Operations Improvement in a Semiconductor Capital Equipment Manufacturing Plant: Resource Optimization, Labor Flexibility, and Inventory Management

by

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Abstract

A semiconductor capital equipment manufacturing plant is a high-mix low-volume manufacturing environment where the complex products produced requires skilled manual assembly and expensive raw materials. The semiconductor capital equipment industry is sporadic with high demand variability and hence, semiconductor capital equipment manufacturers must be able to allocate resources to meet demand at minimum cost to maintain their manufacturing competitiveness.

This thesis draws heavily on the research done at Varian Semiconductor Equipment, a manufacturer of ion implantation machines for the semiconductor industry, over a period of seven months as part of the Master of Engineering in Manufacturing program at the Massachusetts Institute of Technology and aims to enable Varian to make optimal resource allocation, capacity planning and personnel decisions that will allow it to meet demand at minimum cost. The goal of this thesis is achieved through the development of three optimization models, a labor flexibility framework, and an inventory management policy. The first optimization model, resource optimization for cost minimization, will allow Varian to determine the optimal combination of workers and assembly bays for each production process that will allow it to meet demand at minimum cost. The second optimization model, labor cost minimization, will enable Varian to determine the optimal combination of regular time and overtime that will allow it to meet demand at minimum labor cost. The final model, labor flexibility, will allow Varian to determine the optimal movement of workers that will allow the Varian's plant to meet demand with the minimum total cost of work hours to be provided. The final model is based on a labor flexibility framework introduced in this thesis. We also present an inventory management policy to manage certain assemblies produced at Varian's supermarket build area that will allow Varian to reduce those assemblies' safety stock levels by 30%.

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Chapter 1

Introduction

1.1 Motivation

Ion implantation machines, which are critical semiconductor capital equipment used in the semiconductor industry, are produced in a high-mix low-volume manufacturing environment at Varian Semiconductor Equipment[1]. Given the high degree of customization required for ion implantation machines, the production processes at Varian are highly complex and are performed solely using skilled manual assembly. Therefore, Varian's manufacturing competiveness is dependent, in part, on the availability of a skilled workforce and Varian's effective usage of this workforce. The semiconductor capital equipment industry is also highly sporadic with high demand variability and hence, Varian's manufacturing competitiveness is also dependent, in part, on its ability to allocate resources meet demand at a competitive cost.

In this thesis, we develop three optimization models to aid Varian in making optimal resource allocation, capacity planning and personnel decisions that will allow Varian to maintain and improve its manufacturing competitiveness in the semiconductor capital equipment industry.

The first model is a resource optimization for cost minimization model subject to a production capacity constraint. In other words, we want to tell Varian how it can achieve the required throughput target (which is related to demand) at the minimum cost of workers and assembly bays for each process. An assembly bay is a location on the production floor where a production process is performed and represents the work-in-process inventory of that process. In

[1] Varian Semiconductor Equipment is a business unit of Applied Materials Inc. and is henceforth referred to as Varian.

this model, the decision variables are the number of assembly bays and the number of workers at each assembly bay for each production process.

The second model is a labor cost minimization model subject to an effective work hours constraint. In other words, we want to tell Varian how it can achieve the number of required effective work hours (which are related to demand) at the minimum cost of regular time and overtime for each process. Regular time is the number of hours of work paid at the regular hourly rate and overtime is the number of number of hours of work paid one and overtime is number of hours paid at one and a half times the regular hourly rate. In this model, the decision variables are the number of regular time hours and the number of overtime hours for each production process.

The third model is a labor flexibility model subject to a required effective work hours constraint. That is, we want to tell Varian how it can achieve the number of required effective work hours (which are related to demand) with minimum total cost of work hours to be provided to the production plant. We present a labor flexibility framework for use with this model and the numbers of work hours to be provided at each skill level are the decision variables.

In this thesis, we also present an inventory management policy for certain high-volume assemblies assembled at Varian that are placed on gold squares. Gold squares are shelf locations on the production floor that are sized to hold a specific number of assemblies and work on a signal-based replenishment system. The proposed policy reduces those assemblies' safety stock levels by 30% and aims to improve their service levels.

This thesis is based on seven months of research carried out at Varian's production plant in Gloucester, Massachusetts by a team of three students as part of the Master of Engineering in the Manufacturing program [2] at the Massachusetts Institute of Technology, Cambridge, Massachusetts. The team consisted of Venkataraman Ramachandran [1], Yiming Wu [2] and the author of this thesis, Lohithaksha Chengappa. The gold square inventory management policy that is presented in this thesis is a result of the collaborative work done by the team. In addition to the work done on the gold square inventory management policy, this thesis develops and presents

[2] The Master of Engineering in Manufacturing degree is master's degree run by the Department of Mechanical Engineering at the Massachusetts Institute of Technology that prepares students for leadership in manufacturing.

three optimization models to enable Varian to make optimal resource allocation, capacity planning, and personnel decisions, Ramachandran [1] explores and presents recommendations on the issues of capacity management and inventory policies, and Wu [2] explores and presents recommendations on the issue of assembly level and component level inventory management.

The rest of this chapter is organized as follows. An overview of the semiconductor capital equipment industry, a brief overview of Varian and an outline of Varian's product range is presented in Section 1.2. The goals and contributions of this thesis are summarized in Section 1.3 and the structure of the thesis is outlined in Section 1.4.

1.2 Overview of the Industry and Varian

In this section, we present an overview of the semiconductor capital equipment industry, an overview of Varian and an outline of Varian's product offerings.

1.2.1 Overview of the Semiconductor Capital Equipment Industry

Semiconductor fabrication refers to the process of creating integrated circuits (ICs) comprising billions of miniature electronic devices on a wafer. The wafer fabrication process consists of hundreds of processing steps, the most important steps of which are lithography, etching, deposition, chemical mechanical planarization, oxidation, ion implantation, and diffusion [3]. In addition, there are also important steps associated with die preparation, IC packaging and IC testing [4]. Owing to the large number of process steps in semiconductor fabrication, there are about 18 different kinds of major equipment for semiconductor fabrication [5].

Semiconductor capital equipment manufacturers, such as Applied Materials Inc., supply semiconductor capital equipment to semiconductor fabrication plants (also referred to as fabs), where integrated circuits are manufactured. Fabs order new semiconductor equipment to either increase their capacity, upgrade to different wafer sizes or transfer to a new technology [5]. Semiconductor manufacturers develop their own proprietary technique to fabricate chips and therefore, require customization for their fabrication tool. The semiconductor manufacturing industry is dominated by several large companies, which have strong bargaining power over upstream suppliers — semiconductor equipment manufacturers — on issues like price, customization of tools and flexibility of delivery dates. The necessity to comply with customers' demands in terms of tool customization, engineering change orders, and delivery date changes is a major challenge for the manufacturing operations of semiconductor equipment manufacturers. This need for highly customized equipment leads to a high-mix low-volume manufacturing environment where automation is nearly impossible and majority of the assembly has to be done manually using skilled labor.

1.2.2 Overview of Varian

Varian designs and manufactures ion implantation equipment which is used in semiconductor chip fabrication. Ion implantation is a critical process of semiconductor fabrication, in which the generated ions are accelerated by an electrical field and bombarded into a solid substrate to change its physical, chemical or electrical properties [6]. In 1948, Varian Semiconductor Equipment was founded as Varian Associates.

In 1999, it spun off from Varian Associates and operated as the publically-traded Varian Semiconductor Equipment Associates till it was acquired by Applied Materials in November 2011. At the time of its acquisition, Varian Semiconductor Equipment Associates was the world's leading ion implantation equipment supplier, with highest market share in the high current, medium current, high energy and plasma doping (PLAD) segments. As the global market leader in the design and manufacture of ion implantation equipment, Varian's major customers include leading semiconductor chip manufacturers from across the world.

Globally, the semiconductor capital equipment industry witnessed high growth after the economic slowdown of 2008 and 2009. The industry's worldwide revenues grew from $15.92 billion in 2009 to $39.93 billion in 2010, and continued its growth by 7% from 2010 to 2011 reaching $43.53 billion. In this period, the global wafer processing equipment market segment increased 15% [7]. Varian expects this growth in the semiconductor capital equipment industry to continue.

1.2.3 Varian's Product Range

Varian is a high-mix low-volume manufacturer and this section serves to illustrate the different products that are produced by Varian. Varian offers Ion Implantation machines in four categories as follows:

1. High current (HC) technology,
2. Medium current (MC) technology,
3. High energy (HE) technology, and
4. Plasma Doping (PLAD) technology.

The current determines the ion concentration on the wafer surface and the energy controls to the depth of penetration of ions into the wafer. PLAD technology machines use plasma doping for ultra-high dose applications. The ion implantation machines are also supplied with capabilities of processing 200 mm or 300 mm diameter wafers.

Varian's product range as summarized by Chen [8] is detailed in Table 1-1. Within these broad product categories, each customer typically chooses options[3] and selects[4] to customize each ion implantation machine.

This variety in products offered by Varian as illustrated in Table 1-1 along with the nature of the semiconductor industry as described earlier leads to the significant complexity of Varian's production floor and leads to difficulty in aligning resources to meet demand at a competitive cost.

[3] Options are additional features which the customer can opt to have installed on a machine.
[4] Selects refer to assemblies that must be mandatorily selected by the customer from a host of possible assemblies.

Table 1-1: Varian's Product Range

High Current (HC)	**Medium Current (MC)**	**High Energy (HE)**	**Ultra High Dose (PLAD)**
VIISTA HCP 200 mm	VIISTA 810XP 200 mm	VIISTA 3000 XP 200 mm	VIISTA PLAD 200 mm
VIISTA HCP 300 mm	VIISTA 810XP 300 mm	VIISTA 3000 XP 300 mm	VIISTA PLAD 300 mm
VIISTA HCPv2.0	VIISTA 900XP 200 mm		
VIISTA HCS 300 mm	VIISTA 900XP 300 mm		

1.3 Thesis Goals and Contributions

The goals of this thesis is to provide valuable insight about optimal resource allocation, capacity planning and personnel decisions to Varian's manufacturing management team that will aid them in making informed decisions that will help Varian maintain and improve its manufacturing competiveness.

In this thesis, the goal of providing valuable insights to Varian's manufacturing team is achieved by investigating four major topics. They are:

1. Resource optimization for cost minimization subject to a production capacity constraint,
2. Labor cost minimization subject to an effective work hours constraint,
3. Labor flexibility subject to a required effective work hours constraint, and

4. Gold square inventory management.

In particular, we consider Topic 1 to be the primary focus from the perspective of model development. This is because the results and parameters used in the development of the resource optimization model are extended to Topics 2 and 3. However, Topics 2 and 3 also have unique attributes that are not covered in Topic 1. Topic 1 will be used to provide insights with respect to resource allocation and capacity planning while Topics 2 and 3 will be used to provide insights with respect to personnel decisions.

Topic 3 is especially useful to Varian as the labor flexibility framework developed as part of that topic will allow Varian to address the critical question of labor flexibility[5] that Varian considers to be a pressing issue. Topic 4 will allow Varian to reduce assembly shortages that occur on its production line and will reduce the safety stock levels of certain assemblies.

The contributions of this thesis include the development of the three optimization models, the labor flexibility framework and the architecture for the software program to enable Varian to utilize the developed optimization models in addition to the team's development of the Gold Square inventory management policy.

1.4 Structure of Thesis

The remaining of this thesis is organized as follows

- An outline of Varian's production operations including its production floor layout, material and information flow, and inventory management techniques. (Chapter 2)
- A description of the preliminary analysis conducted and the hypothesis-driven approach adopted to identify, understand and formulate solutions for the problems facing Varian. (Chapter 3)
- A summary of the literature review undertaken. (Chapter 4)

[5] Flexibility, in this thesis, is defined as the ability of the workforce to move across processes in the production plant.

- A resource optimization for cost minimization model subject to a production capacity constraint is developed. (Chapter 5)

- A labor cost minimization model subject to a required effective work hours constraint is developed. (Chapter 6)

- A labor flexibility model subject to a required effective work hours constraint is developed and a labor flexibility framework is presented. (Chapter 7)

- An inventory management policy is presented to reduce safety stock and improve service levels for the gold square assemblies. (Chapter 8)

- Summary and insights derived from the thesis's contributions are outlined. (Chapter 9)

- Conclusions and direction for future work are described. (Chapter 10)

Chapter 2

Description of Operations

In this chapter[6], we provide a description of Varian's product production process, material and information flow, inventory management techniques and labor management systems. The description of operations provided in this chapter forms the basis for the three optimization models developed in Chapters 5, 6 and 7, the labor flexibility framework presented in Chapter 7 and the gold square inventory management policy presented in Chapter 10.

This chapter is organized as follows. An overview of Varian's product production process including an outline of the production planning process at Varian, and a description of the material and information flow within the production plant is provided in Section 2.1. The inventory and labor management policies used at Varian are summarized in Section 2.2 and Section 2.3 respectively.

2.1 Varian's Product Production Process

The Varian's production plant is dedicated to the production of ion implantation machines. In this production plant, components purchased from domestic and international suppliers are assembled to produce modules which are tested and shipped individually to the customer for integration at the customer's site.

The production of the various modules drives the production floor of Varian. Each product needs a specific set of modules and each module requires a specific set of processes. The

[6] This chapter was written in collaboration with Ramachandran [1] and Wu [2] and a similar chapter can be found in their respective theses.

different modules and production processes required for the production of a High Current (HC) machine is illustrated in Figure 2-1.

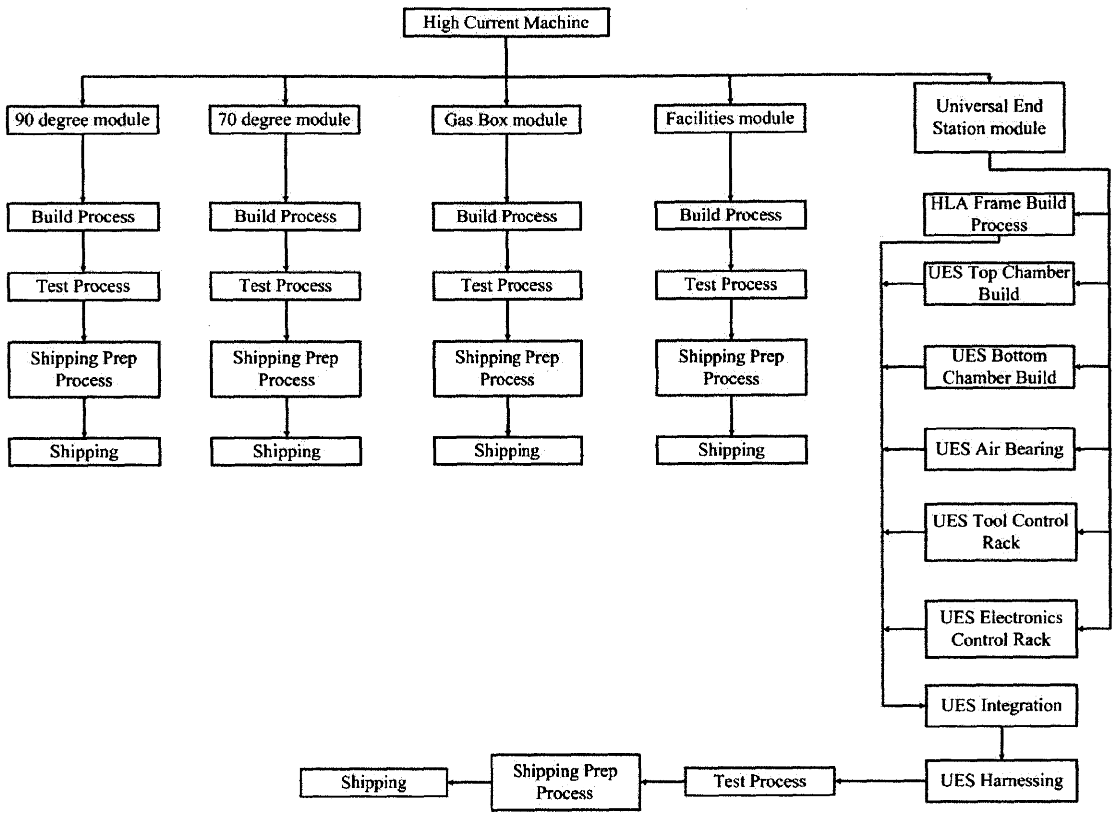


Figure 2-1: Production of High Current (HC) Machine at Varian

As illustrated in Figure 2-1, each product is broken down into a number of modules and each module is produced using a number of processes. Each process represented in Figure 2-1 can be performed at a number of assembly bays by a number of workers at each assembly bay. The capacity of each individual process is defined by the number of assembly bays and number of workers present at each assembly bay for that process. This relation between resource allocation and process capacity is explored further in Chapters 5, 6 and 7.

2.1.1 Production Planning

Varian's sales team works with existing and potential customers to develop six-month sales forecasts. Build plans, which allocate machines to build bays and assign build dates, are developed based on these forecasts. The configurations for the forecasted builds are based on previous purchases by a customer or based on the sales team's predictions. However, exact machine requirements are known only when a customer places a machine order (also called a tool order) which contains information such as the date of delivery, required configuration and price. If the forecasted demand for a machine does not materialize, the machine is removed from the build schedule.

It is common practice at Varian for all the modules of a machine to be started on the same date known as a lay-down[7] date. The manufacturing lead time[8] for each type of machine is known based on the prior experience of Varian's manufacturing team. The laydown date is determined by working backward from the target shipping date with a time-cushion built into the schedule to cover for inventory shortages and quality troubleshooting. The schedule for a six-month horizon is loaded into the Materials Requirement Planning (MRP) System and is continually revised. The parts required to build each machine are driven by Varian's MRP System. Based on the Master Production Schedule and the build lead times, the system calculates the required quantity for each component. By comparing the required quantity with the quantity on-hand, purchase orders are issued at the required date based on the delivery lead time.

2.1.2 Material and Information Flow

Varian's production floor is organized as distinct areas as illustrated in Figure 2-2. As can be seen from Figure 2-2, the production floor is divided into production build areas as well as inventory management areas. The different modules as mentioned earlier are built in their respective module build areas.

[7] Lay-down, at Varian, is defined as act of starting the build processes for a module.
[8] This is commonly referred to as cycle time at Varian.

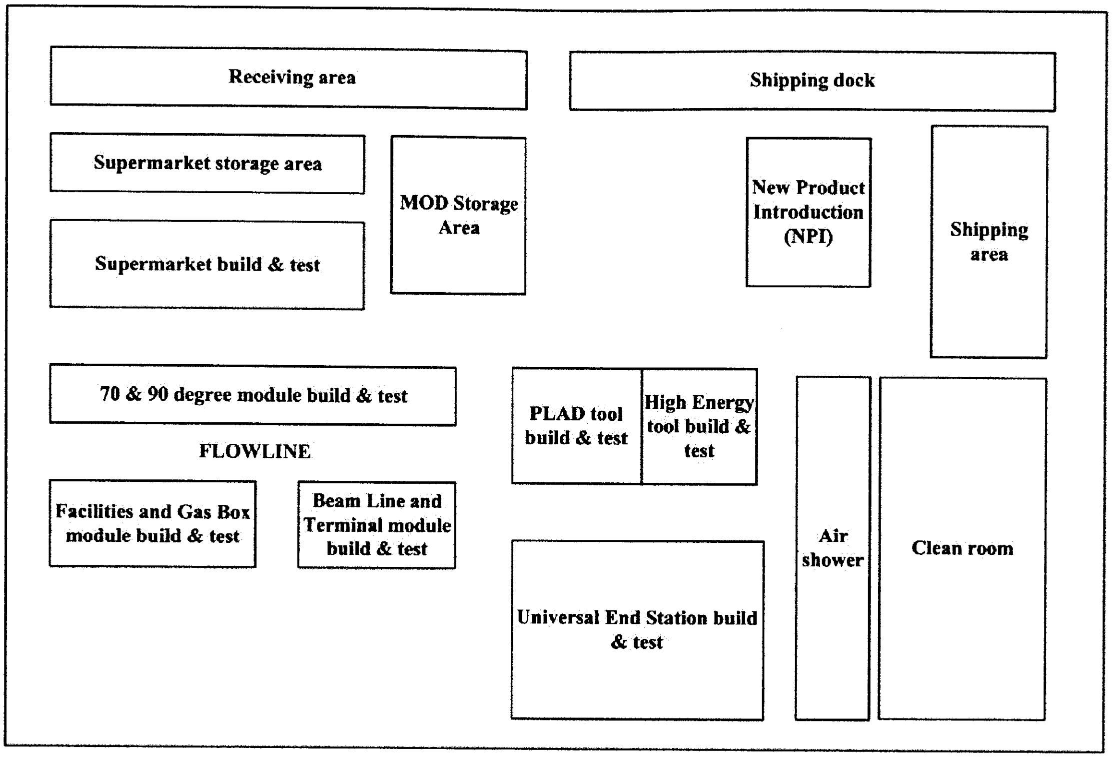


Figure 2-2: Production Floor Layout at Varian (not to scale)

As can be seen from Figure 2-2, the production floor is divided into distinct areas with each area performing a specific function. A summary of the functions performed different areas of the production floor is provided in Table 2-1.

Each product floor area outlined in Table 2-1 is described in detail in the remaining parts of this section.

2.1.2.1 Receiving Area

The receiving area is the part of the facility where parts from external suppliers are received. Crates sent by suppliers are unloaded and the parts are sorted. Parts addressed to Building 80 warehouse are separated and sent over. Parts addressed to Building 35 (location of the shop floor

Table 2-1: Summary of the Functions of the Production Floor Areas

Floor Area	**Function Performed**
Receiving Area	Parts received from suppliers are unpacked and recorded in MRP system.
Supermarket Storage Area	Piece parts and components used to produce the assemblies in the supermarket build area are stored.
Supermarket Build Area	Assemblies are built and tested.
Mixed Module Line	Building and testing of 90 degree, 70 degree and Facilities modules for High Current (HC) machines.
	Building and testing of Beamline and Terminal module for Medium Current (MC) machines.
	Building and testing of Gas Box module for both HC and MC machines.
Universal End Station Line	Building and testing of End Station modules for all machine types.
Air Shower	Modules are disassembled, wiped and cleaned. Seismic kits are installed.
Clean Room	Modules assembled and tested for full build machine orders.
Shipping Area	Final inspection, packaging and crating of modules for shipping.

being described) are unpacked and checked against the order sheet. The parts received are recorded and logged onto the MRP system. If any of the received parts are urgently required on the shop floor, they are immediately sent over. Other parts are stacked into their designated storage locations in the supermarket storage area or MOD storage area.

2.1.2.2 Supermarket

The supermarket[9] at Varian consists of two distinct areas: the supermarket storage area and the supermarket build area. The supermarket storage area stores the piece parts and components required to build the assemblies at the supermarket build area. The supermarket build area builds and tests the assemblies needed for final assembly of the machine in the Mixed Module line and Universal End Station (UES) line or to be sold as spare parts. Shop orders are issued by production control, which contain details of the assemblies to be built by the supermarket area, five days before the laydown date. A shop order is a list of assemblies to be built and also provides details of the parts required to build each assembly, their quantity and their storage location.

The kit picker picks the required parts for each assembly in the right quantity from the storage location, arranges it in a kit tray which is then delivered to the assembler. There are 32 assembly desks in the supermarket. Any assembler is capable of building any assembly with the exception of a few assemblies which can only be built by certified assemblers. Certain types of assemblies need to be tested before they are delivered downstream. There are generic test stands for performing these tests.

2.1.2.3 Mixed Module Line

The Mixed Module line or flow line refers to the area of the floor where the 70 degree module, 90 degree module, Facilities module (for High Current machines), Beamline and Terminal Module (for Medium Current machines) and Gas Box module (for both High Current and

[9] In manufacturing environments, a supermarket commonly refers to a storage location with shelves of parts where the parts are replenished based on consumption.

Medium Current machines) are built. The term, flow line, is a misnomer, since the modules do not flow down the line from one assembly bay to the next. Instead, the entire module is built up on a single assembly bay and then moved to a test bay.

The frame or High Level Assembly (HLA) on which the module is built is brought to the designated build bay on the laydown date. The shop orders for assemblies supplied by the supermarket are issued five days before the laydown date and are thus expected to be available on the laydown date. Some of the high volume fast moving assemblies are managed on a make-to-stock basis by the supermarket and are always expected to be available for use on the gold gquares. Parts required from the warehouse are pulled 24 hours in advance of laydown using the Z pick kit codes. Parts required from MOD storage area are pulled using Z pick lists. Inventory required for build is stored in shelves adjacent to the bays. There is typically a minimum of one person working on building the module at any given time. On completion of the build process, the module is moved to a test bay where it is powered up and a functional test is performed. Any quality problems or defects found are resolved before shipping to the customer.

2.1.2.4 Universal End Station (UES) Line

The End Station module is required for every type of machine. End station modules for every product type are built on the same line and hence, it is referred to as the Universal End Station line. The UES line is the bottleneck of the factory. The manufacturing lead time of the UES line is approximately twice that of the Beamline module. The End Station is further made up of many sub-modules.

Each of the sub-modules are built up in parallel and then integrated. Once the sub-modules are integrated, the harnessing is performed. Harnessing is the bottleneck process within the UES line. Each machine must be harnessed according to the options and select chosen by the customer. It is a highly specialized task which only a few workers are qualified to perform. It is the task which generally takes the longest time. After harnessing, a functional test of the module is performed. Any defects or quality problems found at this stage are resolved before shipping to the customer. The time spent by the module in the test bay depends on the quality problems found and the rework that needs to be done to resolve the problem.

The frame or High Level Assembly (HLA) on which the module is built is brought to the designated build bay on the laydown date. The shop orders for assemblies supplied by the supermarket are issued five days before the laydown date and are thus expected to be available on the laydown date. Some of the high volume fast moving assemblies are managed on a make-to-stock policy by the supermarket and are always expected to be available for use on the gold squares. Parts required from the warehouse are pulled 24 hours in advance of laydown using the Z pick kit codes.

2.1.2.5 Shipping

Once the modules have come off the line after test, they are prepped for shipping. The modules are placed in the air shower where they are wiped and cleaned. Quality checks are performed before the modules are wrapped and crated. Spare assemblies which need to be shipped along with the machine are also included in the crate.

2.2 Inventory Management

The Varian Production Floor has parts inventory stored at multiple locations as summarized in Table 2-2.

The inventory at the different inventory locations are managed using a variety of inventory management techniques as described in the remaining parts of this section.

2.2.1 Kit Codes

In order to simplify the pulling of parts from different storage locations, they have been organized into kit codes. A kit for a module can consist of anywhere between 1 to 300 parts. There are two types of kit codes: Z pick kit codes and Z pick lists. Z pick kit codes are for parts stored in external storage locations like buildings 80, 70, and 5 and are pulled 24 hours before machine laydown. Z pick lists are for parts in internal storage locations like the MOD storage area.

Table 2-2: Inventory Locations at Varian

Location	Part Types
Building 80	Small parts required in the supermarket build area or downstream assembly lines
Buildings 5 and 70	Large size parts like machine enclosures
MOD Storage Area	Parts needed on flow line
Supermarket Storage	Majority of parts used for supermarket subassembly building.
Line Side Inventory	Fast moving parts used on flow line and UES assembly line.
Gold Squares	Stock of fast moving high volume assemblies made by supermarket for flow line an UES line. Managed on make-to-stock policy
Machine Racks	Stores all parts made by supermarket for downstream assembly except those on Gold Squares. Managed on make-to-order policy.

2.2.2 Gold Squares

Gold squares refer to the finite buffers of specific sizes for the high-volume fast-moving assemblies built in the supermarket build area and are managed on a signal-based make-to-stock basis. Each gold square has a specific shelf location with a finite shelf size and the consumption of an assembly from a gold Square creates a blank spot on the shelf, which is a signal for the supermarket build area to build one more assembly of that type to fill the blank spot on that gold square. Thus, this is designed to be a pull system such where inventory is pulled by consumption as opposed to being pushed through according to the production schedule. The gold square inventory management system is discussed in detail in Chapter 8.

2.2.3 Piece Parts Management

The Supermarket storage area holds inventory of parts required for building assemblies in the supermarket. There are four inventory management systems for these parts as follows:

1. *Materials Requirement Planning (MRP) system:* Based on the production schedule at the machine level, the quantity and time of requirements of parts in the lower levels of the bill of materials is known. By comparing the inventory on hand, the quantity that needs to be ordered is computed. The replenishment order is placed based on the delivery lead time.

2. *Two-Bin Kanban System:* This is a pull system with the Kanban bins sized to hold two weeks' worth of inventory. When the parts in the first bin are consumed, an order is triggered to replenish it and the second bin is used. The second bin is expected to hold enough inventory to satisfy demand until the first bin is replenished.

3. *Vendor Managed Inventory (VMI):* these parts are completely managed by the vendor who has visibility to the current inventory levels and consumption rate in the factory. Small inexpensive parts required in large volumes like nuts, screws and so on are typically managed in this way.

4. *Consignment System:* Varian has an agreement with certain vendors to store an inventory of these parts in the factory but pay for them only when they are actually consumed. The company would however partially compensate the vendor if the parts were to go unused.

2.3 Labor Management

Varian's production plant works on five work shifts as summarized in Table 2-3.

Table 2-3: Work Shift Timings at Varian

Shift	Days	Duration
I	Monday - Friday	0700 hrs – 1530 hrs
II	Monday - Friday	1500 hrs – 2330 hrs
III	Monday - Thursday	2300 hrs – 0730 hrs
IV	Fri-Sat-Sun; Sat - Sun-Mon; Sat- Sun- Wed.	0700 hrs – 1900 hrs

The different areas of the production floor work on different shift cycles depending on production floor build area as detailed in Table 2-4.

Table 2-4: Production Build Area Shift Cycles at Varian

Area	Shifts
Receiving Area	I,II and IV
Supermarket Area	I,II and IV
Flow Line	I,II, III and IV
Universal End Station Line	I,II,III and IV
Shipping Area	I,II,IV

2.4 Summary

In this chapter, we provided an outline of Varian's product production process and the production floor layout has been detailed. We described the information and material flow within Varian's production plant and summarized Varian's inventory and labor management techniques.

Chapter 3

Preliminary Analysis and Hypothesis Tree

In this chapter[10], we describe the hypothesis-driven analysis that was adopted to identify, understand and formulate solutions for the issues that were facing Varian.

This chapter is organized as follows. The overall problem statement and the hypothesis-driven methodology used to analyze the problem are presented in Section 3.1. The initial hypothesis-driven breakdown of the overall problem statement into its contributing factors is presented in Section 3.2. An updated hypothesis-driven breakdown of the problem statement based on the observations at Varian is described in Section 3.3.

3.1 Overall Problem Statement

The problem that was presented to the team by Varian was insufficient production capacity and is henceforth referred to as Varian's overall problem. For the purposes of this thesis, production capacity is defined as the number of machines that can be produced at Varian's production plant in a given year.

3.1.1 Problem Statement Validation

We evaluated Varian's overall problem through interviews with Varian's manufacturing management team and shop floor employees. We believed that it was pertinent to determine that the problem being addressed is valid and pressing. We also believed that it was important to ensure that distinctive and positive impact to Varian's bottom line would be possible through the

[10] This chapter was written in collaboration with Ramachandran [1] and Wu [2] and a similar chapter can be found in their respective theses.

solving of the problem presented. Based on interviews and observations, we decided that insufficient production capacity was indeed a pressing and critical problem that would have a direct impact on Varian's bottom line. Increasing the production capacity within the confines of current space[11] would allow the company to service more customer orders without added capital expenditure. It would also allow Varian to more effectively and efficiently utilize its current resources thereby reducing operating costs. Hence, through the increase of production capacity without adding space, the company will secure large savings in capital expenditure and operating costs while increasing revenues because it will be able to ship more machines per year.

3.1.2 Hypothesis-driven Methodology

Given the complexity and vastness of Varian's overall problem, we decided that Varian's problem should be broken down into components to aid in the understanding of the underlying issues that contribute to insufficient production capacity. We formulated a hypothesis-driven approach in order to ensure the effectiveness and efficiency of the problem breakdown process [9]. The approach formulated is illustrated in Figure 3-1 and Figure 3-2 and is described in detail in the rest of this section.

3.1.2.1 Overall Problem Definition

The Varian's overall problem was the problem of the plant's insufficient production capacity. This was the problem that we defined and used for the purposes of the hypothesis-driven approach.

3.1.2.2 Hypotheses Formulation

We parsed the overall problem into several alternate contributing hypotheses with each hypothesis being a reason for the problem of insufficient capacity. We took care to ensure that

[11] This constraint was specified by Varian as their production floor space is currently limited.

each contributing hypothesis was mutually exclusive and collectively exhaustive so that each hypothesis represented a distinct path without any overlap between hypotheses.

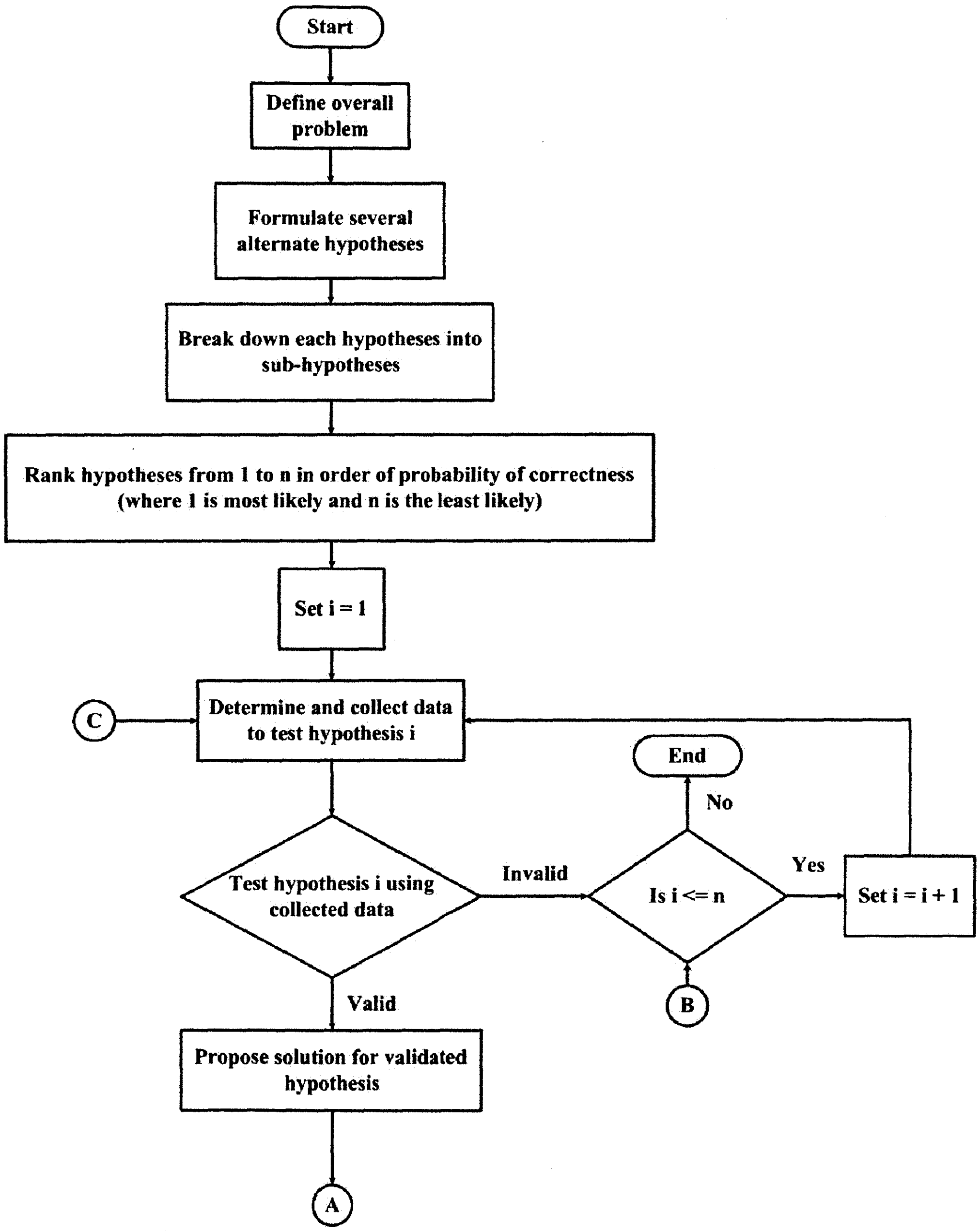


Figure 3-1: Hypothesis-driven methodology (Part 1)

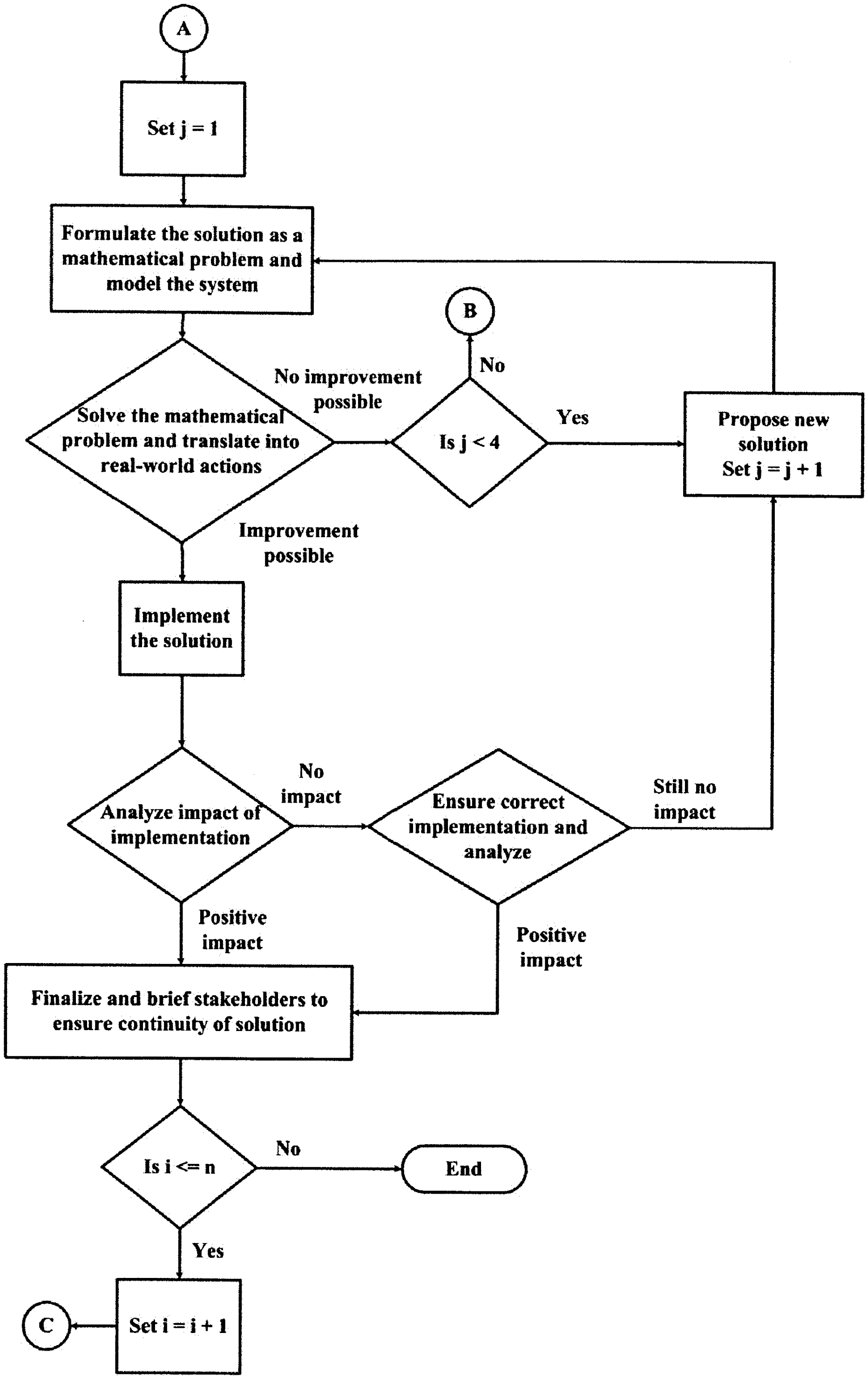


Figure 3-2: Hypothesis-driven methodology (Part 2)

3.1.2.3 Hypotheses Breakdown

We broke down each formulated hypothesis into contributing hypotheses and each contributing hypothesis was in turn further broken-down into contributing hypothesis and so on till the most basic issues for each hypothesis were reached. This was done to ensure that the root causes for the overall problem, as represented by the lowest level hypotheses, were clearly identified and understood. The resulting hypothesis tree from this process is shown in Figure 3-3 and is described in detail in Section 3.2.

3.1.2.4 Hypotheses Ranking

We ranked each formulated hypothesis from 1 to n in the order of the probability of correctness (where 1 is most likely and n is least likely). Once ranked, we evaluated the hypotheses in that order. This was done to ensure effective use of time as the most probable hypothesis would be evaluated and addressed first. This approach will also ensure that each hypothesis is thoroughly investigated before moving on to the next hypothesis. Hence, we investigate the top-ranked hypothesis first and within the top-ranked hypothesis, we investigate the lowest level hypotheses first as each lowest level hypothesis contributes to its preceding higher level hypothesis and each higher level hypothesis contributes its preceding higher level hypothesis and so forth.

3.1.2.5 Data Collection for Testing

In order to test the hypothesis under investigation, we first determine what data would be required to test the hypothesis. Once we have determined what data would be required to test the hypothesis, only that data is then collected through interviews, observations, and from the data available in the company's Material Requirements Planning system. This ensures that we do not collect and compute excessive and irrelevant data.

3.1.2.6 Hypothesis Testing

Once we collect the necessary data, we test the hypothesis being investigated with that data. If the hypothesis is validated, we advance the hypothesis to the next step in the methodology which is solution development. If the hypothesis is invalidated, we select the next hypothesis in the rank order for investigation and we restart the loop.

3.1.2.7 Solution Development

Once a lowest level hypothesis of the cause of Varian's overall problem has been validated, we formulate the validated problem in mathematical terms, model the system and then solve the mathematical problem. Once the mathematical problem has been solved, we translate the solution into real-world actions. If the results appear to provide a possible improvement over the current situation, we advance the solution to the next step which is implementation. If the results do not appear to provide a possible improvement over the current situation, we propose a new solution and we restart the loop. After four iterations of the solution loop, if possible improvements do not seem possible, the hypothesis is then invalidated and we investigate the next hypothesis in the rank order.

3.1.2.8 Solution Implementation and Impact Analysis

We implement the solution which appears to provide a possible improvement over the current situation through a pilot project in collaboration with Varian and the impact of the implemented solution is analyzed. If the implemented solution provides a positive impact to the company, we advance the solution to the next step of the methodology which is finalization. If the implemented solution does not seem to provide a positive impact, we first check the implementation to ensure correctness. If the implemented solution still does not provide positive impact to the company, we invalidate the solution, propose a new solution and restart the solution loop. It is also possible that the hypothesis for which the solution was proposed was invalid.

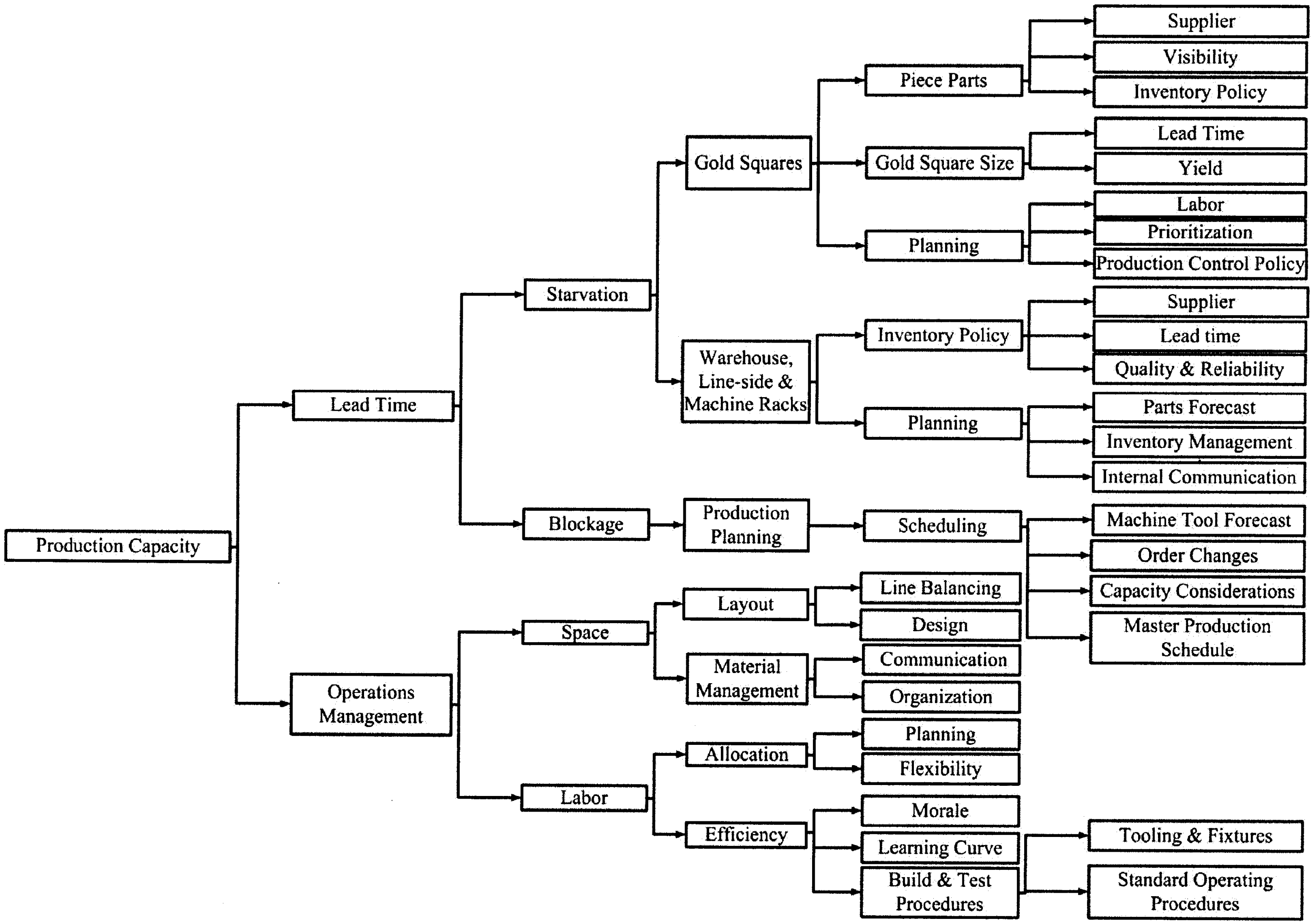
3.1.2.9 Finalization and Stakeholder Briefing

We refine and finalize the first solution whose implementation provides a positive impact to the company. We develop a detailed roadmap and implementation plan for the solution and thoroughly brief all the stakeholders at the company with respect to the problem and the solution so as to ensure continuity and sustainability of the solution. Once a solution has been finalized, if there are other hypotheses left to be investigated, we select the next hypothesis in the rank order is and restart the loop.

3.2 Hypothesis Tree

Based on the approach outlined in Sections 3.1.2.2, 3.1.2.3, and 3.1.2.4, we formulated several alternate hypotheses to understand the overall problem of insufficient production capacity and we broke down each alternate hypothesis into several contributing hypotheses before ranking them in the order of the probability of correctness. A hypothesis tree illustrating the breakdown of the overall problem was developed and is illustrated in Figure 3-3.

We developed the hypotheses through micro- and macro-level observations of the production floor and its working as well as through detailed interviews with Varian's manufacturing and materials managers and shop-floor employees. We structured the hypothesis tree such that each branch is located based on the rank order of the probability of correctness of the hypothesis with a higher branch having a higher probability of correctness than a lower branch. For example, we believed the lead time hypothesis has a higher probability of correctness than operations management and within lead time, starvation has a higher probability than blockage and so on and so forth. This allows for clear understanding of the hypothesis tree and provides a visual sense of the importance of the various hypotheses being investigated. Each branch of the hypothesis tree is described in detail in the rest of this section.



Production Capacity
Lead Time
Operations Management
Starvation
Blockage
Space
Labor
Gold Squares
Warehouse, Line-side & Machine Racks
Production Planning
Layout
Material Management
Allocation
Efficiency
Piece Parts
Gold Square Size
Planning
Inventory Policy
Planning
Scheduling
Line Balancing
Design
Communication
Organization
Planning
Flexibility
Morale
Learning Curve
Build & Test Procedures
Supplier
Visibility
Inventory Policy
Lead Time
Yield
Labor
Prioritization
Production Control Policy
Supplier
Lead time
Quality & Reliability
Parts Forecast
Inventory Management
Internal Communication
Machine Tool Forecast
Order Changes
Capacity Considerations
Master Production Schedule
Tooling & Fixtures
Standard Operating Procedures

Figure 3-3: Hypothesis Tree

3.2.1 Excess Lead time[12]

Lead time, for the purposes of this thesis, is defined as the time taken from machine laydown until the machine is ready for shipping. Interviews with Varian's manufacturing management team and shop floor employees revealed that excess machine lead time was believed by Varian to be an important contributing factor to insufficient production capacity. It was believed, by Varian's managers and employees, that reduction in lead time would allow the company to increase its production capacity without adding space. This led us to select lead time as a hypothesis for insufficient production capacity. We then investigated the lead time hypothesis and parsed it into its contributing hypotheses, starvation and blockage.

3.2.1.1 Reduction in Starvation

Starvation, in this context, is defined as the situation when a part required for the assembly of the machine is not available at the time when it is required. In most cases of starvation, the workers assembling the machine will work around the missing part and the missing part will be assembled into the machine at a later time when it arrives. This could cause an increase in the lead time due to a number of reasons. First, when a worker has to work around a missing part, the worker is not following standard procedure and this adds time to the task. Second, when the missing part arrives at a later time, some amount of work done must be undone and redone to assemble the part into the machine and this adds further time to the task. Finally, working around a part, undoing and redoing assembly work increases the possibility of quality issues and identifying and resolving these quality issues also adds time and cost to the process. Hence, a case of starvation that causes a worker to work around a missing part could increase the lead time of the machine.

An extreme case of starvation is when a worker assembling a machine cannot work around a missing part and is forced to wait for the part to arrive. This adds considerable time to the assembly task and could considerably increase the lead time of the machine tool. Hence, we selected reduction in starvation as a hypothesis to reduce lead time. We then investigated the

[12] Lead time was later replaced by effective operation time and this change is discussed in Section 3.3.

starvation hypothesis and divided it into two contributing hypotheses, (A) gold squares and (B) warehouse, line-side, and machine racks, based on the source of the starvation.

3.2.1.1.A Starvation due to Gold Squares

Gold squares are finite buffers of specific sizes for the high-volume assemblies that are produced by the supermarket build area for consumption on the assembly lines. We determined that reducing starvation due to gold squares would require: (I) Improving availability of piece parts to make the Gold Square assemblies at the supermarket, (II) Optimizing the size of the Gold Squares, and (III) Optimizing the planning of the Gold Square management process. We then further broke down each contributing hypothesis its constituent hypotheses.

3.2.1.1.A.I Suboptimal Availability of Piece Parts

Piece parts are the constituent parts that are used to make the assemblies at the supermarket build area. We hypothesized that improving the availability of piece parts would depend on improving the performance of the supplier of the parts, improving the visibility of the level of piece part inventory being held in storage and optimizing the inventory policy for the piece parts and hence these were selected as the contributing hypotheses for the piece part hypothesis.

3.2.1.1.A.II Suboptimal Gold Square Size

The gold squares are sized every three months using a safety stock formula that assumes a lead time of one week and a 95% service rate. We concluded that optimizing the gold square sizes would depend on considering the effect of lead time on the gold square sizes and considering the effect of the supermarket yield on the golden square size and hence these were selected as the contributing hypotheses for the gold square size hypothesis.

3.2.1.1.A.III Suboptimal Planning

The planning of the manufacture of the gold square assemblies at the supermarket build area is performed by the production control team in association with the supermarket supervisor. We hypothesized that optimizing the planning of the manufacture of the gold square assemblies would depend on optimizing the labor available at the supermarket, optimizing the prioritization system for the manufacture of the assemblies and optimizing the production control policy for the Gold Square assemblies and hence these were selected as the contributing hypotheses for the planning hypothesis.

3.2.1.1.B Starvation due to Warehouse, Line-side and Machine Racks

Warehouse parts are parts that are stored in Varian's warehouses, line-side parts are parts that are stored directly on the assembly lines, and machine rack parts are parts that are produced by the supermarket build area that are stored in racks on the production floor. We determined that reducing starvation due to the warehouse, line-side and machine racks parts would require: (I) Optimizing the inventory policy of the respective parts and (II) Optimizing the planning of the respective parts. We then further broke down each contributing hypothesis its constituent hypotheses.

3.2.1.1.B.I Suboptimal Inventory Policy

The inventory policy hypothesis deals with the various inventory policies that are in place to manage the warehouse, line-side and machine racks parts. We concluded that optimizing the inventory policy of the parts would depend on improving the performance of the supplier of the parts, considering the lead time of the parts, and considering the quality and reliability of the parts and hence these were selected as the contributing hypotheses for the inventory policy hypothesis.

3.2.1.1.B.II Suboptimal Planning

The planning of the warehouse, line-side and machine racks parts is performed by the materials management team in association with the manufacturing engineering team. We hypothesized that optimizing the planning of the manufacture of parts would depend on optimizing the parts forecast, optimizing the inventory management systems for the parts and optimizing the internal communication with respect to the parts within and hence these were selected as the contributing hypotheses for the planning hypothesis.

3.2.1.2 Reduction in Blockage

Blockage, in this context, is defined as the situation where a machine is not able to advance to the next step in its assembly production sequence because the bay required for it is occupied by a preceding machine. This adds considerable waiting time to the production sequence and could considerably increase the lead time of the machine. Hence, we selected reduction in blockage as a hypothesis to reduce lead time. We investigated the blockage hypothesis and identified its contributing hypothesis, Production Planning.

3.2.1.2.A Suboptimal Production Planning

Production planning is the process of determining the production schedule and mix for the factory. We concluded that reducing blockage due to production planning would require optimizing the scheduling of the machine tool production and hence this was selected as the contributing hypothesis for production planning.

3.2.1.2.A.I Suboptimal Scheduling

The plant's production schedule is determined by Varian's materials management team in association with the manufacturing engineering team. We hypothesized that optimizing the production schedule would depend on improving the accuracy of the machine tool forecast, considering the impact of order changes on the production schedule, considering the impact of capacity on the production schedule and optimizing the master production schedule of the factory and hence these were selected as the contributing hypotheses for the scheduling hypothesis.

3.2.2 Suboptimal Operations Management

Operations Management, for the purposes of this thesis, is defined as the effectiveness of the usage of the various resources that are available to the company. Varian's managers believed that improvement in operations management would allow the company to increase its production capacity and hence we selected suboptimal operations management as a hypothesis for insufficient production capacity. We investigated the operations management hypothesis and parsed into its contributing hypotheses, suboptimal use of space and suboptimal use of labor.

3.2.2.1 Suboptimal Use of Space

Space, in this thesis, is defined as the amount of available production floor space for production of assemblies and machine and for material storage. The suboptimal use of space could lead to insufficient production capacity and hence, we selected suboptimal use of space as a hypothesis. We then investigated the space hypothesis and divided it into two contributing hypotheses, (A) suboptimal layout and (B) suboptimal material management.

3.2.2.1.A Suboptimal Layout

The layout, in this thesis, is defined as the way the entire production floor is designed and utilized. We determined that improving the layout would require: (I) Optimizing the line balancing of the assembly lines and (II) Optimizing the design of the layout.

3.2.2.1.B Suboptimal Material management

Material management, in this thesis, is defined as the way materials are stored and managed in the factory. We concluded that improving the material management would require: (I) Optimizing the communication with respect to materials and (II) Optimizing the organization of the materials.

3.2.2.2 Suboptimal Use of Labor

Labor, in this thesis, is defined as the number of available direct-labor employees for the production of assemblies and machines. The suboptimal use of labor could lead to insufficient production capacity and hence, we selected suboptimal use of labor as a hypothesis.

We investigated the suboptimal use of labor hypothesis and divided it into two contributing hypotheses, (A) suboptimal labor allocation and (B) suboptimal labor efficiency.

3.2.2.2.A Suboptimal Labor Allocation

Labor Allocation, in this thesis, is defined as the way labor is allocated to the different tasks in the factory. We determined that improving labor allocation would: (I) Optimizing the planning of the labor and (II) Optimizing the flexibility of the labor.

3.2.2.1.B Suboptimal Labor Efficiency

Labor Efficiency, in this thesis, is defined as the efficiency with which the direct-labor employees complete their designated tasks. It was determined that improving the efficiency would require: (I) Improving the morale of the employees, (II) Reducing the learning curve required to perform the tasks and (III) Optimizing the build and test procedures used in the production process.

3.3 Updated Hypothesis Tree

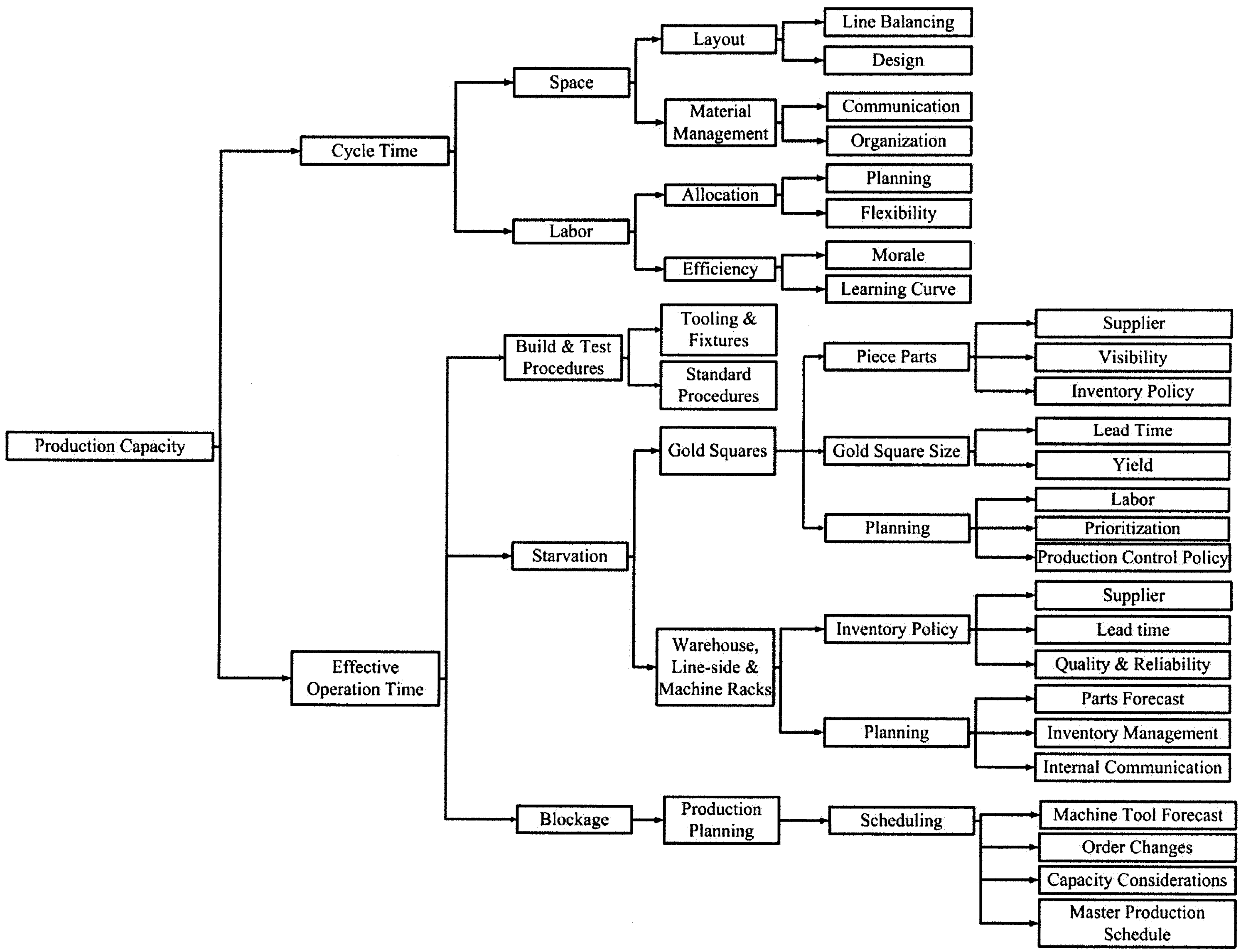
Over the course of the work carried out at Varian, we explored and tested several branches of the hypothesis tree. We validated certain branches and developed solutions accordingly. We also invalidated certain branches and developed appropriate alternate hypotheses to accurately explain the conditions on the production floor. Hence, an updated hypothesis tree was developed to illustrate the breakdown of the problem statement with the alternate hypotheses that were established and is shown in Figure 3-4.

As can be seen in the updated tree shown in Figure 3-4, several changes have been made from the initial hypotheses tree that was shown in Figure 3-3. The two significant changes in the updated hypothesis tree are the modification of the lead time hypothesis branch to effective operation time and the operations management hypothesis branch to cycle time. The lead time branch was modified because we found that starvation and blockage on the production floor would lead to an increase in effective operation time and the operations management branch was modified because we found that an improvement in Varian's production floor operations management would lead to an increase in production capacity only if the improvement in the operations management leads to a decrease in the cycle time.

The sub-hypotheses under cycle time are the same as that of operations management except for the build and test procedures sub-hypothesis. We concluded that any improvement in the build and test procedures would lead to a decrease in effective operation time and hence that sub-hypothesis was moved accordingly. The other sub-hypotheses under cycle time were left unchanged. The sub-hypotheses under starvation and blockage were also left unchanged.

3.4 Task Split-up

The work at Varian was carried out in a team of three as explained in Chapter 1. The hypothesis tree was developed collaboratively as a team. Initially, the team worked together to explore some branches of the hypothesis tree before exploring other branches individually.


Production Capacity
Cycle Time
Space
Layout
Line Balancing
Design
Material Management
Communication
Organization
Labor
Allocation
Planning
Flexibility
Efficiency
Morale
Learning Curve
Effective Operation Time
Build & Test Procedures
Tooling & Fixtures
Standard Procedures
Starvation
Gold Squares
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Planning
Parts Forecast
Inventory Management
Internal Communication
Blockage
Production Planning
Scheduling
Machine Tool Forecast
Order Changes
Capacity Considerations
Master Production Schedule

Figure 3-4: Updated Hypothesis Tree

As mentioned earlier, the hypotheses were explored in their rank order of their probability of correctness and hence the effective operation time branch was explored as a team first. Under the effective operation time branch, the gold squares sub-hypothesis was explored as a team and the collaborative work done in understanding and developing solutions for the gold squares sub-hypothesis is presented in Chapter 10.

The other branches of the hypothesis tree were explored individually to enable efficient and effective use of the team's time at Varian. In this thesis, we explore and present solutions for the space and labor sub-hypotheses of the cycle time branch in Chapters 5, 6 and 7. Ramachandran [1] explores and presents solutions for the inventory policy sub-hypothesis of the piece parts branch of the gold squares hypothesis branch and the space sub-hypothesis of the cycle time branch. Wu [2] explores and presents solutions for the visibility and inventory policy sub-hypotheses of the piece parts branch of the gold squares hypothesis branch.

3.5 Summary

In this chapter, we presented the preliminary analysis and hypothesis-driven approach that was adopted to identify, understand and form solutions for the problems that were facing Varian. The hypothesis-driven approach was outlined and the initial hypothesis tree that was developed is described. Each branch and the different sub-hypotheses of the hypothesis tree are detailed and highlighted. The subsequent updated hypothesis tree that was developed over the course of the work at Varian is then presented and the changes from the initial hypothesis tree are explained. Finally, the task split-up in exploring and developing solutions for the various branches of the hypothesis tree is presented and described.

Chapter 4

Literature Review

In this chapter[13], we outline the various literature topics that were reviewed over the course the work at Varian.

4.1 Inventory Management

In this section, we present a review of the theoretical background behind the concepts used the development of the inventory management policy for the gold squares presented in Chapter 8.

4.1.1 Inventory Policies

Simchi-Levi et al [10] provide a detailed description of cycle stock, safety stock and the basic inventory management strategies that are covered in this chapter. These concepts, as discussed by Simichi-Levi et al, are summarized in this section.

4.1.1.1 Cycle Stock and Safety Stock

Cycle Stock refers to the quantity of inventory that needs to be kept on hand to meet demand during the lead time. Safety stock refers to the quantity of extra inventory above the cycle stock which must be kept on hand to prevent stock-outs due to variations in demand.

[13] This chapter was written in collaboration with Ramachandran [1] and Wu [2] and a similar chapter can be found in their respective theses.

4.1.1.2 Continuous Review Policy

The Continuous Review Policy (also called Q-R policy) is a commonly used inventory management strategy. For Q-R inventory policy, Q is a given fixed ordering quantity, and R is the re-order point to be chosen. The inventory is replenished for quantity Q once its level drops below re-order point R. The Q-R policy is pulled by demand, and its equations are as follows

The re-order point R is given by,

$$R = \mu L + z\sigma\sqrt{L} \tag{4-1}$$

The average inventory level of Q-R policy is given by,

$$E[I] \approx \frac{E[I^-] + E[I^+]}{2} = \frac{Q}{2} + Z\sigma\sqrt{L} \tag{4-2}$$

where,

μ – the consuming rate

σ – the standard deviation of the consuming rate

z – the safety factor

L – the lead time of an ordering quantity Q

Q – the fixed ordering quantity

4.2 Process Capacity

Hopp and Spearman [11] discuss the basic principles of factory behavior which relate cycle time, line capacity and line throughput. According to Hopp and Spearman, if a production line is not starved, the cycle time and capacity may be calculated as follows

The cycle time at a given station in hours is given by

$$C.T_{\text{station}} = \frac{\text{Process Time}_{\text{station}}}{\text{Number of Machines}} \tag{4-3}$$

The cycle time of the line is equal to the maximum of the cycle time of all the stations.

The capacity of a station in jobs/hour is given by,

$$\text{Capacity}_{\text{station}} = \frac{1}{C.T_{\text{station}}} \tag{4-4}$$

Equations (4-3) and (4-4) illustrate the method used to calculate cycle time and station capacity and provide a theoretical background for the resource optimization for cost minimization model developed in Chapter 5.

4.3 Summary

In this chapter, we summarized the various inventory management and process capacity concepts that were reviewed over the course of the work at Varian.

Chapter 5

Resource Optimization for Cost Minimization

In this chapter, we develop an optimization model for minimizing cost through the optimal allocation of workers and assembly bays[14] for the various module production lines at Varian. As indicated in Chapter 1, resource optimization for cost minimization is one of the four major topics of this thesis. The optimization model developed in this chapter will be extended to the labor cost minimization model presented in Chapter 6 and the labor flexibility model presented in Chapter 7. Some valuable insights that can be derived from the usage of the developed models are discussed in Chapter 9 and the future work that can be carried out at Varian using these models is described in Chapter 10.

This chapter is organized as follows. The problem statement is outlined and a model of Varian's production line is detailed is Section 5.1. The problem formulation is introduced and the solution techniques are described in Section 5.2. An alternate problem to allow Varian to measure the performance of existing production floor conditions is described in Section 5.3. Numerical results and analysis are provided in Section 5.4 to show the accuracy and efficiency of the model developed. The architecture for the software program to enable Varian to utilize this model is presented in Section 5.5.

5.1 Problem Statement and Model of Varian's Production Line

Varian's production line, as described in Chapter 2, consists of five module production areas with each module production area consisting of a number of assembly bays. In the case of the 90

[14] An assembly bay, at Varian, is the location where a process is performed and covers assembly, test and prep bays. It also represents the work-in-process inventory that would be present at that location.

module, 70 module, Gas Box module, Facilities module, Beamline module, and Terminal module, each module is built completely in a single assembly bay before being transported to and tested in a test bay. Once the module is tested and approved for shipping, the module is transported to a shipping prep bay where it is prepped for shipping and then transported to Varian's shipping area.

In the case of the Universal End Station (UES) module, there are five parallel processes performed in separate assembly bays to produce five different components of the UES module. These five components are then integrated in an integration bay before harnessing is performed in a harnessing bay. The completely built UES module is then transported to a test bay for testing. Once the module is tested and approved for shipping, it is moved to a shipping prep bay where it is prepped for shipping before it is sent to Varian's shipping area. A detailed description of the Varian's production line including the process and material flow for each individual module area is provided in Chapter 2.

5.1.1 Problem Statement

Given the complexity of Varian's production line, it is critical that each process being performed at Varian has the required capacity to meet demand. Capacity, in this context, is defined as the maximum throughput possible at any point of time. However, it is also critical that each process does not have excess capacity that will lead to increased cost and hence reduced profit for Varian. The semiconductor capital equipment industry, as described in Chapter 1, is highly sporadic and volatile with high demand variability from week to week. This sporadic nature of the industry requires Varian's manufacturing managers to constantly adjust the plant's capacity to meet demand whilst ensuring that costs are controlled.

The nature of Varian's production line dictates that each individual process performed in the plant must have the requisite capacity to meet demand since each process within a module production area is performed once and is required to complete each module. This nature also causes any process within a module production area that has excess capacity to lead to excess cost for the plant since no process is required more than once for a single module.

The capacity of each process in a module build area depends on the number of parallel assembly bays used for that process as well as the number of workers working on each assembly bay, or in other words, the resources available to that process. The cost of workers is high as is the cost of work-in-process inventory that will be present at each assembly bay till the process is complete and hence, it is highly prudent that the number of assembly bays being utilized and the number of workers working at each assembly bay is optimized to meet demand at minimum cost. If a process is complete ahead of when its respective downstream process requires, the completed component from the previous process will be subjected to waiting in addition to the cost of excess capacity.

Therefore, in order to be able to meet demand at minimum cost, the following problem statement was developed address the issue of resource allocation at Varian:

- Given desired throughput (products/week), what is the number of assembly bays and the number of effective workers[15] at each assembly bay for each process that will yield minimum cost and hence maximum profit?

The relationship between workers, assembly bays, cost, and capacity for each process is illustrated in Figure 5-1. As illustrated by Figure 5-1, the number of assembly bays and the number of effective workers at each assembly bay define the capacity of each process at Varian. The number of assembly bays and the number of effective workers at each assembly bay also define the cost of each process and hence, optimization of capacity to meet demand at minimum cost is useful.

The problem statement described above represents a critical question that Varian's manufacturing managers must answer every week while making resource allocation and capacity planning decisions. Currently, Varian's manufacturing management team depends on its deep manufacturing experience to make resource allocation and capacity planning decisions. The optimization model described in this chapter aims to enable a data-driven systems approach to making resource allocation and capacity planning decisions that will allow Varian to align their resources and capacity to demand at minimum cost.

[15] An effective worker is defined as the equivalent of 40 work hours per week.

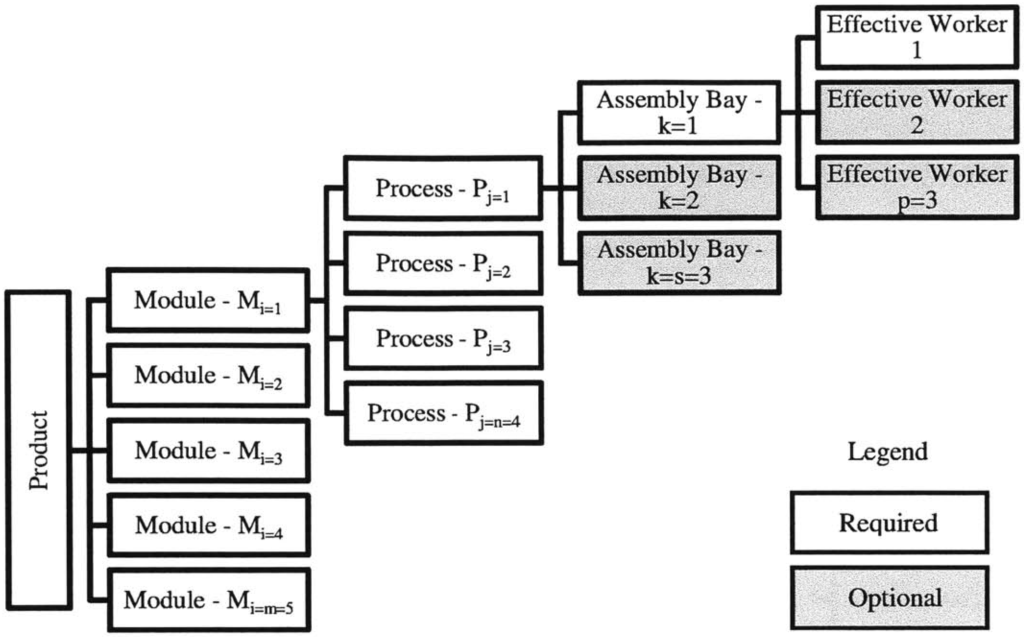
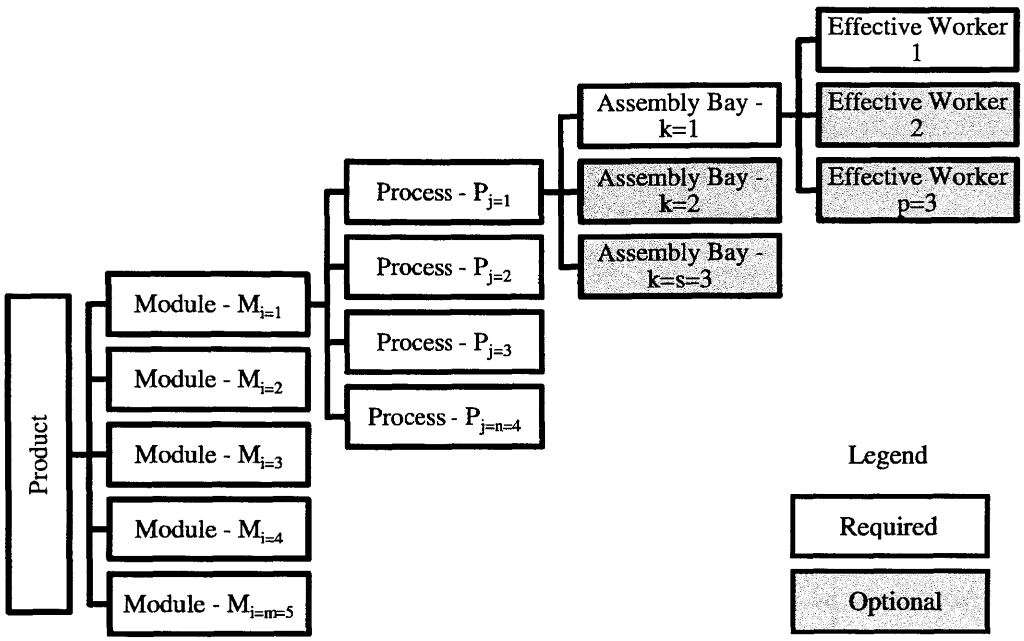


Figure 5-2: Breakdown of the Varian's Production Line for a product type

For each type of product, it is required that all *m* modules must be built and hence all *n* processes must be performed. However, each process, P_j, needs only a minimum of one assembly bay to be performed. In turn, each Assembly Bay needs only a minimum of one effective worker to perform Process, P_j. The usage of additional assembly bays and workers is assumed to be optional.

The processing time for each process is assumed to be deterministic and constant. We also assume that all the *m* module build areas start their operations at the same time. Transportation time is assumed to be negligible compared to operation time. It is also assumed that all parts required to perform Process, P_j, are available when required.

The total number of Assembly Bays to be used for Process, P_j, is denoted by A_j, the total number of Workers to be used for Process, P_j, is denoted by W_j, and the total number of Workers at each Assembly Bay, *k*, is denoted by G_k. Hence, total number of Workers to be used for Process, P_j, is given by, $W_j = \sum_{k=1}^{A_j} G_k$



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The number of modules, processes, assembly bays, and workers are assumed to be integers for the purposes of this evaluation. For the Varian production line of a particular product type, A_j and W_j, $\forall_j = 1, 2, \ldots, n$, are considered as the decision variables. Therefore, for each Module, M_i, there are $2n$ decision variables and for the complete production line of one product type of m modules, there are $2n.m$ decision variables.

Each process being performed at an assembly bay will a take specific amount of time to be completed defined as the assembly bay cycle time. The assembly bay cycle time at assembly bay, k, for process, P_j, is a function of the number of workers, G_k, performing the process at that assembly bay and is denoted by, $C_{jk}(G_k)$. At Varian, the assembly bay cycle time, $C_{jk}(G_k)$, can be determined directly from a table which consists of empirically-determined values for each Process, P_j,. Sample[17] assembly bay cycle times are illustrated in Table 5-1.

Table 5-1: Sample Assembly Bay Cycle Times as a function of the number of workers

Module	**Process**	**C_{jk} (G_k=1)**	**C_{jk} (G_k=2)**	**C_{jk} (G_k=3)**
90 module	Build	90 hours	63 hours	56 hours
70 module	Build	43 hours	30 hours	25 hours

The capacity for process, P_j, is denoted by $\hat{T}_j$ (units/week). The capacity for assembly bay, k, is denoted by $\hat{T}_{jk}$ (units/week). The assembly bay cycle time, C_{jk}, at assembly bay, k, is related to assembly bay capacity, $\hat{T}_{jk}$, as follows

$$\hat{T}_{jk} = \frac{U_j}{C_{jk}} \text{ (units/week)}$$

where, U_j is a parameter defined as the available time (hours/week) for process, P_j and is given by

[17] This sample is based interviews with production floor supervisors and is not intended to represent actual values.

U_j = (number of hours per shift) * (number of shifts per day)

* (number of working days per week) * (utilization) (hours/week)

where,

Utilization is defined by Varian as the fraction of available time that is billed to a specific product.

Since U_j is a parameter, the assembly bay capacity, $\hat{T}_{jk}$, of assembly bay, *k*, is a linear function of the assembly bay cycle time at that assembly bay and is denoted by, $\hat{T}_{jk}$ (C_{jk}).

The Capacity for process, P_j, is the summation of the individual capacities of each of the assembly bays performing that process and is given by

$$\hat{T}_j = \sum_{k=1}^{A_j} \hat{T}_{jk}(C_{jk}) \text{ (units/week).}$$

For process, P_j, the capacity, $\hat{T}_j$, is defined as a function of the total number of assembly bays, A_j, and the number of workers at each assembly bay, G_k. Hence, $\hat{T}_j = \hat{T}_j\ (A_j, G_1, \ldots, G_{A_j})$ is a function of assembly bays and workers.

The cost per week of process, P_j, is formulated as

Process Cost = Labor Cost + Assembly Bay Cost + All other costs

This may be represented as

$$\text{Process Cost} = a_j \cdot W_j + b_j \cdot A_j + Q \tag{5-1}$$

where,

$a_j > 0$ (\$/worker/week) is the cost coefficient associated with the number of workers, W_j.

$b_j > 0$ (\$/assembly bay/week) is the cost coefficient associated with the number of assembly bays, A_j.

Q (\$/week) stands for all costs other than those due to workers and assembly bays.

Since, Q is independent of A and W, we simplify Equation (5-1) and write our objective function as

$$I_j(A_j, W_j) = a_j \cdot W_j + b_j \cdot A_j \tag{5-2}$$

where,

$I_j(A_j, W_j)$ is defined as the cost per week of process, P_j.

5.2 Problem Formulation and Solution Technique

In this section, we introduce the mathematical model that is used to optimize resources to meet demand at minimum cost. We also introduce the solution technique that is going to be used to obtain the optimum values.

5.2.1 Constrained Problem

The primary goal is a constrained problem where we aim to minimize the costs of each process, P_j, subject to a capacity constraint. The constrained problem is formulated as follows

$$\begin{aligned} \text{Minimize} \quad & I_j(A_j, W_j) = a_j \cdot W_j + b_j \cdot A_j \\ \text{subject to} \quad & \hat{T}_j(A_j, G_1, \ldots, G_{A_j}) \geq S_j \cdot D_j, \qquad (5\text{-}3) \\ & A_j \geq 0 \quad \text{and} \\ & G_k \geq 0. \\ \text{where} \quad & W_j = \textstyle\sum_{k=1}^{A_j} G_k, \\ & \hat{T}_j = \textstyle\sum_{k=1}^{A_j} \hat{T}_{jk}(C_{jk}), \end{aligned}$$

$$\hat{T}_{jk} = \frac{U_j}{C_{jk}} \quad \text{and}$$

$C_{jk}(G_k)$ is determined from a table of values such as Table 5-1.

The first constraint is defined as the capacity constraint where D_j is the target demand rate or desired throughput of process, P_j, and $S_j \geq 1$ is a parameter called the Safety Factor that is introduced to adjust the capacity, $\hat{T}_j$, of process, P_j, in order to account for part shortages and other unforeseen issues that might occur at Varian. It is important to note that D_j is the same for all values of *j* and is equal to the target Demand rate or desired throughput for the specific type of product under evaluation. If multiple types of products need the same modules and hence would need the same processes to be performed, then D_j would be the summation of the individual target demand rates or desired throughputs of the individual products for each process.

The second constraint is the assembly bay constraint that comes from the natural property of assembly bays since it is not possible to have a negative number of assembly bays.

The third constraint is the Worker constraint that comes from the natural property of workers since it is not possible to have a negative number of workers at each assembly bay.

However, in order for all *n* Processes to be completed, each Process, P_j, needs to have at least one assembly bay and that assembly bay needs to have at least one effective worker. Hence, we introduce $A_{j\,min} \geq 1$ and $G_{j\,min} \geq 1$ which are the minimum number of assembly bays and the minimum number of workers at each assembly bay required to complete Process, P_j. We also define a parameter, $G_{j\,max}$, which is the maximum number of workers that can work at assembly bay, *k*, to perform process, P_j.

Therefore, Equation (3) can be written as:

$$\text{Minimize} \quad I_j(A_j, W_j) = a_j \,.\, W_j + b_j \,.\, A_j$$

$$\text{subject to} \quad \hat{T}_j(A_j, G_1, \ldots, G_{A_j}) \geq S_j \,.\, D_j, \tag{5-4}$$

$$A_j \geq A_{j\,min} \quad \text{and}$$

$$G_{j\,max} \geq G_k \geq G_{j\,min}.$$

where $W_j = \sum_{k=1}^{A_j} G_k$,

$\widehat{T}_j = \sum_{k=1}^{A_j} \widehat{T}_{jk}(C_{jk})$,

$\widehat{T}_{jk} = \frac{U_j}{C_{jk}}$ and

$C_{jk}(G_k)$ is determined from a table of values such as Table 5-1.

The constrained problem illustrated in Equation (4) does not have a limit on the number of assembly bays that can be used to perform a process, P_j. This constrained problem will be useful in future capacity planning decisions and will allow Varian to understand resource requirements for the minimum cost condition.

However, it will also be useful to Varian if an additional constraint is placed on the maximum number of assembly bays that can be used. This will allow Varian's manufacturing management team to optimize the use of their existing available assembly bays. Hence, we introduce, $A_{j\,max}$ which is a parameter defined as the maximum number of assembly bays that can be used to perform process, P_j.

Therefore, Equation (4) can be written as:

Minimize $I_j(A_j, W_j) = a_j \,.\, W_j + b_j \,.\, A_j$

subject to $\widehat{T}_j(A_j, G_1, \ldots, G_{A_j}) \geq S_j \,.\, D_j$, (5-5)

$A_{j\,max} \geq A_j \geq A_{j\,min}$ and

$G_{j\,max} \geq G_k \geq G_{j\,min}$.

where $W_j = \sum_{k=1}^{A_j} G_k$,

$\widehat{T}_j = \sum_{k=1}^{A_j} \widehat{T}_{jk}(C_{jk})$,

$\widehat{T}_{jk} = \frac{U_j}{C_{jk}}$ and

$C_{jk}(G_k)$ is determined from a table of values such as Table 6-1.

Therefore, Equations (5-4) and (5-5) can be used to determine the optimal number of assembly bays and the optimal number of effective workers per assembly bay that can meet demand at minimum cost subject to their respective constraints.

5.2.2 Solution Technique

The constrained problem illustrated in Equation (5-4) has a linear objective function but is subject to a non-linear capacity constraint. Hence, it would need to be solved by non-linear optimization. A number of commercial and open-source non-linear programming solvers are available on the market that can be utilized to solve this constrained problem.

The constrained problem illustrated in Equation (5-5) also has a linear objective function subject to a non-linear capacity constraint. However, since this problem has a constraint on the maximum number of assembly bays that can be used for each process in addition to the constraint on the maximum number of workers that can be used at each assembly bay, the solution space is small enough that it can be solved by enumeration of the cost of all the possible combinations that meet the constrain requirements and finding the minimum cost.

Varian's current production floor has the maximum number of assembly bays for any process as eight and the maximum number of workers at each assembly bay as three. Hence, there are 3^8, that is, 6561 possible solutions to Equation (5-5). This demonstrates that although Equation (5-5) is a non-linear optimization problem, it can be solved by enumeration of the cost for all the possible combinations of solutions that meet the constraint requirements and selecting the solution with the minimum cost as the number of possible solutions is small.

5.3 Performance of Current Production Floor Conditions

The problems described in Equations (5-4) and (5-5) will allow Varian to effectively determine the optimal number of assembly bays and the optimal number of workers at each assembly bay to meet demand at minimum cost. However, it will also be useful to Varian if Varian's manufacturing management team can specify existing production floor resource conditions and determine the capacity provided by those resources and their associated cost.

5.3.1 Problem Statement, Model of the line, Assumptions and Notations

In order to be able to measure current production floor performance as a function of assembly bays and workers at each assembly bay, the following problem statement was developed:

- Given the number of assembly bays and the number of effective workers at each assembly bay for each process, what is the associated cost and capacity of that process?

The capacity of the process as determined from the problem statement mentioned in Section 5.3.1 can be compared with the required demand to check if the current production floor scenario would be able to meet the required demand. This problem statement also represents a critical question that Varian's manufacturing team must answer due to the cyclical nature of the industry. It will allow Varian's manufacturing team to compare their existing production floor conditions with the minimum cost condition and will be an additional data point in their decision making process.

The same model of the line, assumptions and notations as detailed in Section 6.1 are used for this problem statement as well. This problem statement does not represent an optimization problem but rather a problem that describes current production floor performance. In addition to the notations introduced in Section 6.1, we introduce the parameter $A_{j\,\text{current}}$ which is defined as the number of assembly bays currently being used for process, P_j. We also introduce the parameter $G_{k\,\text{current}}$ which is defined as the number of workers currently working at assembly bay, *k*.

Therefore, the current capacity, $\widehat{T}_{j\,\text{current}}$, of process, P_j, is a summation of the current capacities of the individual assembly bays performing that process. That is,

$$\widehat{T}_{j\,\text{current}} = \sum_{k=1}^{A_{j\,\text{current}}} \widehat{T}_{jk\,\text{current}}\,(C_{jk})$$

The current individual assembly bay capacity, $\widehat{T}_{jk\ current}$, at assembly bay, k, is given by

$$\widehat{T}_{jk\ current} = \frac{U_j}{C_{jk}} \qquad \text{(units/week)}$$

where

C_{jk} ($G_{k\ current}$) is a function of the number of workers currently working at assembly bay, *k*, and is determined from a table of values such as Table 5-1,

U_j is the available time for process, P_j, as described in Section 5.1 earlier.

The current cost, $C_{j\text{-}current}$, of process, P_j, is given by

$$I_{j\ current}\ (A_{j\ current}, W_{j\ current}) \quad = \quad a_j \,.\, W_{j\ current} + b_j \,.\, A_{j\ current} \qquad (5\text{-}6)$$

where

a_j and b_j are the same cost coefficients described earlier in Equation (5-1),

$W_{j\ current}$ is the total number of workers currently working on process, P_j, and is given by $W_{j\ current} = \sum_{k=1}^{A_{j\ current}} G_{k\ current}$,

$A_{j\ current}$ is the number of assembly bays currently being used to perform process, P_j.

5.3.2 Problem Formulation and Solution Technique

In this section, we are going to introduce the mathematical model and the solution technique that we are going to use to measure the current performance and cost of process, P_j.

The performance measurement problem is formulated as:

Process Cost $\quad I_{j\,current}\,(A_{j\,current}, W_{j\,current}) \quad = \quad a_j \,.\, W_{j\,current} + b_j \,.\, A_{j\,current}$

Process Capacity $\quad \hat{T}_{j\,current} = \sum_{k=1}^{A_{j\,current}} \hat{T}_{jk\,current}\,(C_{jk})$

where $\quad \hat{T}_{jk\,current} = \frac{U_j}{C_{jk}}$ and (5-7)

$C_{jk}\,(G_{k\,current})$ is determined from a table of values such as Table 6-1.

Current Total Workers $\quad W_{j\,current} = \sum_{k=1}^{A_{j\,current}} G_{k\,current}$

The problem described in Equation (5-7) is simple to solve as all the required parameters will be specified by Varian. Using Equation (5-7), the process cost and process capacity of every production process at Varian can be determined.

In order to check if current production floor conditions can meet the required demand, the current capacity, $\hat{T}_{j\,current}$, of every process can be compared as follows:

Is $\quad \hat{T}_{j\,current} \quad \geq \quad S_j \,.\, D_j$? (5-8)

where S_j is the safety factor for process, P_j, and D_j is the demand for process, P_j, as described earlier in Equation (3).

If yes, the current conditions are feasible to meet demand.

If no, the current conditions are not feasible to meet demand.

Using Equation (5-8), Varian's Manufacturing Management team can check if current production floor conditions are feasible to meet demand. Equations (5-7) and (5-8) together can inform Varian's Manufacturing Management team the current capacity of a process, the current cost of running that process and if the current capacity of that process can meet demand.

If used along with the Resource Optimization models illustrated in Equations (5-4) and (5-5), the performance measurement models shown in Equations (5-7) and (5-8) can provide valuable insight to aid resource allocation and capacity planning decisions at Varian.

5.4 Numerical Experiment and Results

In this section, we illustrate the accuracy and efficiency of the different models developed in this chapter through a numerical experiment. This numerical experiment serves to demonstrate the usage of the models as a part Varian's resource allocation decisions.

For the demonstration of the working of the resource optimization model mentioned in Equation (5-5) of this chapter, the Gas Box build is selected as the example process. Equation (5-5) which includes the maximum number of assembly bays constraint is used in this experiment as it accurately reflects the optimization that Varian will be running on a weekly basis. The process is denoted as P_1 and all subsequent notations are used accordingly.

5.4.1 Parameters used for the Numerical Experiment

The different parameters[18] that will be used in the demonstration of Equation (5-5) are detailed in Table 5-2.

We determined the parameters detailed in Table 8-1 through observations of Varian's production floor and through interviews with Varian's Manufacturing team. We determined some of the parameters were empirically while others were calculated using the formulas mentioned in Section 5.1.

[18] Some parameters have been scaled to protect confidential information.

Table 5-2: Parameters for Gas Box build used in the Numerical Experiment

Notation		**Calculation Method**	**Value**
Process, P_1		-	Gas Box build
Available Time, U_1		from [2]	104 hours/week
Minimum Number of Assembly Bays, $A_{1\text{-min}}$		Empirical	1 bay
Minimum Number of Effective Workers per Assembly Bay, $G_{k\text{-min}}$		Empirical	1 worker
Maximum Number of Effective Workers per Assembly Bay, $G_{k\text{-max}}$		Empirical	2 workers
Maximum Number of Assembly Bays, $A_{1\text{-max}}$		Empirical	2 bays
Cycle Time at each Assembly Bay as a function of the Number of Effective Workers at that Bay	C_{1k} (1)	Empirical	14 hours
	C_{1k} (2)	30% reduction in cycle time with added worker	10 hours
Cost coefficient associated with the Number of Effective Workers, b_1		$255/hour * 40 hours	$10200/worker/week
Cost coefficient associated with the Number of Assembly Bays, c_1		From yearly carrying cost of inventory	$2187.5/assembly bay/week

5.4.2 Optimization and Results

The resource optimization for cost minimization model developed in this chapter is used in the optimization. The Equation (5-5) is shown here as a reminder.

$$\text{Minimize} \quad I_j(A_j, W_j) \quad = \quad a_j \,.\, W_j + b_j \,.\, A_j$$

$$\text{subject to} \quad \hat{T}_j(A_j, G_1, \ldots, G_{A_j}) \geq S_j \,.\, D_j, \tag{5-5}$$

$$A_{j\,max} \geq A_j \geq A_{j\,min} \quad \text{and}$$

$$G_{j\,max} \geq G_k \geq G_{j\,min}.$$

$$\text{where} \quad W_j = \sum_{k=1}^{A_j} G_k\,,$$

$$\hat{T}_j = \sum_{k=1}^{A_j} \hat{T}_{jk}(C_{jk})\,,$$

$$\hat{T}_{jk} = \frac{U_j}{C_{jk}} \quad \text{and}$$

$C_{jk}(G_k)$ is determined from a table of values such as Table 6-1.

The possible solutions to Equation (5-5) with their corresponding process costs and capacities for a demand of 12 units / week and a safety factor of 1.2 are detailed in Table 8-2. We determined the solution by enumerating of all the possible solutions and selecting the solution with the minimum costs that meets the constraints.

As can be seen from Table 5-3, values for A_1 and W_1 that will meet the required demand of 12 units / week with a safety factor of 1.2 at minimum cost are 2 assembly bays and 1 worker per assembly bay respectively. The minimum cost for this process in order to meet demand is \$24775. Hence, this illustrates the usage of the resource optimization for cost minimization model in making resource allocation decisions.

Table 5-3: Resource Optimization Possible Solutions for the Gas Box Build Process

Number of Assembly Bays, A_1	Effective workers at each assembly bay, k		Total number of effective workers, W_1	Capacity, $\hat{T}_1$ (units/week)	Cost, C_1 (A_1, W_1) ($/week)
	G_1	G_2			
1	1	0	1	7.42	$12387.5
1	2	0	2	10.4	$22587.5
2	1	1	2	14.42 (meets capacity constraint)	$24775 (minimum cost)
2	2	1	3	17.6 (meets capacity constraint)	$34975
2	2	2	4	20.8 (meets capacity constraint)	$45175

As mentioned in this chapter, the resource optimization model can also be used to measure the performance of the system. In order to illustrate the performance measurement aspect of the model, we present the numbers of units that can be produced per quarter of the Gas Box using the given parameters for the different combinations of assembly bays and workers per assembly bay in Table 5-4.

Table 5-4: Gas Box Quarterly Capacity for the Given Parameters

Number of Assembly Bays, A_1	**Effective workers at each assembly bay, *k***		**Total number of effective workers, W_1**	**Capacity, $\hat{T}_1$ (units/week)**	**Quarterly[19] Capacity (units/quarter)**
	G_1	**G_2**			
1	1	0	1	7.42	89.04
1	2	0	2	10.4	124.8
2	1	1	2	14.42	173.04
2	2	1	3	17.6	211.2
2	2	2	4	20.8	249.6

As can be seen from Table 5-4, the maximum quarterly capacity of the Gas Box is 249 units/quarter for the given parameters using two assembly bays and two workers at each assembly bay.

The value of W_1 determined from the numerical experiment with resource optimization model performed in this chapter will used in the numerical experiment with the labor cost minimization model performed in Chapter 6.

[19] A quarter is defined as 13 weeks.

5.5 Architecture for the Software Program

In this section, we develop the architecture for the software program to be developed by Varian to automate the resource optimization for cost minimization model developed in this chapter. The implementation, usage and insights that can be derived from the use of the software program is presented in Chapter 9 and the future work that can be carried out with respect to the software program is outlined in Chapter 10.

The software program's architecture is developed from a functional and logical viewpoint with the target users as Varian's manufacturing management team. The software program will obtain all the necessary parameters from the user and will utilize the optimization models described in this chapter as well as those developed in Chapters 6 and 7 to provide the user with the optimal results. The software program is to consist of three parts corresponding with the three models developed in this thesis. The first part of the software program corresponding with the resource optimization model is presented in the remaining part of this section.

5.5.1 Functional Architecture for the Resource Optimization Model

The first part of the software program corresponds with the resource optimization for cost minimization model developed in this chapter. The parameters and results obtained in this segment will be used subsequently in the other two parts as well that are presented in Chapter 6 and 7. The chart illustrated in Figure 5-3 shows the functional architecture of the software program for the first segment.

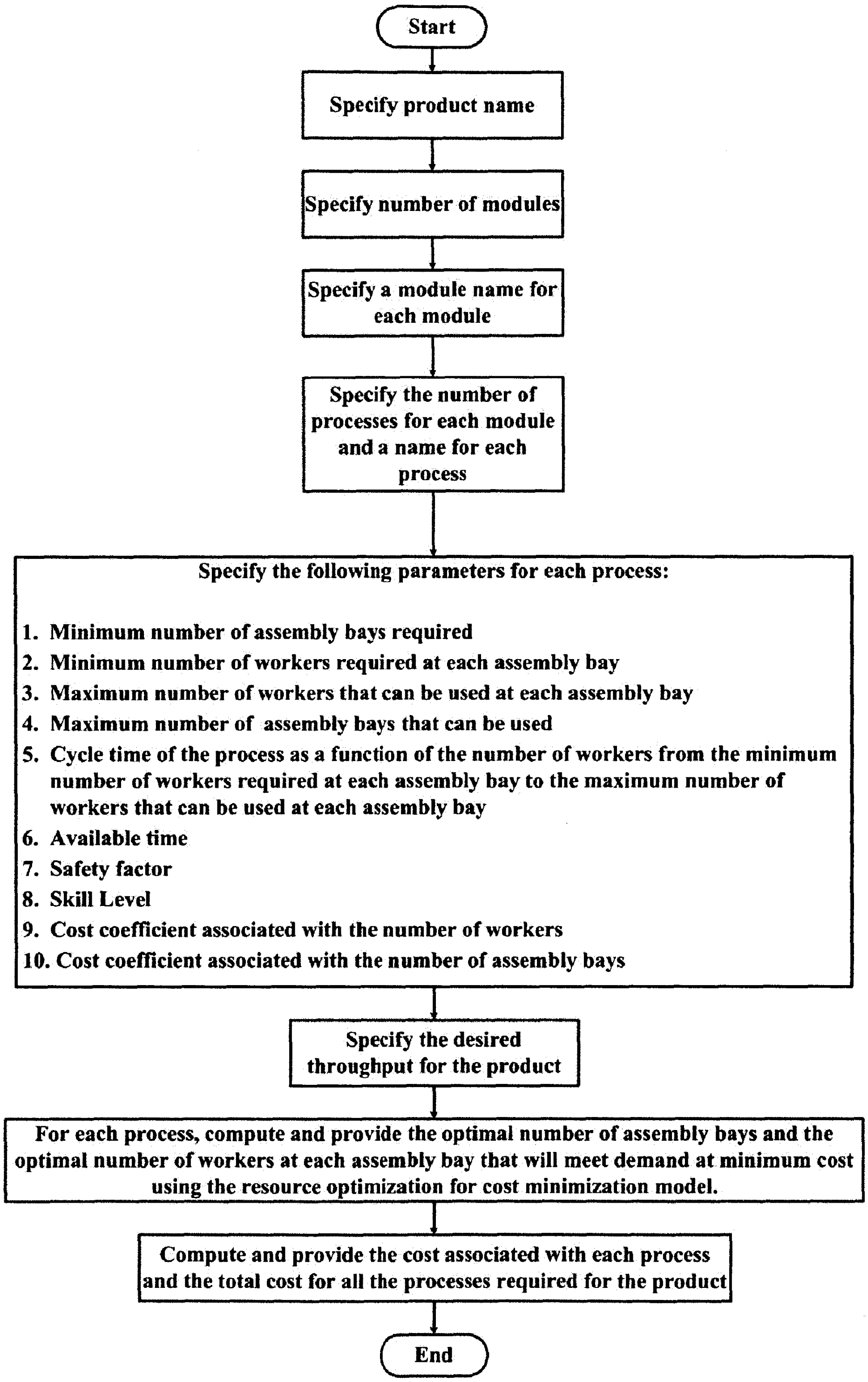

Figure 5-3: Functional Architecture for the Resource Optimization Part

As can be seen in Figure 5-3, the first part of the software program asks the user to specify the various parameters that would be required for the resource optimization for cost minimization model. Once the optimization is performed, the results of the optimization, that is, the number of assembly bays and number of workers per assembly bay required for each process to meet demand at minimum cost is presented to the user. The user is also presented with the cost for each process and the total cost of all the processes required for the product. The results and parameters obtained from the first part of the software program are then carried over to the second part as described in Chapter 6.

5.6 Summary

In this chapter, we developed the resource optimization for cost minimization model subject to a production capacity constraint. We defined a process cost function as the sum of the labor cost and assembly bay cost associated with the process and we aimed to minimize this process cost subject to certain constraints. We developed constrained problems and the solution techniques to solve those problems were outlined. We also developed an alternate problem statement to allow Varian to measure its current production floor performance and described the usage of that problem statement. We performed a numerical experiment to illustrate the working of the resource optimization model and presented the architecture for a software program to enable Varian to utilize this model efficiently.

Chapter 6

Labor Cost Minimization

In this chapter, we develop an optimization model for minimizing labor cost through the optimal allocation of regular time[20] and overtime[21] for the various module production lines at Varian. As indicated in Chapter 1, labor cost minimization is one of the four major topics of this thesis and is an extension of the resource optimization for cost minimization model presented in Chapter 5.

This chapter is organized as follows. The problem statement is outlined and a model of Varian's production line is detailed is Section 6.1. The problem formulation is introduced and the solution techniques are described in Section 6.2. Two alternate scenarios for the usage of the model are detailed in Section 6.3. Numerical results and analysis are provided in Section 6.4 to show the accuracy and efficiency of the model developed. The architecture for the software program to enable Varian to utilize this model is presented in Section 6.5.

6.1 Problem Statement and Model of Varian's Line

A detailed description of Varian's production line has already been provided in Chapter 2 and Chapter 5. The number of effective workers required to meet demand at minimum cost for each process can be determined using the resource optimization for cost minimization model presented in Chapter 5. The primary problem that is being addressed in this chapter is the optimization of labor cost through the optimal allocation of regular time and overtime for the given number of effective workers that is required for each process.

[20] Regular time is the number of hours paid for at the regular hourly rate and is 40 hours per week per worker
[21] Overtime is the number of hours paid for at one and a half times the regular hourly rate

6.1.1 Problem Statement

Varian's manufacturing competitiveness is derived, in part, to the availability of an experienced and dedicated workforce around Gloucester, Massachusetts, where its production plant is located. As already described earlier in chapters 1 and 5, the semiconductor capital equipment industry is highly sporadic and demand variability is high. Hence, Varian's manufacturing management team has to continuously make complex personnel decisions that will affect their ability to meet demand.

The resource optimization model detailed in Chapter 5 will aid Varian's Manufacturing Management team in making resource allocation and capacity planning decisions. However, in addition to the number of effective workers that would be required to meet demand for each process at minimum cost, the optimal combination of regular time and overtime to meet demand at minimum cost will allow Varian to make more informed personnel decisions.

Therefore, in order to be able to meet demand at minimum labor cost, the following problem statement was developed address the issue of resource allocation:

- Given the number of effective workers required to meet demand (products/week) at minimum cost for each process, what is the optimal combination of regular time and overtime that will yield minimum cost and hence maximum profit?

The relationship between regular time, overtime, cost, and capacity for each process is illustrated in Figure 6-1. As illustrated by Figure 6-1, the amount of regular time and overtime defines the capacity of each process at Varian. The amount of regular time and overtime also defines the cost of each process and hence, optimization of between regular time and overtime to meet demand at minimum cost is useful.

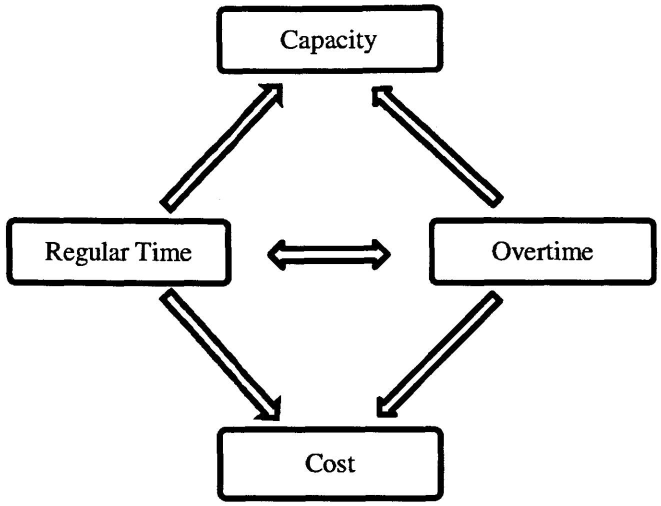

Figure 6-1: The relationship between capacity, regular time, overtime, and cost for a process

Similar to the resource optimization model, the problem statement described above also represents a critical question that Varian's manufacturing managers must answer every week while making resource allocation and capacity planning decisions. As with the resource optimization model, this problem statement also aims to provide a data-driven systems approach to personnel decisions that Varian currently uses its vast manufacturing experience to make.

6.1.2 Model of the line, Assumptions and Notations

As the labor cost optimization problem statement is an extension of the resource optimization for cost minimization model, the same model of the line, assumptions and notations as described in Section 5.1 of Chapter 5 are used here. In addition, several new notations are also introduced in this model.

The number of effective workers required to meet demand at minimum cost for Process, P_j, is given by W_j as determined from Equation (5-5) mentioned in Chapter 5. The number of workers currently available for Process, P_j, is denoted by N_j and the number of regular work hours per worker per week for Process, P_j, is denoted by h_j (hours/week). The number of regular time hours per week for Process, P_j, is denoted by R_j and the number of overtime hours per week for Process, P_j, is denoted by V_j. Finally, the number of regular workers per week for Process, P_j, is denoted by E_j.

The Labor Cost per week of Process, P_j, is defined as

Labor Cost = Regular Time Cost + Overtime Cost + Cost of Benefits + Overhead costs associated with labor

This may be formulated as

$$\text{Labor Cost} = r_j . R_j + (1.5)^{22} . r_j . V_j + (0.28)^{23} \{r_j . R_j + (1.5) . r_j . V_j\} + T$$

where, (6-1)

$r_j > 0$ (\$/regular time hour) is the cost coefficient associated with the number of Regular Time hours, R_j.

T (\$/week) stands for the overhead costs associated with labor.

Since Z is independent of number regular time hours and overtime hours, we simplify Equation (6-1) and write our objective function as

$$L_j(R_j, V_j) = r_j . R_j + (1.5) . r_j . V_j + (0.28) . \{r_j . R_j + (1.5) . r_j . V_j\} \qquad (6\text{-}2)$$

where,

L_j is defined as the Labor Cost per week of Process, P_j.

[22] At Varian, overtime is paid at one and a half times the cost of the regular hourly rate
[23] At Varian, the cost of benefits is calculated as 28% of the total salaries paid per week.

6.2 Problem Formulation and Solution Technique

In this section, we introduce the mathematical model that is used to optimize the mix of regular time and overtime to meet demand requirements at minimum cost. We also introduce the solution technique that is going to be used to obtain the optimum values and two different scenarios that Varian can use for optimization.

6.2.1 Constrained Problem and Solution Technique

The primary goal is a constrained problem where we aim to minimize the labor costs of each process, P_j, subject to an effective work hours constraint. The constrained problem is formulated as follows

$$\begin{aligned} \text{Minimize} \quad L_j(R_j,V_j) &= r_j \,.\, R_j + (1.5) \,.\, r_j \,.\, V_j + (0.28) \,.\, \{r_j \,.\, R_j + (1.5) \,.\, r_j \,.\, V_j\} \\ \text{subject to} \quad R_j + V_j &\geq W_j \,.\, h_j \end{aligned} \tag{6-3}$$

where W_j is the number of effective workers required as determined from the resource optimization model described in chapter 5.

The constraint in this problem is defined as the effective work hours constraint where W_j is the effective number of workers required per week for process, P_j, and h_j, is the number of regular hours per week per worker for Process, P_j.

The problem illustrated in Equation (6-3) consists of a linear objective function subject to a linear constraint and hence can be easily solved using one of the numerous commercial or open-source linear optimization solvers available on the market.

Once the optimal values of R_j and V_j have been determined, the number of regular workers required, E_j, and the overtime fraction, f_j can be determined as follows

$$\text{Regular Workers required,} \quad E_j = \frac{R_j}{h_j} \tag{6-4}$$

$$\text{Overtime fraction,} \quad f_j = \frac{V_j}{E_j \,.\, h_j} \tag{6-5}$$

6.3 Scenarios for Optimization

As mentioned earlier, Varian derives its manufacturing competitiveness from its workforce and personnel decisions are complex and must weigh a number of different factors. Hence, in order to simplify the decision making process for Varian, two scenarios have been developed that can be used by Varian for optimization.

6.3.1 Regular Workers is constrained by Available Workers

In the first scenario, the number of regular workers, E_j, for process, P_j, is constrained by the number of available workers, N_j, on the production floor for that process. Hence, in this scenario, the number of regular time hours is set as $R_{j\,avail} \leq N_j \cdot h_j$ (hours/week) where $R_{j\,avail}$ is defined as the number of regular time hours that can be performed by the available workers for that process.

Therefore, in this scenario, the constrained problem is formulated as

$$\text{Minimize} \quad L_j(R_{j\,avail}, V_j) = r_j \cdot R_{j\,avail} + (1.5) \cdot r_j \cdot V_j + (0.28) \cdot \{r_j \cdot R_{j\,avail} + (1.5) \cdot r_j \cdot V_j\}$$

$$\text{subject to} \quad R_{j\,avail} + V_j \geq W_j \cdot h_j \qquad (6\text{-}6)$$

$$R_{j\,avail} \leq N_j \cdot h_j$$

where W_j is the number of effective workers required as determined from the resource optimization model described in chapter 5

N_j is the number of workers available on the production floor to perform that process.

This constrained problem will provide the number of regular time hours and overtime hours required for process, P_j, that is required to meet demand at the minimum cost subject to the number of workers available to perform that process. The overtime fraction for this scenario can be calculated using equation (6-5) mentioned earlier. The labor cost for the process will also be provided to Varian and Varian's manufacturing management team can make informed personnel decisions based on the results of this model.

6.3.2 Number of Regular workers is unconstrained

In this scenario, the number of regular workers, E_j, and hence the number of regular hours, R_j, is unconstrained. This results in the same optimization problem as described in (6-3) and the number of regular workers and overtime fraction can be calculated using Equations (6-4) and (6-5) described earlier.

This scenario will allow Varian's Manufacturing Management team to determine the minimum cost condition to meet the demand for a process, P_j, and can be used by them to make personnel decisions in conjunction with the results obtained from the first scenario.

The accuracy and efficiency of the models developed in this chapter will be illustrated through a numerical experiment presented in Section 6.4.

6.4 Numerical Experiment and Results

For the demonstration of the working of the labor cost minimization model mentioned in Equations (6-3) and (6-6) of this chapter, the results from the numerical experiments run with the resource optimization model for the Gas Box build performed in Chapter 5 is utilized. Once again, the process is denoted as P_1 and all subsequent notations are used accordingly.

6.4.1 Parameters used for Numerical Experiment

The different parameters[24] used in the demonstration of Equations (6-3) and (6-6) are detailed in Table 6-1.

Table 6-1: Parameters for Gas Box build used in the Numerical Experiment

Notation	Calculation Method	Value
Process, P_1	-	Gas Box build
Number of Effective Workers Required, W_1	From Resource Optimization Model	2
Number of Regular Hours per Worker, h_j	Empirical	40 hours/week
Cost coefficient associated with the number of regular time hours, r_j	Empirical	\$255 / hour
Number of workers available, N_1	Assumed	1

We determined the parameters detailed in Table 6-1 through observations of Varian's production floor and through interviews with Varian's manufacturing team.

6.4.2 Optimization and Results

The labor cost minimization models developed in this chapter are used in the optimization for two scenarios as described in the chapter. Equations (6-3) and (6-6) are shown here as a reminder.

[24] Some parameters have been scaled to protect confidential information.

When the number of regular workers is unconstrained,

$$\text{Minimize} \quad L_j(R_j, V_j) = r_j \,.\, R_j + (1.5) \,.\, r_j \,.\, V_j + (0.28) \,.\, \{r_j \,.\, R_j + (1.5) \,.\, r_j \,.\, V_j\}$$

$$\text{subject to} \quad R_j + V_j \geq W_j \,.\, h_j \qquad (6\text{-}3)$$

where W_j is the number of effective workers required as determined from the resource optimization model.

When the number of regular workers is constrained by the number of available workers,

$$\text{Minimize} \quad L_j(R_{j\,avail}, V_j) = r_j \,.\, R_{j\,avail} + (1.5) \,.\, r_j \,.\, V_j + (0.28) \,.\, \{r_j \,.\, R_{j\,avail} + (1.5) \,.\, r_j \,.\, V_j\}$$

$$\text{subject to} \quad R_{j\,avail} + V_j \geq W_j \,.\, h_j \qquad (6\text{-}6)$$

$$R_{j\,avail} \leq N_j \,.\, h_j$$

where W_j is the number of effective workers required as determined from the resource optimization model.

N_j is the number of workers available on the production floor to perform that process.

The solutions to Equations (6-3) and (6-4) with their corresponding labor costs that will meet the constraints for a W_1 value of 2 workers and N_1 value of 1 are detailed in Table 6-2.

As can be seen from Table 6-2, when the number of regular workers is unconstrained, values for number of regular time hours, R_1, and number of overtime hours, V_1, that will meet the required demand are 80 hours and 0 hours respectively. The minimum cost for this process in order to meet demand is $26112.

Table 6-2: Labor Cost Minimization Solutions for the Gas Box Build Process

Scenario	Number of regular time hours, R_1	Number of overtime hours, V_1	Number of regular workers, E_1	Overtime fraction, f_1	Labor cost, L_1
Number of regular workers is unconstrained	80	0	2	0	\$26112
Number of regular workers is constrained by the number of available workers	40	40	1	100	\$28766

As illustrated in Table 6-2, when the number of regular workers is constrained by the number of available workers, the value for number of overtime hours, V_1 that will meet the required demand is 40 hours. The cost for this process in order to meet demand is \$28766.

Hence, this illustrates the usage of the labor cost minimization model in making personnel decisions.

6.5 Architecture for the Software Program

The second part of the software program introduced in Chapter 5 corresponds with the labor cost minimization model developed in this chapter. The parameters and results obtained from the first part of the software program as descried in Chapter 5 will be used in this part. The parameters and results obtained in this part will be used subsequently in the third part. The chart illustrated in Figure 6-2 shows the functional architecture of the software program for the second part.

As can be seen in Figure 6-2, the second part of the software program uses the parameters and results from the first part of the software program. In addition, the second part asks the user to specify the various parameters that would be required for the labor cost minimization model. Once the optimization is performed, the results of the optimization, that is, the number of regular time hours, number of overtime hours, number of regular workers and overtime fraction required to meet demand at minimum cost when the number of regular workers is unconstrained and when the number of regular workers is constrained by the number of available workers is presented to the user.

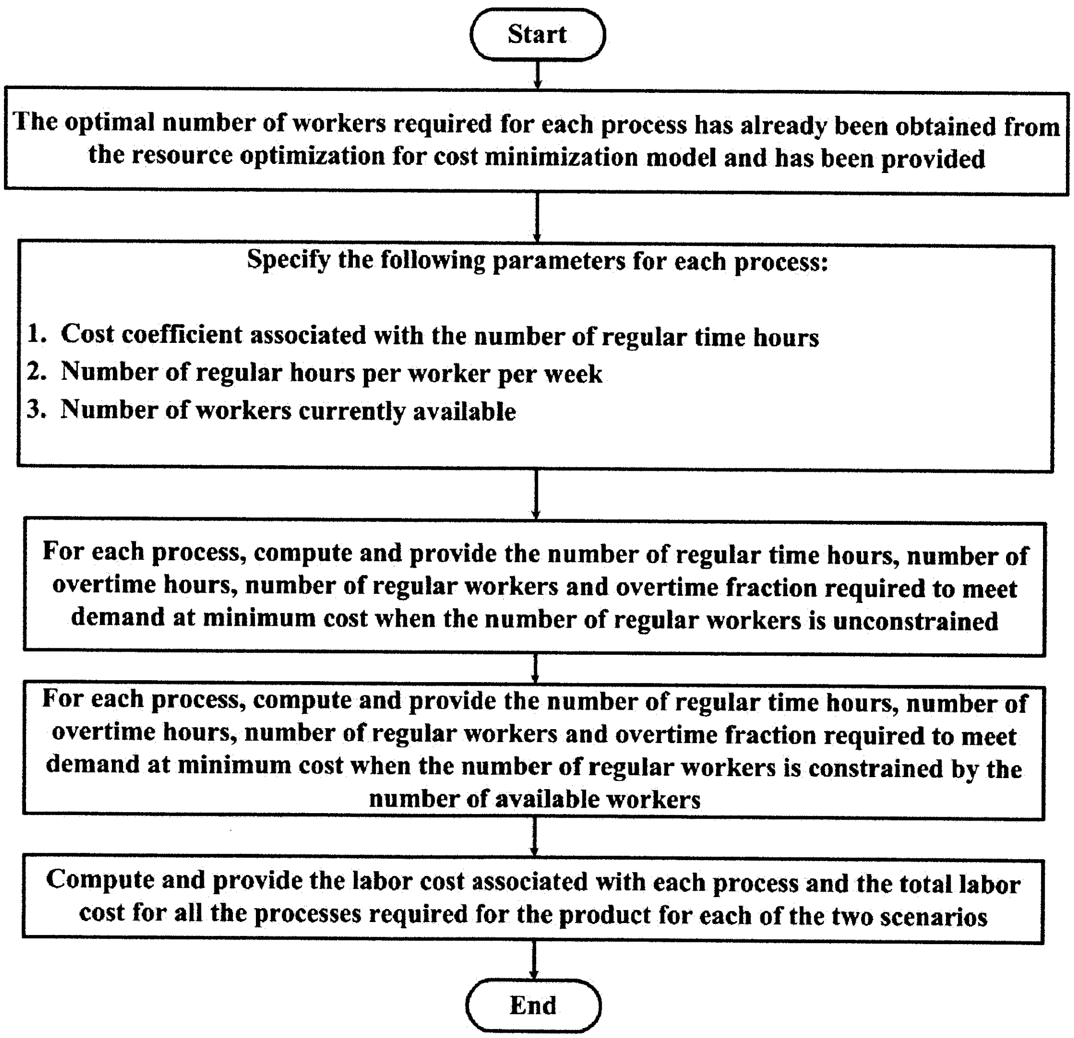

Figure 6-2: Functional Architecture for the Labor Cost Minimization Part

The user is also presented with the labor cost for each process and the total labor cost of all the processes required for the product for each of the two scenarios. The results and parameters obtained from the first part of the software program and the second part of the software program are then carried over to the third part that is presented in Chapter 7.

6.6 Summary

In this chapter, we developed a labor cost minimization model subject to a required effective work hours constraint. We defined Labor cost as the sum of regular time cost, overtime cost and the cost of benefits and we aimed to minimize labor cost subject to certain constraints. We developed a constrained problem where the number of regular workers is unconstrained and the solution technique for that problem was outlined. We also developed an alternate problem where the number of regular workers is constrained by the number of available workers and the solution technique for that problem was outlined as well. We performed a numerical experiment to illustrate the working of the labor cost minimization model and presented the architecture for a software program to enable Varian to utilize this model efficiently.

Chapter 7

Labor Flexibility

In this chapter, we develop a labor flexibility framework and an optimization model for minimizing the total cost of work hours to be provided to Varian's production plant through the optimal movement of workers across the production processes at Varian. As described in Chapter 1, labor flexibility[25] is one of the four major topics of this thesis and is a pressing issue facing Varian owing to the sporadic nature of the semiconductor capital equipment industry. The labor flexibility framework and optimization model presented in this chapter is to be used in conjunction with the resource optimization model developed in Chapter 5 and the labor cost minimization model developed in Chapter 6 to improve Varian's manufacturing competitiveness.

This chapter is organized as follows. The problem statement is outlined, the labor flexibility framework is introduced and the model of the line is presented in Section 7.1. The problem formulations are introduced, the solution techniques are described and the limitations of the models in their current form are outlined in Section 7.2. An implementation plan for the labor flexibility framework is presented in Section 7.3. Numerical results and analysis are provided in Section 7.4 to show the accuracy and efficiency of the model developed. The architecture for the software program to enable Varian to utilize this model is presented in Section 7.5.

7.1 Problem Statement and Labor Flexibility Framework

A detailed description of Varian's production line has already been provided in Chapters 2, 5 and 6. The number of regular workers and the corresponding number of overtime hours required to meet demand at minimum cost for each process can be determined using the labor cost

[25] Labor Flexibility, at Varian, is defined as the ability of the workforce to move across processes in the production plant.

minimization model presented in Chapter 6. The primary problem that is being addressed in this chapter is the minimization of the total cost of work hours to be provided to Varian's production plant through the optimal movement of regular workers across the various production processes at Varian.

7.1.1 Problem Statement

As described in Chapter 6, Varian's manufacturing competitiveness is derived, in part, from its experienced and dedicated workforce. As already described earlier in chapters 1, 5 and 6, the semiconductor capital equipment industry is highly sporadic requiring Varian's manufacturing management team has to continuously make personnel decisions that will affect their ability to meet demand and maintain the effectiveness of their workforce.

Currently, Varian's workforce flexibility is constrained significantly by module. Each worker is assigned to a particular process within a module build area and is moved only to other processes within the same module build area. There is also lack of clear visibility regarding the ability of workers to perform different processes in the production plant and there is also lack of clear visibility regarding the skills that each process would require. Varian's manufacturing management team currently rely heavily on their module production supervisors to make assignments of workers to processes. We also observed that there is resistance amongst the module production supervisors to allow workers to move across modules to perform processes. Hence, it is highly critical that a framework is developed that provides Varian's manufacturing management team with the ability to enable workforce flexibility.

Therefore, in order to be able to meet demand with the minimum cost of work hours to be provided, the following problem statement was developed:

- Given the number of effective workers required to meet demand at minimum cost, what is the optimal movement of workers that will yield minimum cost and hence maximum profit?

The problem statement described above represents a highly critical question that Varian's manufacturing managers would like to address and workforce flexibility has been a dominant topic of discussion amongst Varian's manufacturing management team.

7.1.2 Labor Flexibility Framework

In order to address the problem statement presented above, a labor flexibility framework was developed that would allow Varian's workforce to move across processes efficiently and effectively.

Based on observations at Varian, we discovered that several processes across different module build areas required a similar set of skills and could be grouped together to form a specific skill level. We later discovered that this was true for all the processes at Varian and hence, that it would be possible all of the processes into a finite set of distinct skill levels with each skill level requiring a specific set of skills.

We also discovered that workers performing different processes across the plant could also be grouped according to the same skill levels as for the processes. This was because workers having the skills to perform one process could perform another different process that required a similar set of skills as the first. So, workers in a specific skill level could perform all the processes in that skill level with minimum training or initiation as they already possessed the skills required to perform all the processes.

We also recognized that workers performing processes that required advanced-level skills could perform processes that required beginner-level skills and that this could be used to enable further flexibility in the plant. Finally, we learned that Varian has a thorough set of operating instructions for the various processes being performed in the plant and we concluded that this would minimize the initiation that a worker would require to move across processes as long as the worker possessed the necessary skills.

Hence, a labor flexibility framework was developed that would allow the grouping of processes according to the skill levels that would be necessary to perform them. The workers on the production floor would also be classified into the same system of grouping allowing workers grouped in the same skill level to perform all the processes grouped in that skill level.

As mentioned earlier, we discerned that workers in a higher skill level would be able to perform processes in a lower skill level thereby allowing for downward vertical movement across skill levels in addition to the horizontal movement across the same skill level.

Four distinct skill levels were proposed as follows

- *Skill Level One* This is the beginner skill level and workers in this skill level can perform processes that require beginner level skill sets. Workers in this skill level cannot move upward to perform processes that require higher skill levels.

- *Skill Level Two* This is the intermediate skill level and workers in this skill level can perform processes that require intermediate skill sets. Workers in this skill level can move downward to perform processes that require level one skill sets but cannot move upward to perform processes that require higher skill levels.

- *Skill Level Three:* This is the advanced skill level and workers in this skill level can perform processes that require advanced skill sets. Workers in this skill level can move downward to perform processes that require level one and level two skill sets but cannot move upward to perform processes that require a special skill level.

- *Skill Level Special:* This is a special skill level and workers in this skill level can perform processes that require special skill sets. Workers in this skill level are dedicated and do not move vertically across skill sets. The number of special skill levels need to be equal to the number of distinct special processes. For the purposes of this thesis, only one special skill level has been defined. We propose that Varian define as many special skill levels as they have distinct special processes to ensure that every special process will have the requisite number of workers available to perform it.

Based on observations on Varian's production floor and discussions with Varian's module production supervisors, production floor workers and manufacturing management team, we classified the current production processes according to the skill levels outlined in this chapter. The labor flexibility table is shown in Table 7-1 illustrates the usage of labor flexibility to classify processes at Varian.

Table 7-1: Sample Labor Flexibility Table for Varian's Production Processes

Skill Level	**Process**
Level S	UES Air Bearing
Level 3	UES Integration, UES Harnessing, Tool Control Rack
Level 2	90 Module, Beamline Module, Terminal Module, UES Top Chamber, UES Bottom Chamber, UES Wafer Handler
Level 1	Gas Box module, Facilities module, UES Electronics Control Rack, 70 Module, UES HLA Frame

As can be seen from Table 7-1, the labor flexibility framework allows for processes that require the same skill levels to be grouped together although they may be performed in different module build areas. This allows for the pool of workers who are classified in a particular level to perform any process in that level without being constrained to a particular module build area. Table 7-1 only classifies the production build processes but similar classifications can be done for test and shipping prep processes as well.

To illustrate the advantages of the skills classification framework, the current production floor situation is compared with the skills classification framework. Currently, a worker performing the 90 degree module build process will not be moved to perform a process in the UES module build area and vice versa. However, in the labor flexibility table shown in Table 7-1, it can be seen that a worker who can perform the 90 degree module build process can be moved to several other processes in other module build areas allowing for more fluid flexibility of the workforce as well as clear visibility of the workforce's flexibility to Varian's manufacturing management team.

We concluded that, while it will be highly useful to use skill levels to classify processes and workers, it might be imprudent to use the same terminology to identify groups of workers and processes. This is because of the morale impact on the workers due to being classified into a lower or higher skill level. Instead, we believe that a neutral naming system for the skill levels would enable Varian to extract the benefits from the skill level classification while avoiding impact to worker morale. We developed a sample neutral naming system for the skill levels as illustrated in Table 7-2.

Table 7-2: Sample Neutral Naming System for the Skill Levels

Skill Level	**Level Name**
Level S	Team Green
Level 3	Team Blue
Level 2	Team Red
Level 1	Team Yellow

Through the use of a neutral naming system, as shown in Table 7-2, Varian will be able to enable labor flexibility without the impact on worker morale from being classified according to their skill levels. A neutral naming system can also create a sense of belonging and comradeship amongst members of a team, improving worker morale. Finally, a neutral naming system will allow Varian's manufacturing management to have clear visibility of the labor flexibility.

This labor flexibility framework is extended to develop a labor flexibility optimization model that can be used in conjunction with the resource optimization model and labor cost minimization model to optimize Varian's production floor and to minimize their production costs.

7.1.3 Model of the line, Assumptions and Notations

As the labor flexibility problem statement is an extension of the resource optimization for cost minimization model and the labor cost minimization model, the same model of the line, assumptions and notations as described in Section 5.1 of Chapter 5 and Section 6.1 of Chapter 6 are used here. In addition, several new notations are also introduced in this model.

The number of effective workers required to meet demand at minimum cost for Process, P_j, is given by W_j as determined from Equation (5-5) mentioned in Chapter 5. The number of regular workers required to meet demand at minimum cost for Process, P_j, is given by E_j as determined from Equations (6-3) and (6-4) mentioned in Chapter 6. The number of regular work hours per week is denoted as h_j (hours/week).

The number of Level 1 work hours to be provided to the production plant is denoted by Z_1, the number of Level 2 work hours to be provided to the production plant is denoted by Z_2, the number of Level 3 work hours to be provided to the production plant is denoted by Z_3 and the number of Special Level work hours to be provided to the production plant is denoted by Z_S.

The number of Level 1 workers required to meet demand is denoted by X_1 and is summation of the number of effective workers required to perform all Level 1 processes. The skill level required for each process is to be specified as a parameter in the resource optimization model and so the value of W_j calculated for each Level 1 process will be summed to determine X_1. That is

$$X_1 = \sum W_j \text{ (of Level 1 processes).}$$

The number of Level 2 workers required to meet demand is denoted by X_2, the number of Level 3 workers required to meet demand is denoted by X_3 and the number of Special Level workers required to meet demand is denoted by X_S. As with the case of X_1:

$$X_2 = \sum W_j \text{ (of Level 2 processes)}$$

$$X_3 = \sum W_j \text{ (of Level 3 processes)}$$

$$X_S = \sum W_j \text{(of Level S processes)}$$

Hence, the total cost of work hours to be provided to Varian's production plant is denoted by M and we write our objective function as

$$M\,(Z_1, Z_2, Z_3, Z_S) \quad = \quad Z_1 \,.\, m_1 + Z_2 \,.\, m_2 + Z_3 \,.\, m_3 + Z_S \,.\, m_s \qquad (7\text{-}1)$$

where

$m_1 > 0$ (\$/hour) is the cost coefficient associated with number of Level 1 work hours

$m_2 > 0$ (\$/hour) is the cost coefficient associated with number of Level 2 work hours

$m_3 > 0$ (\$/hour) is the cost coefficient associated with number of Level 3 work hours

$m_S > 0$ (\$/hour) is the cost coefficient associated with number of Level S work hours

7.2 Problem Formulation and Solution Technique

In this section, we introduce the mathematical model that is used to minimize the total cost of work hours to be provided to Varian's production floor. We also introduce the solution technique that is going to be used to obtain the optimum values.

7.2.1 Constrained Problem and Solution Technique

The primary goal is a constrained problem where we aim to minimize the total cost of workers to be provided to Varian's production floor subject to minimum required work hours constraints.

The constrained problem is formulated as follows

$$\text{Minimize} \quad M(Z_1, Z_2, Z_3, Z_S) = Z_1 \cdot m_1 + Z_2 \cdot m_2 + Z_3 \cdot m_3 + Z_S \cdot m_s$$

$$\begin{aligned} \text{subject to} \quad Z_S &\geq X_S \cdot h_j \qquad\qquad (7\text{-}2) \\ Z_3 &\geq X_3 \cdot h_j \\ Z_3 + Z_2 &\geq X_3 \cdot h_j + X_2 \cdot h_j \\ Z_3 + Z_2 + Z_1 &\geq X_3 \cdot h_j + X_2 \cdot h_j + X_1 \cdot h_j \end{aligned}$$

The constrained problem described in Equation (7-2) consists of a linear objective function subject to linear constraints and hence can be easily solved using the various commercial or open–source linear optimization solvers available on the market.

7.2.2 Alternate Scenario – Based on Required Regular Workers

In order to enable effective decision making by Varian's manufacturing management team, an alternate optimization scenarios was developed where the number of required workers is based on the number of regular workers, E_j, required for each process, P_j as obtained from the labor cost minimization model described in Equations (6-3) and (6-4) in chapter 6.

In this scenario, the notations used for the number of workers to be provided remain the same as described in Section 7.1.3. However, new notations are introduced for the number of workers required to meet demand.

The number of Level 1 workers required to meet demand is denoted by Y_1 and is summation of the number of regular workers required to perform all Level 1 processes. The skill level required for each process is to be specified as a parameter in the resource optimization model and labor cost minimization model and so the value of E_j calculated for each Level 1 process will be summed to determine Y_1. That is:

$$Y_1 = \sum E_j \text{ (of Level 1 processes).}$$

The number of Level 2 workers required to meet demand is denoted by Y_2, the number of Level 3 workers required to meet demand is denoted by Y_3 and the number of Special Level workers required to meet demand is denoted by Y_S. As with the case of Y_1:

$$Y_2 = \sum E_j \text{ (of Level 2 processes)}$$

$$Y_3 = \sum E_j \text{ (of Level 3 processes)}$$

$$Y_S = \sum E_j \text{(of Level S processes)}$$

Hence, the total cost of work hours to be provided to Varian's production plant is denoted by M and we write our objective function as

$$M\ (Z_1, Z_2, Z_3, Z_S) \quad = \quad Z_1 \,.\, m_1 + Z_2 \,.\, m_2 + Z_3 \,.\, m_3 + Z_S \,.\, m_s \qquad (7\text{-}3)$$

where

$m_1 > 0$ (\$/hour) is the cost coefficient associated with number of Level 1 work hours

$m_2 > 0$ (\$/hour) is the cost coefficient associated with number of Level 2 work hours

$m_3 > 0$ (\$/hour) is the cost coefficient associated with number of Level 3 work hours

$m_S > 0$ (\$/hour) is the cost coefficient associated with number of Level S work hours

The primary goal of this scenario is similar constrained problem as before where we aim to minimize the total cost of work hours to be provided to Varian's production floor subject to minimum required workers constraints. The constrained problem is formulated as follows:

$$
\begin{aligned}
\text{Minimize} \quad & M(Z_1, Z_2, Z_3, Z_S) = Z_1 \,.\, m_1 + Z_2 \,.\, m_2 + Z_3 \,.\, m_3 + Z_S \,.\, m_s \\
\text{subject to} \quad & Z_S \geq Y_S \,.\, h_j \qquad (7\text{-}4) \\
& Z_3 \geq Y_3 .\, h_j \\
& Z_3 + Z_2 \geq Y_3 .\, h_j + Y_2 \,.\, h_j \\
& Z_3 + Z_2 + Z_1 \geq Y_3 .\, h_j + Y_2 .\, h_j + Y_1 \,.\, h_j
\end{aligned}
$$

The constrained problem described in Equation (7-4) also consists of a linear objective function subject to linear constraints and hence can be easily solved using the various commercial or open –source linear optimization solvers available on the market.

The two models described in Equations (7-2) and (7-4) will allow Varian to effectively make personnel decisions and can be used based on their requirements. The use of the models is illustrated in Section 7.4 through a numerical experiment. We understand that in their current condition, the two models described in Equations (7-2) and (7-4), have some limitations and these are described in the rest of this section.

7.2.3 Limitations of the Models

In this section, we developed two optimization models to minimize the total cost of work hours to be provided to Varian's plant. However, through the use of the models in the current condition, Varian would only be able to determine the number of required work hours or the number of regular work hours for each skill level. This is because, in the absence of any additional cost functions, the models shown in Equations (7-2) and (7-4) would provide the minimum cost solution as the number of required work hours or regular work hours for each skill level depending on the model being used. While, it is useful to Varian to know what the current minimum cost solution is, the models would be more complete if the following costs could be incorporated into the models.

- *Cross-training cost:* The cost of training a worker from one skill level to perform processes in another higher skill level would be useful to determine if it would be more cost-effective to training an existing worker or hire a new one.
- *Worker acquisition and release cost:* The cost of acquiring a new worker or releasing an existing worker would be useful to determine if it would be more cost-effective to move existing workers across processes or hire new ones as well as when it would be more cost-effective to release existing workers.

We believe that the modeling and quantification of the above mentioned costs for inclusion in the labor flexibility models would greatly enhance the effectiveness of the models and would be a prudent direction for future work as presented in Chapter 10.

7.3 Implementation Plan for Labor Flexibility Framework

The labor flexibility framework presented in Section 7.1.2 would require a culture shift from Varian's current production floor situation. Hence, we developed an implementation plan to ensure that the implementation of the labor flexibility framework is smooth and sustainable. The implementation of the labor flexibility framework is to be performed in five steps as illustrated in Figure 7-1. Each of the steps in the implementation plan is discussed in detail in the rest of this section.

7.3.1 Process Classification

Process Classification is the first step of the implementation plan where all the processes at Varian are classified into distinct skill levels. The processes can be classified using the information present in the standard operating procedure manuals for each process as well as using the experience of Varian's manufacturing team. It is important to ensure that grouping of processes is done based on the set of skills required and is not constrained by module, product or production floor location.

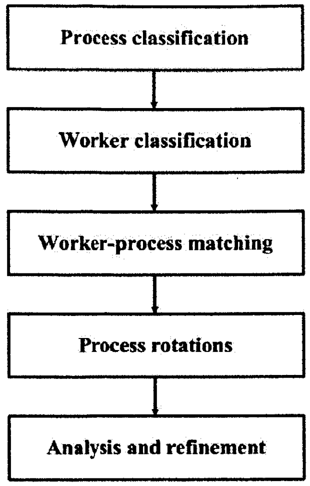

Figure 7-1: Labor Flexibility Implementation Plan

7.3.2 Worker Classification

Worker Classification is the second step of the implementation plan where all the workers are classified into the same distinct skill levels as for processes. The workers can be classified using the information present in their training and experience records as well as using the experience of Varian's manufacturing team and production floor supervisors.

7.3.3 Worker-process Matching

Worker-process matching is the third step of the implementation plant where the workers classified in the distinct skill levels are matched with the processes in that skill level. It is important to note that during worker-process matching, distinctions between need not be made within the same skill level and any worker can be matched to any process within the same skill level. This matching process is to be performed using the results from the optimization models presented in Equations (7-2) and (7-4). In the optimization models, higher skill levels are matched first and once all higher level processes are provided with workers, excess higher skill level workers may be provided to lower skill level processes till all processes have been staffed with workers.

7.3.4 Process Rotations

Process rotations is the fourth step of the implementation plan where workers within a skill level are rotated to different processes after a specific time period. The recommended time period is currently four weeks keeping in mind Varian's current production floor situation. In process rotations, as with worker-process matching, distinctions between need not be made within the same skill level and any worker can be matched to any process within the same skill level.

The process rotation step can be planned such that every worker in a specific skill level will be provided with an opportunity to perform every process in that skill level over a six-month or twelve-month time period. The process rotation step will ensure that every worker in a skill level will be able to perform every process in that skill level ensuring high flexibility in the workforce.

7.3.5 Analysis and Refinement

Analysis and refinement is the fifth and final step in the implementation plan where the classification of processes and workers is analyzed and refined based on the experience of the manufacturing team with the first four steps of the implementation plan. This step will ensure that the implementation of the labor flexibility framework is sustainable and effective as the framework is continuously refined based on Varian's experience with it.

The successful implementation of the labor flexibility framework through the use of the implementation plan outline in this section will allow Varian to improve its manufacturing competitiveness and meet demand at minimum cost.

7.4 Numerical Experiment and Results

For the demonstration of the working of the labor flexibility model mentioned in Equation (7-2) of this chapter, the values for required parameters were assumed as those parameters were not available for a complete product at the time of writing this thesis. Equation (7-2) is used for this demonstration as both Equations (7-2) and (7-4) work in the same manner and differ only by the numerical values of their respective parameters.

7.4.1 Parameters used for Numerical Experiment

The different parameters used in the demonstration of Equation (7-2) are detailed in Table 7-3.

Table 7-3: Parameters used in the Numerical Experiment for Labor Flexibility

Notation	Calculation Method	Value
The number of Level 1 workers required, X_1	Assumed	10
The number of Level 2 workers required, X_2	Assumed	16
The number of Level 3 workers required, X_3	Assumed	12
The number of Level S workers required, X_S	Assumed	4
Cost coefficient associated with the number of Level 1 work hours, m_1	Assumed	$200/hour
Cost coefficient associated with the number of Level 1 work hours, m_2	Assumed	$237.5/hour
Cost coefficient associated with the number of Level 1 work hours, m_3	Assumed	$275/hour
Cost coefficient associated with the number of Level 1 work hours, m_S	Assumed	$287.5/hour
Number of Regular Hours per Worker per week, h_j	Empirical	40 hours

As mentioned before, the parameters detailed in Table 7-3 were created solely for the purposes of this demonstration and do not reflect actual values. However, we believe that they will be satisfactory in demonstrating the working of the labor flexibility model.

7.4.2 Optimization and Results

The labor flexibility model developed in this chapter is used in this optimization. Equation (7-2) is shown here as a reminder.

When the number of required workers is based on the number of effective workers required,

$$
\begin{aligned}
\text{Minimize} \quad M(Z_1, Z_2, Z_3, Z_S) &= Z_1 \cdot m_1 + Z_2 \cdot m_2 + Z_3 \cdot m_3 + Z_S \cdot m_s \\
\text{subject to} \quad Z_S &\geq X_S \cdot h_j \\
Z_3 &\geq X_3 \cdot h_j \\
Z_3 + Z_2 &\geq X_3 \cdot h_j + X_2 \cdot h_j \\
Z_3 + Z_2 + Z_1 &\geq X_3 \cdot h_j + X_2 \cdot h_j + X_1 \cdot h_j
\end{aligned}
\tag{7-2}
$$

The solution to Equations (7-2) that will meet the constraints for the given parameters is detailed in Table 7-4.

As can be seen from Table 7-4, when the number of required workers is based on the number of effective workers required, values for number of Level 1 work hours, Z_1, number of Level 2 work hours, Z_2, number of Level 3 work hours, Z_3, and number of Level S work hours, Z_S that will meet the required demand are 400 hours, 640 hours, 480 hours and 160 hours respectively.

Table 7-4: Labor Flexibility Solution

Notation	Value
The number of Level 1 work hours to be provided, Z_1	400 hours
The number of Level 2 work hours to be provided, Z_2	640 hours
The number of Level 3 work hours to be provided, Z_3	480 hours
The number of Level S work hour to be provided, Z_S	160 hours
The total cost of the work hours to be provided, M	$410,000 / week

Hence, this illustrates the usage of the labor flexibility minimization model in making personnel decisions.

7.5 Architecture for the Software Program

The third part of the software program introduced in Chapters 5 and 6 corresponds with the labor flexibility model developed in this chapter. The parameters and results obtained from the first and second part of the software program will be used in this part. The chart illustrated in Figure 7-2 shows the functional architecture of the software program for the third part.

As can be seen in Figure 7-2, the third part of the software program uses the parameters and results from the first and second part of the software program presented in Chapters 5 and 6 and does not require any additional parameters from the user.

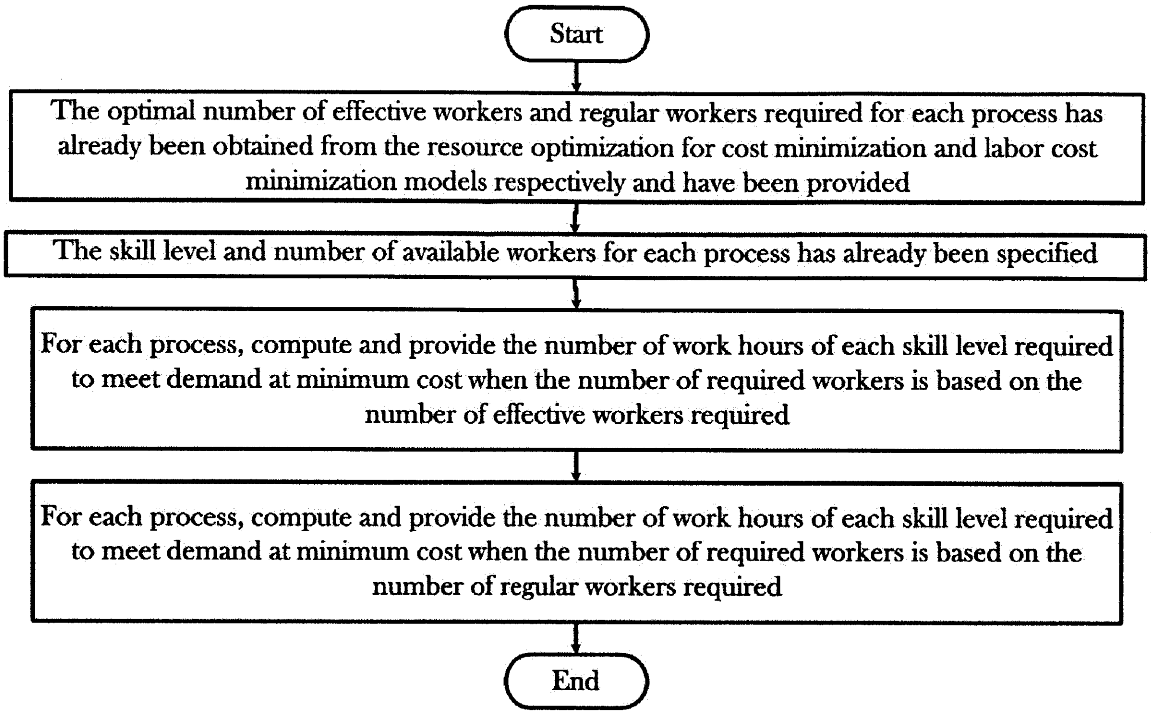

Figure 7-2: Functional Architecture for the Labor Flexibility Part

Once the optimization is performed, the results of the optimization, that is, the number of work hours at each skill level required to meet demand at minimum cost when the number of required workers is based on the number of effective workers required and when the number of required workers is based on the number of regular workers required is presented to the user.

Hence, the three parts of the software program will provide the user with comprehensive information to make resource allocation, capacity planning and personnel decisions.

7.4 Summary

In this chapter, we developed a labor flexibility model subject to a required effective workers constraint. We also introduced the labor flexibility framework and illustrated its usage. We developed two alternate constrained problems and the solution techniques for each of those problems were outlined. We presented the limitations of the two models and identified scope for future research. We also presented an implantation plan for the labor flexibility framework. We performed a numerical experiment to illustrate the working of the labor cost minimization model and presented the architecture for a software program to enable Varian to utilize this model efficiently.

Chapter 8

Gold Squares Inventory Management

In this chapter[26], we describe the gold square inventory management system that is used at Varian to manage the high-volume assemblies made in the supermarket build area, the issues that arise due to its current structure and implementation, and the recommendations that were developed to address those issues.

This chapter is organized as follows. The gold square system is introduced, the deviations between the system that was planned and the system currently implemented are presented, and the issues that arise due to the current implementation of the gold squares are outlined in Section 8.1. The methodology used to address these issues and the analysis to identify the operating parameters of the recommended inventory system is presented in Section 8.2. The implementation plan, the challenges expected to be faced in implementing the new designed system, and the advantages of using the proposed gold square system are described in Sections 8.3 and 8.4 respectively.

8.1 Overview of the Current Gold Square Policy

The gold square inventory management system is utilized at Varian in order to manage and control high-volume assemblies that are assembled by Varian's Supermarket assembly area. The high-volume assemblies are standard assemblies that are required by almost all of the ion implantation machines manufactured by Varian and hence are needed with high frequency.

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[26] This chapter was written in collaboration with Ramachandran [1] and Wu [2] and a similar chapter can be found in their respective theses.

In this chapter, we analyze the gold square system used for the assemblies feeding the Universal End Station (UES) module of the ion implantation machines because their shortage would lead to starvation of the bottleneck UES line. The gold square systems used for the mixed module line is identical to the system used for the UES modules and hence the issues faced and the recommendations developed are applicable to the Gold Square system of the other modules as well.

8.1.1 Planned Gold Square System

The gold square inventory management system was planned as a signal-based, pull system where a set number of assemblies are placed in a specific rack location called a gold square and the withdrawal of each assembly triggers the build and replacement of that assembly on the Gold Square as detailed in Figure 8-1.

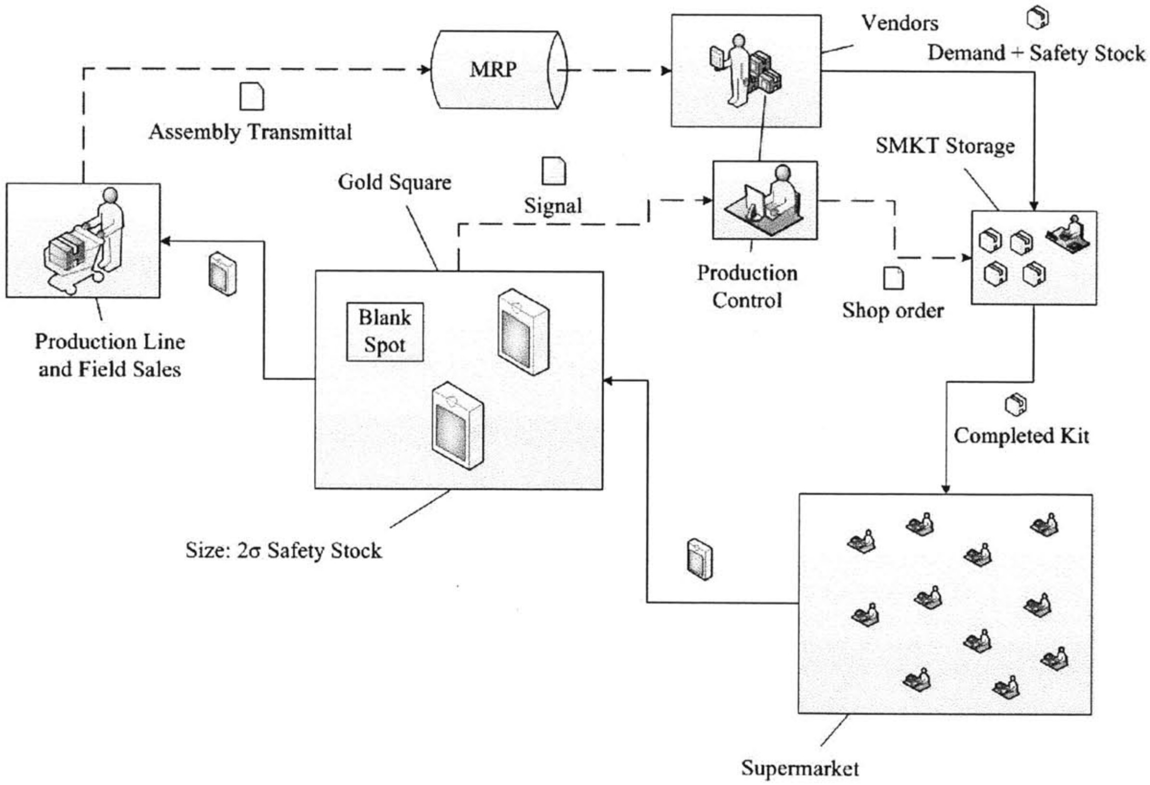

Figure 8-1: Planned Gold Square System at Varian

Each gold square is sized using the formula, 2σ, where σ is the standard deviation of the weekly demand forecast for that assembly over a three month time-frame. This is similar to the commonly used formula to determine inventory safety stock in industrial settings, $2*\sigma*\sqrt{L}$, where L is the lead time.

Once a gold square size has been determined, the number of assemblies equal to this size is held on the gold square. During production, when an assembly from gold square shelf is consumed, the blank spot caused by the removal of this assembly is the signal for the production control personnel at the supermarket assembly area to build and replace the assembly. It is important to note that this signal, however, is not instantaneous as the production control personnel only review the status of each gold square shelf at a specific time each day.

Once the production control personnel have determined that a gold square assembly is to be built, they issue a shop order which triggers the piece parts for that assembly to be picked from the supermarket storage area and delivered to an assembler at the supermarket assembly area. Once the assembler at the supermarket build area completes building the assembly, the finished assembly is placed on the gold square shelf bringing the number of assemblies on the gold Square back to its determined size.

An assembly on the gold square shelf may also be consumed for field sales wherein the assembly is taken from the gold square, packaged and shipped to a customer as a spare part. This process also triggers the same blank spot signal and involves the same replenishment process as if the assembly was consumed on the production line.

Once an assembly is consumed by the production line or by field sales, the production line or field sales personnel submit a transmittal which is a form used to inform the inventory control personnel in charge of updating Varian's MRP[27] system that the assembly has been consumed. This causes the inventory personnel control personnel to update the MRP system to reflect the consumption of the assembly. Once the MRP system has been updated, purchase orders are sent to Varian's vendors to replenish the piece parts needed to build another assembly subject to the weekly demand forecast. Hence, while the gold square system at Varian is planned

[27] MRP stands for Materials Requirements Planning

as a pull system, the piece part inventory is controlled by their MRP system. However the system that is currently implemented deviates from the planned system.

8.1.2 Currently Implemented Gold Square System

The gold square system that is currently implemented deviates from the planned system in a number of ways. It is not entirely a signal-based, pull system but is a combination of a signal-based, pull system and an MRP-driven, push system. The gold square system that is currently implemented is detailed in Figure 8-2.

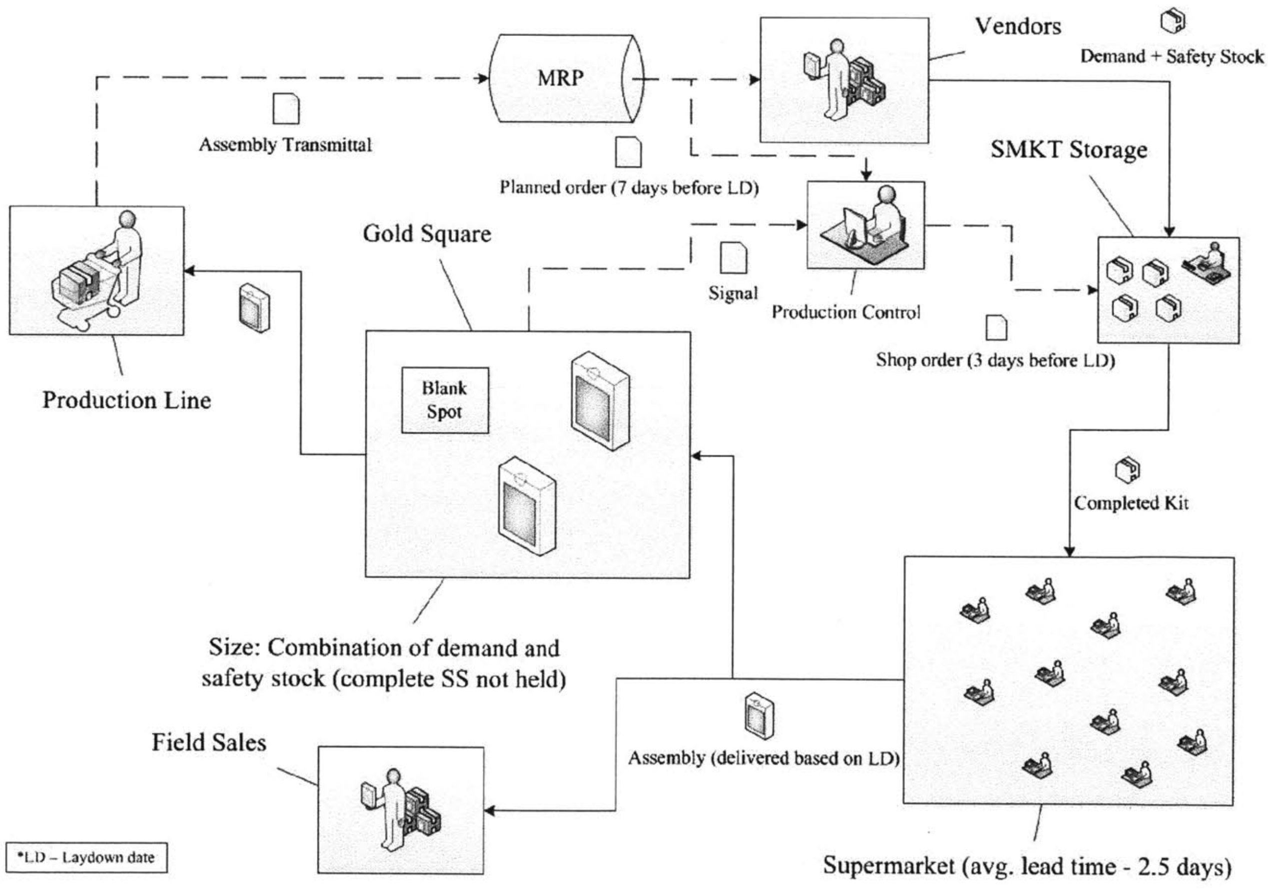

Figure 8-2: Currently Implemented Gold Square System at Varian

In the current system, each gold square shelf is still sized using the same formula as in the planned system. The production control personnel treat this quantity as roughly the upper limit for the inventory on the shelf. However, they also look at the forecasted demand for the coming week through MRP before deciding the quantity to be built. The production control personnel determine the number of assemblies to be built using a combination of the blank spot signal from the gold square and planned orders (orders that are created to meet production line or field sales demand forecasts) released by the MRP system. This causes the production control personnel to not only release shop orders to replace the blank spots on the gold squares but also to meet the planned orders as determined by MRP. Sometimes, production control personnel prioritize confirmed demand for an assembly over building up to the safety stock level of certain assemblies due to limited labor availability. To summarize, production control does not follow a systematic procedure to manage the gold square Assemblies, instead relying on their experience and MRP forecast to make build decisions.

Once a shop order is released, the same process as the planned system is followed and the assembly is built and placed on the gold square shelf. However, it is important to note that in the currently implemented system only the production line consumes assemblies directly from the gold square shelf and assemblies required by field sales are built, packaged and sent to shipping directly based on the MRP system's planned orders.

Once an assembly is consumed by the production line or by field sales, the production line or field sales personnel submit a transmittal to the inventory control personnel and the same process as for the planned system is followed.

8.1.3 Reasons for deviation from planned system

We investigated the planned and currently implemented system through interviews and discussions with the manufacturing management and personnel involved in the gold square system and were able to hypothesize the reason for the deviation of the current system from the planned system.

We hypothesized that the major cause for the deviation of the current system from the planned system is the suboptimal sizing and operating procedures for the gold squares. The formula that is used to size the gold squares, 2σ, does not take into consideration the demand that would be present during the lead time for the replacement of the assemblies. The formula used corresponds to safety stock which is meant to handle the variations in demand. Using this quantity as the upper limit on the inventory would lead to poor service levels. Hence, the production control personnel are required to refer to the MRP system's planned orders to ensure that demand can be met.

We validated the hypothesis through an analysis of the gold square sizes for different assemblies and through discussions with the production control personnel. It was determined that the production control personnel had to refer to MRP to ensure that demand from the production line could be met since the number of assemblies on each gold square were not adequate to meet the lead-time demand. It was also determined that in the case of assemblies with low demand, production control would not build assemblies to fill the complete gold square size since the MRP system's prediction of demand did not require them to do so.

8.1.4 Issues caused due to Current and Planned Gold Square System

We explored the planned and currently implemented system and discovered the following issues that were caused on the production line of the Universal End Station due to gold squares.

The most important issue is assembly shortages on the line. A shortage is said to have occurred when an assembly is not present on the gold square when required by an assembler on the production line as part of the standard build procedure. A shortage of a gold square assembly could cause a line stoppage or a work around.

A line stoppage is the complete halting of the build process of the Universal End Station module due to lack of a critical part needed to proceed with the standard build procedure. Line stoppages are rare and more often, shortages cause a work around. A work-around is said to have occurred when an assembler on the line is forced to follow non-standard build procedures due to the lack of a part need to proceed with the standard build procedure.

There are problems caused by both line stoppages and work-arounds. A line stoppage would increase the lead time of the build process as the build process is halted till the assembly is available to the assembler. This could increase the cycle time of the Universal End Station module if the process which is affected is the bottleneck process, or if the delay at a process causes its cycle time to exceed that of the bottleneck process. An increase in the cycle time of the Universal End Station could reduce the capacity of the plant as the Universal End Station currently dictates the plant capacity being the module with the longest cycle time.

A work-around could also increase the lead time of the build process by forcing the assembler to follow non-standard procedures that are longer and more complex that the standard procedure. The work-around could cause a further increase in lead time if the work has to be undone and then redone in order to add the assembly to the module when it arrives at a later time. This could also increase the cycle time of the Universal End Station module if the process which is affected is the bottleneck process.

Hence, a work-around could also increase the cycle time of the Universal End Station and hence could reduce the capacity of the plant. Another problem that could be caused by a work-around is a quality problem. Since non-standard procedures would be followed during a work-around there is the probability that the assembler might make a mistake in the build process causing a quality problem.

A quality problem could also be caused when work is undone and redone in order to add the assembly to the module when it arrives at a later time. These quality problems could cause either an assembly to fail completely or require re-work on the production line. This may increase the cycle time for test beyond the UES line cycle time resulting in reduced capacity.

If there were no inventory shortages, the process times for each operation could be realistically assumed to be deterministic. The throughput of the UES line with deterministic operating times is compared with the throughput from a UES line with stochastic operating times due to shortages using the simulation model described in Chapter 5.

If there are no inventory shortages, the throughput of the UES line is found to increase by approximately 10%. Gold square assemblies being the high volume fast moving assemblies constitute a significant proportion of assemblies used in the UES line by volume. Thus, stock-outs of gold square assemblies have an adverse impact on the line capacity.

Another issue caused due to the current and planned gold square system is the impact on the production line morale. When a shortage occurs, an assembler is either forced to wait for the assembly to arrive due to a line stoppage or follow non-standard build procedures due to a work-around. This reduces the assembler's efficiency and affects his morale.

As per the shortage communication records between the operators, there were 39 instances of shortages for the gold squares in January 2012. A record keeping exercise for gold square assembly shortages was begun in April 2012. Assembly line personnel were asked to record if the assembly was available when they required it. The data from the shop floor is consolidated in Table 8-1. In the period of April to June 2012, the overall service level for the gold squares was approximately 93% but the individual services levels were as low as 40% to 50% for certain parts.

One assembly is seen to have 100% shortage during the observation period. We believe that this could be attributed to lapses in record keeping by shop floor personnel and thus the percentage of shortages for some assemblies could possibly be slightly lower than shown in Table 8-1. However, this exercise was helpful in quantifying the severity of the problem.

8.2 Proposed Gold Square Inventory Management System

We propose a consumption-based planning system to manage the finished goods inventory of gold square assemblies on a make-to-stock basis. We also recommend storing the demand for the assembly line and field sales on the same shelf. The working of this inventory system is detailed in this section.

Table 8-1: Shortage history for UES Gold Square Assemblies - April - June 2012

Part Number	Instances Present	Instances Short	% Short
E11117460	23	1	4.35%
E11118850	18	2	11.11%
E11131560	5	0	0.00%
E11143600	45	0	0.00%
E11290060	30	0	0.00%
E11292620	29	0	0.00%
E11292630	27	1	3.70%
E11305045	30	5	16.67%
E11307000	23	0	0.00%
E11307010	19	1	5.26%
E11313400	11	0	0.00%
E11313550	32	0	0.00%
E11314090	8	1	12.50%
E11341910	15	3	20.00%
E11347590	1	0	0.00%
E11349360	5	5	100.00%
E11356640	2	0	0.00%
E11414160	10	4	40.00%
E11437760	14	3	21.43%
E11442250	15	2	13.33%
E11478330	8	1	12.50%
E11478360	8	2	25.00%
TOTAL	431	31	7.19%

8.2.1 Working of the Proposed System

The consumption based planning system is a pull system at the finished goods inventory level. It is based on maintaining the quantity of inventory on the shelf and in WIP at the 'base-stock' level. The detailed working of the consumption based planning system is as follows.

For each Gold Square assembly, a target inventory level (B) also called the base-stock level is calculated. Calculation of the base stock level is detailed in the next section. Production control is required to review the quantity of assemblies on the shelf at regular intervals of time called the review period and issued shop orders to produce assemblies to replenish up to the base-stock level.

$$P = B - H - W \tag{8-1}$$

where,

P is the number of assemblies to be built,

H is number of assemblies on hand, and

W is number of assemblies in WIP (work-in-process).

Every time the assembly line worker uses an assembly from the Gold Square shelf, the person is expected to fill out a form abundantly available on the shelf, indicating the assembly part number the machine number where it is to be installed. At the end of every day, these forms are collected and are used to back-flush the MRP system, that is, record the consumption in order and drive inventory of piece parts for the assemblies to be built in the future.

Thus, the consumption based planning is a pull system where assemblies are produced in response to vacancies on the Gold Square shelf as a result of consumption. This is similar to the planned system described in section 8.2.1 in operation but, importantly, this system differs in the inventory parameters that are used.

8.2.2 Calculation of Inventory Parameters

The calculations of the target inventory level or base-stock level for the gold square assemblies are explained in this section. The time period used for calculations appropriate to this case is weeks.

For each assembly, the target inventory or base-stock level B is given by

$$B = \mu \cdot (L + r) + z \cdot \sigma \cdot \sqrt{(L + r)} \qquad \text{--} \qquad (8\text{-}2)$$

and the expected inventory level E[I] is given by

$$(0.5 \cdot \mu \cdot r) + z \cdot \sigma \cdot \sqrt{(L+r)} \qquad \text{--} \qquad (8\text{-}3)$$

where,

μ = mean weekly demand (quantity/week)

L = Lead time (weeks)

r= review period (weeks)

z= safety factor

σ= standard deviation of weekly demand.

The first term in the right hand side of the Equation (8-6) is commonly referred to as cycle stock or, in some cases, pipeline stock. This is the quantity of assemblies required to satisfy demand over the lead time. The second term is referred to as safety stock and is the quantity required to cover for variations in demand.

8.2.2.1 Lead time

We calculate lead time as the time between when a shop order is issued for building the assembly till the time it is completed and appears on the gold square shelf. It includes time spent for picking the components from the bins, waiting in queues and testing if needed. Based on a one month of observation over all assemblies built in the supermarket, the metrics shown in Table 8-2 were calculated for the lead time.

Table 8-2: Supermarket lead time data based on 1 month of observation

Metric	**Value (days)**
Mean	2.27
Standard Deviation	1.67
Minimum	0.5
Maximum	10

While the lead time varies for each assembly, given the time constraints for the project, we were not able to observe the lead times for each assembly over a sufficiently large sample space. Hence, for the purpose of this analysis, the lead time is taken to be two and a half days.

8.2.2.2 Mean Demand

This term represents the mean weekly demand for each assembly for a 3 month horizon.

8.2.2.3 Review Period

This is the time interval between the regular reviews of inventory level on the shelf, based on which shop orders for production are issued. In this case a review period of one day was used, since that was the existing practice.

8.2.2.4 Standard deviation of weekly demand

This term represents the standard deviation of the weekly demand over the forecast horizon.

8.2.2.5 Safety Factor

The safety stock is meant to cover variations in demand. The demand is assumed to be normally distributed. The desired service level is the probability with which the safety stock will cover the variations in demand. It is calculated as the inverse of the normal cumulative distribution function and is given by

$$z = \text{Normsinv (service level)} \quad \text{--} \quad (8\text{-}4)$$

The gold square assemblies were classified based on their importance for the machine assembly build, cost of shortage and stage of use in the build. The service levels were set as shown in Table 8-3.

Table 8-3: Classification of UES Gold Square assemblies

Class	Service Level (%)	Consequences of Shortage
A	99	Significantly delay in build process and/or high probability of quality problem
B	95	Some delay and/or moderate probability of quality problem
C	95	Negligible or low impact on machine build.

We classified the gold square assemblies into the three classes based on discussions with production floor supervisors and workers.

The parameters used in the inventory model that is described above are summarized in Table 8-4.

Table 8-4: Summary of Parameters for Gold Square Inventory Calculations

Parameter	Value
Mean Demand (μ)	Mean of 3 month weekly demand forecast for each assembly
Lead time (L)	0.36 weeks (2.5 days)
Review Period	0.14 weeks (1 day)
Desired Service Level	99% for Class A assemblies
	95% for Class B assemblies
	90% for Class C assemblies
Standard deviation of demand (σ)	Standard deviation of 3 month weekly demand forecast for each assembly

The calculated inventory levels for each assembly are detailed in Table 8-5.

Table 8-5: Recommended Gold Square Inventory Parameters

Part No.	Classification	Cycle Stock	Safety Stock	Base-Stock Level	Current Safety Stock	Expected Inventory Level
E11461110	B	1.73	2.16	4	4	2.4
E11461120	B	1.73	2.16	4	4	2.4
E11347360	A	0.23	1.09	2	3	1.1
E11118850	B	1.54	2.40	4	4	2.6
E11313400	B	1.92	2.17	5	4	2.4
E11478330	A	1.54	3.32	5	4	3.5
E11414160	A	3.54	6.53	11	8	7.0
E11143600	A	5.96	9.53	16	12	10.4
E11349360	C	1.46	1.20	3	3	1.4
E11356640	C	0.88	1.18	3	3	1.3
E11437760	B	1.50	1.96	4	3	2.2
E11478360	A	2.38	2.94	6	4	3.3
E11131560	A	1.42	1.76	4	2	2.0
E11300130	B	0.85	1.37	3	2	1.5
E11327270	A	0.73	1.97	3	2	2.1
E11292620	A	2.46	2.81	6	3	3.2
E11292630	A	2.46	2.81	6	3	3.2
E11292640	B	2.46	1.98	5	3	2.3
E11314090	A	1.54	2.27	4	3	2.5
E11442250	B	1.69	1.81	4	3	2.1
E11327290	B	0.50	1.34	2	2	1.4
E11307000	B	2.46	1.98	5	3	2.3

Part No.	Classification	Cycle Stock	Safety Stock	Base-Stock Level	Current Safety Stock	Expected Inventory Level
E11307010	B	2.46	1.98	5	3	2.3
E11341910	B	2.92	1.77	5	3	2.2
E11290060	A	4.96	5.56	11	7	6.3
E11305045	B	5.31	3.96	10	7	4.7
E11117460	A	7.08	6.64	14	8	7.7
E11313550	A	4.08	7.17	12	9	7.7

The base-stock level is the sum of cycle stock and safety stock rounded to the next integer. The required shelf capacity is equal to the base-stock level, since the shelf needs to be sized to the maximum inventory level. The maximum total quantity in Table 8-5 is thus the sum of the base-stock levels of each assembly. The average inventory level is the expected value of the inventory on the shelf at any given time. It is calculated using Equation (8-3). The total expected inventory is the sum of the expected inventory level for each assembly as presented in Table 8-6.

Table 8-6: Total Gold Square Inventory Summary

Total Safety Stock (Proposed)	84 assemblies
Total Safety Stock (Current)	119 assemblies
Maximum Total Quantity	166 assemblies
Total Expected Inventory	108 assemblies

We can see that the consumption based planning system using a base stock policy has lower safety stock levels than the existing system by approximately 30%. However, due to the deviations in implementation from the planned system explained in section, there is an increase of 40% in the maximum shelf inventory. We cannot compare the average inventory level for the current and proposed policy since it is difficult to compute the average inventory level for the current policy which is not clearly defined and no records of on shelf inventory were available.

As detailed in section 8.2.3, one of the major reasons for the deviations from the planned system is the suboptimal sizing of the Gold Square levels. The recommended inventory levels address this issue and enable the smooth functioning of the planned system.

8.2.3 Implementation of the Proposed System

The inventory levels recommended in Table 8-6 are not to be taken as absolute values to be followed. We encourage the inventory analysts at Varian to monitor the performance of the system and make appropriate changes required to the parameters. In addition to computing the mean and standard deviation of weekly demand every quarter, the safety factor is a lever for the management to respond to issues like change in yield, importance of part in machine build sequence and so on. The implementation approach for the proposed policy is outlined in Figure 8-3.

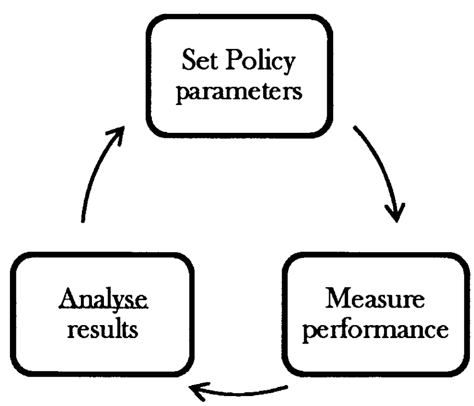

Figure 8-3: Proposed Inventory Policy Implementation Guideline

We provided the inventory analysts at Varian with a spreadsheet based tool to compute the optimal base-stock policy parameters for each three month forecast window moving forward. The analyst can input the following parameters to the model: three month weekly mean and standard deviation of demand, and importance (A, B or C classification which will determine the service level as described in Table 8-5). The cycle stock, safety stock and base-stock level are computed by the tool for the analyst based on the methodology described in the above sections. The analyst can then adjust these numbers to compensate for yield.

8.3 Implementation Challenges for Proposed Policy

For the recommended inventory systems, there are three major challenges in implementation. The first and most important is the availability of piece parts to build gold square assemblies, including both cycle stock and safety stock. The other challenges are the supermarket labor availability to build up the base-stock quantity for every assembly and the additional shelf space to accommodate the base-stock inventory levels.

8.3.1 Piece Parts Availability

Piece parts are raw materials stored in supermarket inventory area which go into the assemblies built by the supermarket. Piece parts are organized in four categories: MRP driven, two-bin Kanban System, vendor managed inventory (VMI), and consignment system. A detailed description of the inventory management systems have already been provided in Chapter 2.

Piece part availability has a direct impact on the service level of supermarket finished goods assemblies. Piece part shortages lead to longer lead time of supermarket finished goods assemblies, thereby causing shortages for those assemblies. Piece part availability is confined by both known shortages and unknown shortages. Known shortages are detected by production control through SAP system before issuing a shop order; while unknown shortages are invisible through SAP, and can only be detected during material picking.

Wu [2] particularly explores in detail the reasons of piece part shortages, investigates unknown shortages and proposes an inventory management roadmap for reducing unknown shortages. Ramachandran [1] discusses the solutions to optimize the inventory policy of MRP driven piece parts to reduce known shortages while achieving savings on inventory holding cost.

8.3.2 Supermarket Labor

In order to implement the recommended inventory management system, the inventory needs to be built up to the recommended base-stock levels. Once this has been achieved, the supermarket needs to build only what is required to maintain the base stock level. Thus, there would be a spike in supermarket and labor requirement to build up the base-stock level. The availability of labor in the supermarket to achieve this is analyzed in this section.

The supermarket works on all days of the week. As of May 2012, there were a total of 32 assemblers in supermarket and this is expected to remain at similar levels in the near future. These assemblers were working 16% overtime while the acceptable overtime percentage is up to 25%. Given that a ramp down in production was forecasted over the coming months at the time of the recommendation being proposed, according to the available weekly labor hours and the forecasted demand, it is feasible to build up safety stock using existing labor.

8.3.3 Shelf Space

Currently, there are five racks located near UES line to accommodate around 30 types of gold square assemblies. In order to calculate the expected additional shelf space needed to hold the recommended increased inventory level, capacity of existing gold square racks were measured to compute additional space requirement.

For most gold square assemblies, the base-stock level can be held in current shelf space, while there are only three assemblies which need additional space. Based on the shelf volume analysis, additional space equivalent to 30% of one of the rack is needed to store the increased in

3 types of assemblies, and it is highly feasible to accommodate this additional reduced sized rack on the UES line.

8.4 Benefits of proposed policy

In the proposed policy, cycle stock will be held as finished goods instead of piece parts. This will help reduce instances of assembly shortages as unknown piece-part shortages and yield problems will be detected earlier compared with the current system. It will, thus, improve the service level of gold square assemblies for UES line.

In addition, the proposed policy has a clear procedure for the production control staff to follow compared with the current system being followed. Furthermore, the proposed policy will enable shorter lead times, a more streamlined process for supermarket production control, and reduce deviations from standard procedure in the downstream assembly lines due to assembly shortage, which leads to quality problems

8.5 Summary

In this chapter, we described the gold square inventory management system that is used at Varian to manage the high-volume assemblies made in the supermarket build area and outlined the issues that arise due to its current structure and implementation. We presented the methodology used to address those issues and the analysis to identify the operating parameters of the recommended inventory system. We provided an implementation plan to implement the suggested changes and discussed the advantages of the proposed system. We also outlined the challenges that might be faced during the implementation of the proposed system.

Chapter 9

Summary and Insights

In this chapter, we present a summary of the work presented in this thesis as well as the insights that can be derived from the various topics investigated.

9.1 Resource Optimization for Cost Minimization

The resource optimization for cost minimization model subject to a production capacity constraint developed in Chapter 5 will allow Varian to determine the number of assembly bays and the number of workers per assembly bay required to meet demand at minimum cost.

This model is extended to the labor cost minimization model and the labor flexibility model presented in Chapters 6 and 7 respectively. The final constrained problem developed for this optimization problem as shown in Equation (5-5) of Chapter 5 is presented here as a reminder and named as Equation (9-1) for use in this chapter.

$$\text{Minimize} \quad I_j(A_j, W_j) = a_j \cdot W_j + b_j \cdot A_j$$

$$\text{subject to} \quad \hat{T}_j(A_j, G_1, \dots, G_{A_j}) \geq S_j \cdot D_j, \tag{9-1}$$

$$A_{j\,max} \geq A_j \geq A_{j\,min} \quad \text{and}$$

$$G_{j\,max} \geq G_k \geq G_{j\,min}.$$

$$\text{where} \quad W_j = \sum_{k=1}^{A_j} G_k\,,$$

$$\hat{T}_j = \sum_{k=1}^{A_j} \hat{T}_{jk}(C_{jk})\,,$$

$$\hat{T}_{jk} = \frac{U_j}{C_{jk}} \quad \text{and}$$

$C_{jk}(G_k)$ is determined from an empirically-determined table of values.

Using the model presented in Equation (9-1), Varian's manufacturing management team can determine the number of assembly bays and number of workers per assembly to meet demand at minimum cost for each production process. This will allow Varian to accurately determine the resources needed to meet demand and will allow them to estimate the resource requirements for future demand requirements as well.

In addition to the constrained problem mentioned in Equation (9-1), a performance measurement problem was also developed in Chapter 5. The performance measurement problem as shown in Equation (5-7) of Chapter 5 is presented here as a reminder and is denoted as Equation (9-2) for use in this chapter.

Process Cost $\quad I_{j\,current}(A_{j\,current}, W_{j\,current}) = a_j \,.\, W_{j\,current} + b_j \,.\, A_{j\,current}$

Process Capacity $\quad \hat{T}_{j\,current} = \sum_{k=1}^{A_{j\,current}} \hat{T}_{jk\,current}\,(C_{jk})$

where $\quad \hat{T}_{jk\,current} = \frac{U_j}{C_{jk}}$ and $\quad$ (9-2)

$C_{jk}\,(G_{k\,current})$ is determined from a table of values such as Table 6-1.

Current Total Workers $\quad W_{j\,current} = \sum_{k=1}^{A_{j\,current}} G_{k\,current}$

Using the performance measurement problem mentioned in Equation (9-2), Varian's manufacturing managers can effectively measure the capacity and cost of the current conditions of each production process. This will allow them to compare the current condition with the optimal condition to aid in the making of resource allocation and capacity planning decisions.

9.2 Labor Cost Minimization

The labor cost minimization model subject to an effective work hours constraint developed in Chapter 6 will allow Varian to determine the number of regular time hours and the number of overtime hours required to meet demand at minimum cost. It will also allow them to determine the number of regular workers required to meet demand at minimum cost.

This model is extended to the labor flexibility model presented in Chapters 7. Two scenarios were developed for this optimization problem. In the first, the number of regular workers is unconstrained and the final constrained problem developed for this optimization problem as shown in Equation (6-3) of Chapter 6 is presented here as a reminder and named as Equation (9-3) for use in this chapter.

$$\text{Minimize} \quad L_j(R_j,V_j) = r_j \cdot R_j + (1.5) \cdot r_j \cdot V_j + (0.28) \cdot \{r_j \cdot R_j + (1.5) \cdot r_j \cdot V_j\}$$

$$\text{subject to} \quad R_j + V_j \geq W_j \cdot h_j \tag{9-3}$$

where W_j is the number of effective workers required as determined from the resource optimization model.

Using the model presented in Equation (9-3), Varian's manufacturing management team can determine the number of regular time hours and number of overtime hours required to meet demand at minimum cost for each production process. They will also be able to determine the number of regular workers required and the corresponding overtime fraction. This will allow Varian to accurately determine the labor resources needed to meet demand and will allow them to estimate the labor resource requirements for future demand requirements as well.

In addition to the constrained problem mentioned in Equation (9-3), an alternate problem was also developed in Chapter 6 where the number of regular workers is constrained by the number of workers available for that process. The alternate problem as shown in Equation (6-6) of Chapter 6 is presented here as a reminder and is denoted as Equation (9-4) for use in this chapter.

$$\text{Minimize} \quad L_j(R_{j\,avail},V_j) = r_j \cdot R_{j\,avail} + (1.5) \cdot r_j \cdot V_j + (0.28) \cdot \{r_j \cdot R_{j\,avail} + (1.5) \cdot r_j \cdot V_j\}$$

$$\text{subject to} \quad R_{j\,avail} + V_j \geq W_j \cdot h_j \tag{9-4}$$

$$R_{j\,avail} \leq N_j \cdot h_j$$

where W_j is the number of effective workers required as determined from the resource optimization model described in chapter 5

N_j is the number of workers available on the production floor to perform that process.

This alternate problem mentioned in Equation (9-4), will provide the number of regular time hours and overtime hours required for each process that is required to meet demand at the minimum cost subject to the number of workers available to perform that process. The overtime fraction for this scenario can also be calculated. The labor cost for each process will also be provided to Varian and Varian's manufacturing management team can make informed personnel decisions based on the results of this model.

9.3 Labor Flexibility

The labor flexibility model subject to a required effective work hours constraint developed in Chapter 7 will allow Varian to determine the optimal movement of workers that will meet demand at minimum cost. A labor flexibility framework was developed that would allow Varian's workforce to move across processes efficiently using the model developed in Chapter 7. The labor flexibility framework aims to classify the processes and workers at Varian into four distinct skills levels: Level 1, Level 2, Level 3 and Special Level where Level 1 is the beginner skill level, Level 2 is the intermediate skill level, Level 3 is the advanced skill level and Special Level is the skill level for special processes.

Two constrained problems were developed for this problem statement. The first constrained problem, where the number of required workers is based on the number of required effective workers, developed for this optimization problem as shown in Equation (7-2) of Chapter 7 is presented here as a reminder and named as Equation (9-5) for use in this chapter.

$$\begin{aligned}
\text{Minimize} \quad M(Z_1, Z_2, Z_3, Z_S) &= Z_1 \,.\, m_1 + Z_2 \,.\, m_2 + Z_3 \,.\, m_3 + Z_S \,.\, m_s \\
\text{subject to} \quad Z_S &\geq X_S \,.\, h_j \\
Z_3 &\geq X_3 .\, h_j \\
Z_3 + Z_2 &\geq X_3 \,.\, h_j + X_2 \,.\, h_j \\
Z_3 + Z_2 + Z_1 &\geq X_3 \,.\, h_j + X_2 \,.\, h_j + X_1 \,.\, h_j
\end{aligned} \tag{9-5}$$

The second constrained problem, where the number of required workers is based on the number of required regular workers, developed for this optimization problem as shown in Equation (7-4) of Chapter 7 is presented here as a reminder and named as Equation (9-6) for use in this chapter.

$$\begin{aligned}
\text{Minimize} \quad M(Z_1, Z_2, Z_3, Z_S) &= Z_1 \,.\, m_1 + Z_2 \,.\, m_2 + Z_3 \,.\, m_3 + Z_S \,.\, m_s \\
\text{subject to} \quad Z_S &\geq Y_S \,.\, h_j \\
Z_3 &\geq Y_3 .\, h_j \\
Z_3 + Z_2 &\geq Y_3 .\, h_j + Y_2 \,.\, h_j \\
Z_3 + Z_2 + Z_1 &\geq Y_3 .\, h_j + Y_2 .\, h_j + Y_1 \,.\, h_j
\end{aligned} \tag{9-6}$$

Using the models presented in Equations (9-5) and (9-6), Varian's manufacturing management team can determine the number of work hours to be provided to the plant at each skill level. This will allow Varian to accurately determine the labor resources needed to meet demand and will allow them to estimate the labor resource requirements for future demand requirements as well. The limitations of the two models shown in Equations (9-5) and (9-6) include the lack of consideration of the cost of cross-training and the cost of worker acquisition and release.

The labor flexibility framework presented in Chapter 7 will allow Varian to effectively move workers across the different processes at Varian with minimum initiation. It will also provide Varian's manufacturing management team with visibility with respect to workers' skills as well as the skills required to perform a process.

9.4 Gold Square Inventory Management

The gold square inventory management system that was planned and that is currently in use at Varian was investigated in Chapter 8 of this thesis. In order to address the issue caused by the planned and current gold square system, a new consumption-based inventory management system was developed for the gold square assemblies.

The inventory levels required for each Gold Square assembly being provided to the Universal End Station module build area were computed using a base-stock model and the various challenges that would be present in the implementation of the proposed inventory management system were addresses.

Through the use of the developed inventory management system, Varian can effectively reduce the amount of safety stock being held by 30% for the gold square assemblies at the finished good levels whilst ensuring higher service levels. Varian's manufacturing management team can also extend the policy developed to the mixed module build area to achieve a reduction in safety stock levels and an improvement in service levels in that part of the production floor as well.

9.5 Discussion of Results from the Numerical Experiments

The results and working of the three models demonstrate that the models presented in Chapters 5, 6 and 7 will be highly useful to Varian in making resource allocation, capacity planning and personnel decisions. As described earlier, Varian currently relies on its manufacturing experience to make the above mentioned decisions and the results obtained from the three models will provide Varian with an optimum condition with which they can compare and make decisions. The results from the numerical experiment run in Chapter 5 also serve to illustrate how the optimization models can be used in measuring the current performance of Varian's manufacturing processes.

The results from the resource optimization model presented in Chapter 5 illustrate the different ways in which capacity can be met at Varian as well as the costs associated with different resource allocation decisions. As can be seen in Chapter 5, there are a number of possible combinations that would yield the required capacity and it is important to be able to identify the combination that would result in the minimum cost.

The results from the labor cost minimization model presented in Chapter 6 illustrate that the minimum cost condition is when the required effective hours is satisfied completely with regular time hours. However, when the regular time is constrained by the number of available workers, the model provides an optimal minimum cost condition that will allow Varian to determine the amount of overtime it will need to use as well as the labor cost associated with that process.

The limitations of the two labor flexibility models, as described in Chapter 7, are also demonstrated from the results of the numerical experiment run in this chapter. However, the numerical experiment also demonstrates how Varian would be able to use the models in their current form to determine the number of hours at each skill level that would be required as well as the total weekly labor cost across the plant.

9.6 Usage of the Software Program

We recommend that Varian specify and update the constant[28] parameters for the software program outlined in Chapters 5, 6 and 7 every three months. We also propose that Varian specify and update the variable[29] parameters every week. This will allow the software program to

[28] Constant parameters, in this thesis, are defined as those that do not change on a weekly basis.
[29] Variable parameters, in this thesis, are defined as those that might change on a weekly basis.

provide accurate results to Varian's manufacturing management team every week when the software is run to aid in resource allocation, capacity planning and personnel decisions.

We propose that the software program is run by Varian for the six-month demand forecasts provided by Varian's sales team so as to allow Varian to plan resource allocation decisions ahead of time. This will also provide Varian with visibility with regards to future personnel requirements allowing Varian to plan for effective use of regular time and overtime to meet demand at minimum cost.

9.7 Summary

In this chapter, we summarized the contributions and finding of this thesis and illustrated the insights that can be derived from the usage of the work presented in this thesis.

Chapter 10

Conclusions and Future Work

In this chapter, we present the conclusions that we have drawn from the work presented in this thesis. We also present the recommendations for future work that can be performed as an extension of the work detailed in this thesis.

10.1 Conclusions

With the goal of optimizing Varian's production processes for minimum cost, this thesis presents three optimization models in Chapter 5, 6 and 7 that can be utilized by Varian to facilitate resource allocation, capacity planning and personnel decisions.

We conclude that the development and usage of a software program as outlined in Chapters 5, 6 and 7 will allow Varian's manufacturing management team to effectively use the developed models to make decisions that will allow Varian to maintain and improve its manufacturing competitiveness by providing Varian with the required information to meet demand at minimum cost.

We also conclude that through the implementation of the Gold Square inventory management policy presented in Chapter 8, Varian can reduce the safety stock held as finished goods for the Gold Square assemblies provided to the Universal End Station module build area and improve their service levels. This gold square inventory management policy can also be extended to the mixed module build area for the same reasons.

10.2 Future Work

There are several directions in which the work presented in this thesis can be extended in the future.

1. Refinement of the solution technique for the resource optimization model

   The current solution technique for the resource optimization model with the maximum number of assembly bays constraint consists of enumerating all the possible solutions and selecting the solution with the minimum cost. While this method is effective when the solution space is small as in the case of Varian, the development of an efficient solution technique for a large solution space is a potential area for future work.

2. Application of the models to other semiconductor capital equipment plants[30]

   The optimization models developed in Chapters 5, 6, and 7 of this thesis were developed keeping in mind the conditions present at Varian's production plant. The modification and application of these optimization models to enable other semiconductor capital equipment plants to meet demand at minimum cost is another potential area for future work.

3. Detailed software program design and development

   The software architecture presented in Chapters 5, 6 and 7 of this thesis can be extended to a more detailed software program with options for a large number of parameters, multiple product lines, shared resources and a sophisticated user interface.

4. Improvement of labor flexibility optimization models

   The labor flexibility optimization models presented in Chapter 7 of this thesis can be improved through the modeling and quantification of the cross-training cost and the worker acquisition and release cost. The inclusion of these two costs will improve the

[30] Semiconductor capital equipment plants of Applied Materials Inc. such as those in Austin, Texas.

accuracy and effectiveness of the model and will provide Varian with additional insight into labor flexibility.

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Appendix A

Glossary

General Terminology

Bottleneck: The production resource which limits a plant's production capacity. It is usually the production resource with the longest cycle time.

Capacity: The maximum throughout rate of a production process measured over a period of time.

Cycle Time: The average length of time between the completions of two successive units on an assembly line.

Manufacturing Lead Time: The time required to manufacture a product.

Operation Time: The expected time required to complete a particular operation.

Varian Semiconductor Equipment Specific Terminology

Machines / Tools: The ion implantation machines which are assembled and shipped to customers across the world. It is the highest level of the bill of materials.

Modules: The independently built systems which are integrated to make the machine. Each machine is comprised of four to five modules. They form the second level of the bill of materials

Assemblies: The functional units which are assembled together on the assembly line to make the modules. They form the third level of the bill of materials. However, some sub-assemblies may be shipped separately to the customer along with the machine.

Piece parts / components: The individual parts which are assembled together at the Supermarket build area to make the assemblies. These constitute the lowest levels of the bill of materials.

Laydown: The act of setting up the frames for each module on the designated bay for building the module. It is common practice at Varian for all the modules for a machine to have the same *laydown date.*

Gold Squares: The specifically-sized storage locations for high-volume fast-moving assemblies made in the Supermarket builds area for the Universal End Station or Mixed Module line. These assemblies are typically managed on a make-to-stock policy.

Supermarket Build Area: The production cells which build and test the assemblies used downstream in the Universal End Station or Mixed Module line.

MOD Storage Area: The storage location for parts needed on the Mixed Module line.

Kit Codes: In order to simplify parts' retrieval from different storage locations, the parts have been organized into kit codes. A kit, which is a set of parts, for a module consists of between one to 300 parts. There are two types of kit codes called the Z Pick Kit codes and Z Pick Lists.

Z Pick Kit Codes: Codes used for retrieving parts stored in the external warehouses: buildings 5 and 80.

Z Pick Lists: Kit codes for parts stored in locations on the production floor of building 35 such as the MOD storage area.

Shortage: The phenomenon of the required quantity of assemblies or piece parts not being available at the moment when an assembler needs them

Known Shortage: The shortages of piece parts which are indicated by the MRP system when an availability check is performed.

Unknown Shortage: The phenomenon of piece parts appearing to be available in the required quantity on the MRP system, but not actually being physically present.

Transmittal Form: A form to be filled by an assembler indicating the quantity of inventory taken from a shelf for the purpose of maintaining accurate inventory record in the MRP system.

Field Sales: Assemblies or piece parts sold directly to customers or shipped to inventory banks across the world managed by Varian. They are usually replacement parts.