THE BEST FOUND
 RE-INSTALLING BEST SOLUTION...
```

1. OBJECTIVE FUNCTION VALUE

1) 464845.90

2. VARIABLE	VALUE	REDUCED COST
Y12	.000000	75.000000
Y13	.000000	333.330000
Y14	.000000	2787.500000
Y15	.000000	908.330010
Y16	.000000	2783.798300
Y17	1.000000	83.330001
Y18	1.000000	83.330001
Y19	1.000000	154.170000
Y22	.000000	75.000000
Y23	.000000	321.694200
Y24	.000000	2662.500000
Y25	1.000000	644.699340
Y26	.000000	2547.398400
Y27	.000000	-387.446310
Y28	.000000	-181.499130
Y32	1.000000	166.395700
Y33	.000000	870.748800
Y34	.000000	388.311600

Y35	.000000	1220.176000
Y36	.000000	249.744700
Y37	.000000	198.555310
Y38	.000000	177.592720
Y42	.000000	166.670000
Y43	.000000	894.070900
Y44	.000000	1666.670000
Y45	.000000	416.670010
Y46	.000000	1250.000000
Y52	.000000	1666.670000
Y53	.000000	1666.670000
Y54	.000000	250.000000
Y55	.000000	1666.670000
Y56	.000000	416.670010
Y62	1.000000	1613.630000
Y63	1.000000	386.964230
Y64	.000000	58.086502
Y71	1.000000	1250.000000
Y81	1.000000	633.330010
X11	.000000	28.077640
X21	.000000	65.811160
X31	.000000	8.257950
X41	.000000	19.187744
X51	.000000	19.003330
X71	.000000	6.802887
X91	.000000	2.292625
X101	.000000	21.312470
X111	1.000000	.000000
X141	.000000	6.668289
X151	.000000	24.908450
X181	.000000	.087259
X191	.000000	.978635
X201	.000000	1.184950
X211	.000000	1.282179
X221	.000000	2.409042
X231	.000000	2.128529
X241	.000000	2.128529
X251	.000000	7.986130
X261	.000000	12.940902
X361	.000000	45.112920
X371	.000000	1.814924
X381	.000000	70.332460
X391	.000000	7.117065
X441	.000000	1.257669
X451	.000000	8.520714
X461	.000000	12.420030
X471	.000000	24.380830
X481	.000000	25.181950
X491	.000000	74.411870
X501	.000000	99.135253
X511	.000000	15.724533
X521	.000000	19.027252
X531	.000000	40.561462
X551	.000000	18.177280

X571	.000000	.000000
X581	.000000	.000000
X591	1.000000	.000000
X661	.000000	19.128662
X781	.864192	.000000
X811	1.000000	.000000
X821	1.000000	.000000
X831	1.000000	.000000
X841	.000000	7.988068
X851	.000000	50.919680
X861	.000000	441.200700
X901	.000000	2.090900
X911	.000000	3.078674
X12	.000000	.000000
X22	.000000	.468384
X32	.000000	.191452
X42	.000000	.099060
X52	.195559	.000000
X72	1.000000	.000000
X92	.000000	.068848
X102	.000000	.000000
X112	.000000	.000000
X142	.000000	.000000
X152	.000000	.000000
X182	.000000	.049633
X192	.000000	.066064
X202	.000000	.064241
X212	.000000	.103857
X222	.000000	.813484
X232	1.000000	.000000
X242	1.000000	.000000
X252	.000000	.042496
X262	.000000	.190247
X362	.114669	.000000
X372	.000000	.694216
X382	.000000	23.528870
X392	.000000	.769012
X442	.000000	.174589
X452	.000000	2.753319
X462	.000000	1.760284
X472	.000000	5.329559
X482	.000000	3.366791
X492	.000000	16.585693
X502	.000000	33.157104
X512	.000000	4.617004
X522	.000000	5.705841
X532	.000000	.207153
X552	.000000	.134064
X572	.000000	.000000
X582	.000000	.000000
X592	.000000	.000000
X662	.000000	.000000
X782	.000000	.000000
X812	.000000	.000000

X822	.000000	.000000
X832	.000000	.000000
X842	1.000000	.000000
X852	1.000000	.000000
X862	1.000000	.000000
X902	1.000000	.000000
X912	1.000000	.000000
X13	1.000000	.000000
X23	1.000000	.000000
X33	1.000000	.000000
X43	1.000000	.000000
X53	.804441	.000000
X73	.000000	.011719
X93	1.000000	.000000
X103	1.000000	.000000
X113	.000000	.000000
X143	1.000000	.000000
X153	1.000000	.000000
X183	1.000000	.000000
X193	1.000000	.000000
X203	1.000000	.000000
X213	1.000000	.000000
X223	1.000000	.000000
X233	.000000	.020416
X243	.000000	.020416
X253	1.000000	.000000
X263	1.000000	.000000
X363	.000000	.000000
X373	1.000000	.000000
X383	1.000000	.000000
X393	1.000000	.000000
X443	1.000000	.000000
X453	1.000000	.000000
X463	1.000000	.000000
X473	1.000000	.000000
X483	1.000000	.000000
X493	1.000000	.000000
X503	1.000000	.000000
X513	1.000000	.000000
X523	1.000000	.000000
X533	1.000000	.000000
X553	1.000000	.000000
X593	.000000	.000000
X663	.000000	.000000
X783	.000000	.000000
X813	.000000	.000000
X823	.000000	.000000
X833	.000000	.000000
X843	.000000	.000000
X853	.000000	.000000
X863	.000000	320.125000
X903	.000000	.000000
X913	.000000	.000000
X14	.000000	7.991852

X24	.000000	18.799133
X34	.000000	2.299736
X44	.000000	5.581329
X54	.000000	5.355560
X74	.000000	1.904114
X94	.000000	.737644
X104	.000000	5.916199
X114	.000000	.000000
X144	.000000	2.621262
X154	.000000	9.877655
X184	.000000	.113031
X194	.000000	.217337
X204	.000000	.312922
X214	.000000	.415939
X224	.000000	.528971
X234	.000000	.531971
X244	.000000	.531971
X254	.000000	2.195305
X264	.000000	3.670471
X364	.885331	.000000
X374	.000000	.312922
X384	.000000	13.446110
X394	.000000	1.901115
X444	.000000	.434673
X454	.000000	1.570747
X464	.000000	3.037201
X474	.000000	5.468811
X484	.000000	6.188965
X494	.000000	16.482300
X504	.000000	19.008730
X514	.000000	3.263260
X524	.000000	3.766052
X534	.000000	11.543460
X554	.000000	5.259949
X574	1.000000	.000000
X584	1.000000	.000000
X594	.000000	.000000
X664	1.000000	.000000
X784	.135808	.000000
X814	.000000	.052841
X824	.000000	.215210
X834	.000000	.000000
X844	.000000	2.819855
X854	.000000	.000000
X864	.000000	364.981930
X904	.000000	.423347
X914	.000000	.586578
X65	.000000	62.689453
X85	.000000	1.714539
X125	.000000	7.456787
X135	.000000	.000000
X165	.000000	.243504
X175	.000000	1.227539
X275	.000000	.121752

X285	.000000	.243504
X295	.000000	1.471039
X305	.000000	1.836273
X315	.000000	3.175537
X325	.000000	3.916016
X335	.000000	14.660160
X345	.000000	10.145510
X355	.000000	.852264
X405	.000000	3.540771
X415	.000000	6.604614
X425	.000000	13.929690
X435	.000000	41.058593
X545	.000000	68.805664
X565	.000000	67.457031
X605	.000000	27.007324
X615	.000000	27.007324
X675	.000000	5.133667
X685	.000000	58.540040
X725	1.000000	.000000
X735	1.000000	.000000
X745	.000000	9.171387
X755	.000000	5.742188
X765	.000000	9.901978
X775	.000000	55.242190
X795	.000000	10.023440
X805	.000000	.000000
X895	.000000	8.065674
X66	1.000000	.000000
X86	1.000000	.000000
X126	1.000000	.000000
X136	1.000000	.000000
X166	1.000000	.000000
X176	1.000000	.000000
X276	1.000000	.000000
X286	1.000000	.000000
X296	1.000000	.000000
X306	1.000000	.000000
X316	1.000000	.000000
X326	1.000000	.000000
X336	1.000000	.000000
X346	1.000000	.000000
X356	1.000000	.000000
X406	1.000000	.000000
X416	1.000000	.000000
X426	1.000000	.000000
X436	1.000000	.000000
X546	1.000000	.000000
X566	1.000000	.000000
X606	1.000000	.000000
X616	1.000000	.000000
X676	1.000000	.000000
X686	1.000000	.000000
X726	.000000	.000000
X736	.000000	.000000

X746	1.000000	.000000
X756	1.000000	.000000
X766	1.000000	.000000
X776	1.000000	.000000
X796	1.000000	.000000
X806	1.000000	.000000
X896	1.000000	.000000
X877	1.000000	.000000
X887	1.000000	.000000
X628	1.000000	.000000
X638	1.000000	.000000
X648	1.000000	.000000
X658	1.000000	.000000
X698	1.000000	.000000
X708	1.000000	.000000
X718	1.000000	.000000

3.

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	-6263.497000
3)	.000000	-14678.820000
4)	.000000	-1862.960000
5)	.000000	-4271.950100
6)	.000000	-4207.710000
7)	.000000	-14326.930000
8)	.000000	-1477.508300
9)	.000000	-390.985500
10)	.000000	-546.040000
11)	.000000	-4818.158200
12)	.000000	-9010.646000
13)	.000000	-1596.233100
14)	.000000	-11409.840000
15)	.000000	-1924.650000
16)	.000000	-7106.390100
17)	.000000	-54.076500
18)	.000000	-270.372500
19)	.000000	-32.120000
20)	.000000	-125.480000
21)	.000000	-289.080000
22)	.000000	-321.200010
23)	.000000	-345.070000
24)	.000000	-481.779600
25)	.000000	-481.779600
26)	.000000	-1766.600000
27)	.000000	-2858.680000
28)	.000000	-24.578250
29)	.000000	-54.076500
30)	.000000	-329.129000
31)	.000000	-411.413720
32)	.000000	-713.124500
33)	.000000	-893.684000
34)	.000000	-3351.330000
35)	.000000	-2192.675000
36)	.000000	-181.147730

37)	.000000	-9544.806000
38)	.000000	-280.350000
39)	.000000	-10217.180000
40)	.000000	-1316.480000
41)	.000000	-776.559200
42)	.000000	-1445.995300
43)	.000000	-3011.620300
44)	.000000	-8876.361300
45)	.000000	-239.360000
46)	.000000	-1214.850000
47)	.000000	-2244.000000
48)	.000000	-4019.390000
49)	.000000	-4577.750000
50)	.000000	-12271.330000
51)	.000000	-14422.430000
52)	.000000	-2415.490000
53)	.000000	-2948.780000
54)	.000000	-9057.830000
55)	.000000	-15723.314000
56)	.000000	-4047.110100
57)	.000000	-15416.113000
58)	.000000	-2350.517300
59)	.000000	-7425.586000
60)	.000000	-7115.301000
61)	.000000	-6172.033000
62)	.000000	-6172.033000
63)	.000000	-25.818250
64)	.000000	-2591.212000
65)	.000000	-4394.177200
66)	.000000	-17783.490000
67)	.000000	-6496.035100
68)	.000000	-1083.926300
69)	.000000	-12361.900000
70)	.000000	-5232.905000
71)	.000000	-11373.181000
72)	.000000	-34946.894000
73)	.000000	-27.380000
74)	.000000	-27.380000
75)	.000000	-1814.079000
76)	.000000	-1181.948000
77)	.000000	-2013.478000
78)	.000000	-11366.780000
79)	.000000	-9226.643000
80)	.000000	-2062.116400
81)	.000000	-6140.600000
82)	.000000	-2890.139100
83)	.000000	-19342.320000
84)	.000000	-379.224800
85)	.000000	-2156.270000
86)	.000000	-22139.144000
87)	.000000	-32874.230000
88)	.000000	-3324.150000
89)	.000000	-17960.580000
90)	.000000	-1703.314300

91)	.000000	-407.469940
92)	.000000	-582.055300
93)	.341207	.000000
94)	134.034000	.000000
95)	23.990000	.000000
96)	92.580993	.000000
97)	13.713000	.000000
98)	22.705000	.000000
99)	.000000	379.608330
100)	.000000	362.453900
101)	3.291640	.000000
102)	.000000	234.781030
103)	.000000	.000000
104)	.000000	.000000
105)	.000000	.000000
106)	.000000	.000000
107)	.000000	.000000
108)	.000000	.000000
109)	.000000	.000000
110)	.000000	.000000
111)	.000000	.000000
112)	.000000	.000000
113)	.000000	.000000
114)	.000000	.000000
115)	.000000	.000000
116)	.000000	.815107
117)	.000000	2.886434
118)	1.000000	.000000
119)	1.000000	.000000
120)	1.000000	.000000
121)	1.000000	.000000
122)	1.000000	.000000
123)	.135808	.000000
124)	.000000	.000000
125)	.000000	.000000
126)	.000000	.000000
127)	1.000000	.000000
128)	1.000000	.000000
129)	1.000000	.000000
130)	1.000000	.000000
131)	1.000000	.000000
132)	1.000000	.000000
133)	1.000000	.000000
134)	1.000000	.000000
135)	.000000	.000000
136)	.000000	.000000
137)	.000000	.000000
138)	.000000	.000000
139)	.135808	.000000
140)	.000000	.000000
141)	.000000	.000000
142)	.000000	.000000
143)	1.000000	.000000
144)	1.000000	.000000

145)	1.000000	.000000
146)	.000000	.000000
147)	.000000	.000000
148)	.000000	.000000
149)	.000000	.000000
150)	.000000	.000000
151)	.000000	.000000
152)	.000000	2.443632
153)	.000000	9.192181
154)	.000000	.000000
155)	.000000	.000000
156)	.000000	20.677631
157)	.000000	242.953040
158)	.000000	.000000
159)	.000000	.000000
160)	.000000	115.101700
161)	.000000	.000000
162)	.000000	13.831500
163)	.000000	134.024000
164)	.000000	.000000
165)	.000000	.000000
166)	.000000	.000000
167)	.000000	41.979700
168)	.000000	280.941130
169)	.000000	124.736400
170)	.000000	.000000
171)	.000000	.000000
172)	.000000	98.500880
173)	.000000	5.253895
174)	.000000	.000000
175)	.000000	.000000
176)	.000000	36.337990
177)	.000000	.000000
178)	.000000	.000000
179)	.000000	.000000
180)	.000000	.106417
181)	.000000	.000000
182)	.000000	.000000
183)	.000000	.000000
184)	.000000	.000000
185)	.000000	.167876
186)	.000000	24.945410
187)	.000000	19.791000
188)	.000000	1.184742
189)	.000000	.000000
190)	.000000	28.358440
191)	.000000	.000000
192)	.000000	29.824102
193)	.000000	.000000
194)	.000000	.000000
195)	.000000	.255295
196)	.000000	9.564767
197)	.000000	.209921
198)	.000000	.000000

199)	.000000	12.925631
200)	.000000	13.662483
201)	.000000	4.149161
202)	.000000	.000000
203)	.000000	.000000
204)	.000000	.000000
205)	.000000	.000000
206)	.000000	.000000
207)	.000000	.000000
208)	.000000	.000000
209)	.000000	12.229380
210)	.000000	9.705272
211)	.000000	.664495
212)	.000000	.000000
213)	.000000	.000000
214)	.000000	.000000
215)	.000000	.000000
216)	.000000	.000000
217)	.000000	.000000
218)	.000000	.000000
219)	.000000	.000000
220)	.000000	.000000
221)	.000000	.000000
222)	.000000	.000000
223)	.000000	.000000
224)	.000000	.000000
225)	.000000	.000000
226)	.000000	.000000
227)	.000000	.000000
228)	.000000	.000000
229)	.000000	.000000
230)	.000000	53.040462
231)	.000000	.000000
232)	.000000	29.705780
233)	.000000	.121752
234)	.000000	.121752
235)	.000000	.000000
236)	.000000	.000000
237)	.000000	.000000
238)	.000000	.000000
239)	.000000	.000000
240)	.000000	.000000
241)	.000000	.000000
242)	.000000	.000000
243)	.000000	.000000

NO. ITERATIONS= 2212
BRANCHES= 14 DETERM.= 1.000E 0

The following analysis of the Hyper LINDO output indicates where each widget model has been allocated. The percentage figures correspond to the percent of the widget's volume that has been allocated to the location. Note that even with the X_{ij} variables being continuous that only three widgets were allocated to multiple locations.

Widget #	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
1			100.00%					
2			100.00%					
3			100.00%					
4			100.00%					
5		19.60%	80.40%					
6						100.00%		
7		100.00%						
8						100.00%		
9			100.00%					
10			100.00%					
11	100.00%							
12						100.00%		
13						100.00%		
14			100.00%					
15			100.00%					
16						100.00%		
17						100.00%		
18			100.00%					
19			100.00%					
20			100.00%					
21			100.00%					
22			100.00%					
23		100.00%						
24		100.00%						
25			100.00%					
26			100.00%					
27						100.00%		
28						100.00%		
29						100.00%		
30						100.00%		
31						100.00%		
32						100.00%		
33						100.00%		
34						100.00%		
35						100.00%		
36		11.50%		88.50%				
37			100.00%					
38			100.00%					
39			100.00%					
40						100.00%		

Widget #	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
41						100.00%		
42						100.00%		
43						100.00%		
44			100.00%					
45			100.00%					
46			100.00%					
47			100.00%					
48			100.00%					
49			100.00%					
50			100.00%					
51			100.00%					
52			100.00%					
53			100.00%					
54						100.00%		
55			100.00%					
56						100.00%		
57				100.00%				
58				100.00%				
59	100.00%							
60						100.00%		
61						100.00%		
62								100.00%
63								100.00%
64								100.00%
65								100.00%
66				100.00%				
67						100.00%		
68						100.00%		
69								100.00%
70								100.00%
71								100.00%
72					100.00%			
73					100.00%			
74						100.00%		
75						100.00%		
76						100.00%		
77						100.00%		
78	86.40%			13.60%				
79						100.00%		
80						100.00%		
81	100.00%							
82	100.00%							
83	100.00%							
84		100.00%						
85		100.00%						

Widget #	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
86		100.00%						
87							100.00%	
88							100.00%	
89						100.00%		
90		100.00%						
91		100.00%						

Appendix C: Information to be Supplied in Stage 1 of the GMFDP

Part of the GMFDP process would be to specify the type of information each player would have to obtain and analyze in stage 1. Although this information was mentioned briefly in Section 6.1.1, a more detailed list of the type of information each player would be responsible to gather is discussed below. The purpose of the list is to spur the players to determine all the possible interactions that exist and how the information in stage 1 might be obtained. The foundation of the list is the analysis and information documented in Chapters 2 and 4 of this thesis.

1. Information each manufacturing area should be documenting:

Equipment Capabilities
- Area's equipment capabilities in primary assembly, pre-joining, joining, final assembly and final test.
- The different widget sizes and subassembly configurations each piece of equipment can process.
- Possible future equipment capabilities with minimum investment.
- Average runtime and downtime for each piece of equipment in an area.

Area Capacity
- Area's rated capacity. Daily production per hour worked over a 50 day period.
- Area's capacity for a particular widget sizes.
- How an area's capacity changes as the model mix changes.
- Comparison of actual production to rated capacity.
- The capacity of each piece of production equipment and how it changes with model mix.

Throughput Analysis and Process Flows
- How an area's throughput rate changes as the model mix changes.
- How different subassembly configurations affect the production rate.
- Documentation of the different process flows a widget model can take.
- How throughput is affected by people.
- How much downtime for changeovers.

Investment Estimates
- The effect of adding a new widget model to existing production equipment. The investment to add the capabilities.
- How investment is related to proliferation.
- How investment is related to capacity.
- Analysis of which production equipment requires continual investment and why.

2. Information Finance will be responsible for:

Cost Drivers
- Identification of what drives widget unit costs in each area.
- Identification of what percentage of the cost is due to fixed costs, material, labor, etc.
- How are overhead costs allocated? Is it effective?
- Is the way MJC calculates burden accurate?

Relevant Costs
- Identification of the costs that really matter when allocating a product.
- What costs can be compared from area to area?
- Can costs between widgets within an area be compared?
- How should MJC compare costs between manufacturing areas?

Effects of Volume on Costs
- How does units costs change for different volume levels within an area?
- How does unit costs change for different product mixes in an area?

Development of a cost model
- Can a unit cost model for each area be built incorporating the answers to the questions above?

3. Information Product Engineering will be responsible for:

New and Altered Widget Models
- Which widget models will have design changes? When will the design changes be required?
- What are the subassembly configurations for future years? Obtain prints for manufacturing engineering.

Production Volumes
- What is the anticipated production volume for future years?
- What is the anticipated product mix for future years?
- What anticipated volume changes are in the pipeline?

The answers to these questions will provide information for the database developed in stage 2 of the GMFDP. Implementation of the process hinges on each player being able to answer the questions above and documenting the answers in a centralized database. Educating the players about this requirement is very important.