Operations Improvement in a Semiconductor Capital Equipment Manufacturing Plant: Component Level and Assembly Level Inventory Management

by

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B.E. in Mechanical Engineering
Huazhong University of Science and Technology, China, 2009

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Engineering in Manufacturing

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2012

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Abstract

Semiconductor capital equipment is manufactured in a high-mix and low-volume environment at Varian Semiconductor Equipment business unit of Applied Materials. Due to the demand growth over the past years, Varian has been continuously improving its operations practices to increase the factory capacity without investing additional floor space or labor shifts.

A hypothesis-driven analysis is used to identify, understand and formulate solutions for the issues that Varian faces in order to increase its production capacity. Based on the preliminary analysis, we develop a hypothesis tree and we identify effective operation time reduction and cycle time reduction to be the two root hypotheses.

Inventory shortages increase the effective operation time of the production lines and lower Varian's production capacity, especially those high-volume low-variety assemblies built in supermarket build area. We present a consumption based assembly level inventory management system based on the base-stock model to reduce assembly shortages on downstream production lines. This system will be used to manage those finished goods inventory of supermarket assemblies on a make-to-stock basis for all downstream consumptions, and it will allow Varian to increase those assemblies' service levels while reducing finished goods inventory level of assemblies by 30%.

Supermarket piece parts are the components used to build assemblies; piece part shortages delay the scheduled delivery of assemblies to the downstream production lines thereby causing assembly shortages. For piece part shortages caused by inaccurate inventory records, Varian lacks an effective solution. We present two component level inventory management systems for reducing piece part shortages. In short to middle term, we present a secured tablet solution as a self-check-out terminal to provide better user experience aiming at reducing inaccurate inventory records by 50%. In middle to long term, we present a Vertical Lift Module solution to completely eliminate inaccurate inventory record while reducing storage space.

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Acknowledgements

I would like to take this opportunity to express my sincere gratitude to plenty of people for their invaluable support throughout the thesis work and along my Master's journey at MIT.

First and foremost, I would like to thank my thesis advisor Dr. Stanley B. Gershwin for being a fantastic teacher, mentor and friend. His time and effort, experience and systematic approach, and encouragement and inspiration bring the entire project to an unprecedented level. His guidance and advisory has made sure that not only a good solution is provided technically but also the solution can be implemented amongst various stakeholders and is able to make a tangible impact. I would also like to thank Dr. Stephen C. Graves for his valuable advices and inputs that guided us through certain milestones of the thesis work.

Second, I would like to thank Scott Sherbondy and Dan Martin at Varian Semiconductor Equipment business unit of Applied Materials. They have given us incredible opportunity, flexibility and support throughout the thesis time and beyond, and they have made this thesis project so fruitful and impactful. I would also like to express my sincere gratitude to Thomas Faulkner, Eric Berkander, Christopher Girardin, Peter Justice, Ronald Dognazzi, Gaetano Peritore, Richard VanKirk, James Firth, Mark Goodhue, Mike Rathe, Robert Cook, Brian McLaughlin, Kendall Stone, Robbie Roberts, Cindy Emerzian, Steve Gillis and everyone else at Varian who gave us numerous support and made this project possible.

I would also like to thank Dr. David E. Hardt and Dr. Brian Anthony for their countless effort in supporting the program and mentoring us, and Jennifer Craig for helping us with thesis writing.

I feel very grateful to work with my teammates, Lohithaksha Chengappa and Venkataraman Ramachandran, who have made our collaboration so fruitful and made our work so enjoyable.

Last but not least, I want to thank my parents, my family and my friends who have given me endless support along my life's journey.

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Chapter 1

Introduction

Semiconductor equipment is manufactured in a high-mix low-volume environment at the Varian Semiconductor Equipment business unit of Applied Materials (henceforth referred to as Varian). Given the complexity and high degree of customization for semiconductor equipment, the manufacturing is heavily dependent on skilled manual labor. Due to the growth in demand over the years, Varian has been continuously improving its manufacturing practices, mainly focusing on reducing the average tool labor hours and effective operation time. Apart from benefits like lower inventory, more streamlined operations, reduced opportunities for order changes from customers and better responsiveness, Varian believes this will help increase the factory capacity to meet demand growth with the existing resources.

The project is conducted by three students in the Master of Engineering in the Manufacturing program at MIT –Lohithaksha Chengappa, Venkataraman Ramachandran and the author of this thesis, Yiming Wu, at the Varian Semiconductor Equipment business unit of Applied Materials in Gloucester, Massachusetts. This thesis first presents the hypothesis-driven methodology followed to analyze the complex operations of the plant and identify factors which were limiting capacity. The resulting hypothesis tree is a useful tool to understand the high level issues faced in the plant and break them down into mutually exclusive sub-problems. Based on this preliminary investigation, assembly level shortages and corresponding component level shortages are identified as potential avenues for effective operation time reduction thereby increasing production capacity. We present a consumption based assembly level inventory management system based on the base-stock model for reducing assembly shortages on downstream production lines. This system will be used to manage those finished goods inventory of supermarket assemblies on a make-to-stock basis for all downstream consumptions, and it will allow Varian to increase those assemblies' service levels while reducing finished goods inventory level of assemblies by 30%. We also present two component level inventory management systems for reducing piece part shortages. In short to middle term, we present a secured tablet solution as a self-check-out terminal to provide better user experience aiming at reducing inaccurate inventory records by 50%. In middle to long term, we present a Vertical Lift Module solution to completely eliminate inaccurate inventory record while reducing storage space. Chengappa's thesis [1] looks at optimal management of labor resources to meet demand and develops a framework for labor flexibility relevant to Varian's operations. Ramachandran's thesis [2] explores and presents recommendations on the issues of capacity management and inventory policies.

This chapter first gives an introduction to the Varian Semiconductor Equipment business unit of Applied Materials where the project was executed. The chapter begins with an overview of the semiconductor capital equipment industry before elucidating the nature of the company's operations, their product range and the significant business challenges faced by the company which motivated this work. An outline of the major findings is presented in this chapter and the structure of the complete thesis is laid out for the reader.

1.1 About Applied Materials – Varian Semiconductor Equipment

1.1.1 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, of which the most important steps 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]. There are about 18 different kinds of major equipment for semiconductor fabrication [5].

Semiconductor capital equipment manufacturers, such as Applied Materials Inc., supply semiconductor equipment to semiconductor fabrication plants (fabs), where integrated circuits are manufactured. The Varian Semiconductor Equipment business unit of Applied Materials is the market leader in developing ion implantation machines. The leading semiconductor manufacturers like Taiwan Semiconductor Manufacturing Company (TSMC), Global Foundries, Samsung, Intel etc. are Varian's customers.

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 recipe 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 date. The necessity to comply with customers' demands in terms of tool customization, engineering change orders, delivery date changes etc. 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 impossible and majority of the assembly has to be done manually.

1.1.2 Company Overview

Varian Semiconductor Equipment 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 chip manufacturers from across the world.

Globally, the semiconductor equipment industry witnessed high growth after the economic slowdown of 2008 and 2009. The industry's worldwide revenue 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.

1.1.3 Varian's Product Range

Varian is a high-mix low-volume manufacturer with a variety of product offerings. Varian Semiconductor offers ion implanters in four categories: high current (HC) technology, medium current (MC) technology, high energy (HE) technology, and 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 implanters 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 and selects[1] to customize each ion implantation machine.

Table 1-1: Varian's Product Range

High Current (HC)	Medium Current (MC)	High Energy	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] Please refer to Appendix A for Varian's definitions of 'options' and 'selects'.

[2] This chapter was written in collaboration with Chengappa [1] and Ramachandran [2] and a similar chapter can be

1.2 Motivation for Project

The global semiconductor equipment industry is highly cyclical in nature. Hence Varian has to constantly live in an environment of fluctuating demand, with sporadic ramp-ups and ramp-downs in production. The demand for ion implantation machines is expected to increase in the future. Varian's objective is to increase capacity through improved operational efficiencies to be able to meet the forecasted increase in demand without having to expand the footprint of the factory or add labor shifts.

1.3 Summary of Findings

We found assembly shortages on the production lines to be a major impediment to achieve capacity improvements. Although Varian is a high-mix low-volume manufacturer some assemblies are required frequently and in high volume on the module assembly lines. The inventory policy utilized to manage the assembly level and component level inventory of the high-volume fast moving assemblies was causing frequent shortages due to suboptimal planning and operating parameters. Revising the inventory policy, its operating parameters and inventory management system is expected to yield higher service level with lower overall safety stock costs.

1.4 Structure of Thesis

The remaining of the thesis is organized as follows

Chapter 2 An outline of Varian's production operations including their material and information flow, build process flow and inventory management techniques.

Chapter 3 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 4	A summary of the literature review undertaken.
Chapter 5	An assembly level inventory management system is presented to improve the service levels for the Gold Square assemblies.
Chapter 6	A component level inventory management system is presented to improve the service levels for the supermarket piece parts.
Chapter 7	Recommendation derived from the thesis's contributions and directions for future work are described.

Chapter 2

Description of Operations

In this chapter[2], 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 component level inventory management presented in Chapter 5 and the assembly level inventory management presented in Chapter 6.

This chapter is organized as follows. An overview of Varian's product production process is provided in Section 2.1 which includes an outline of the production planning process at Varian, and a description of the material and information flow within the production plant. 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 the 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

[2] This chapter was written in collaboration with Chengappa [1] and Ramachandran [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.

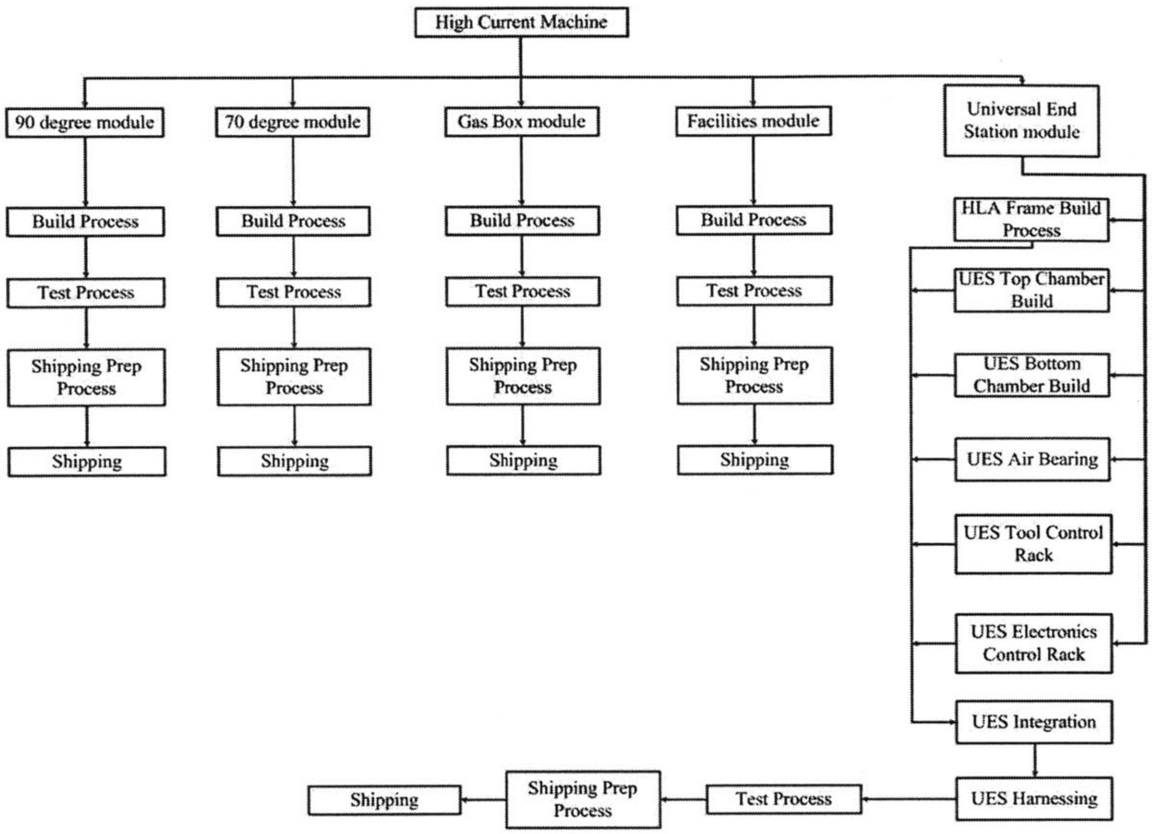


Figure 2-1: Production of High Current (HC) Machine at Varian

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 bay and number of workers present at each assembly bay for that process.

2.1.1 Production Planning

Varian's sales team works with existing and potential customers to develop six-month sales forecast. Build plans, which allocate machines to build bays and assign build dates, are developed based on these forecasts. The configurations for the forecast 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. This may happen during a downturn in demand and leaves the company with excessive inventory on hand.

It is common practice at Varian for all the modules of a machine to be started on the same date known as a laydown date. The manufacturing lead time 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.

As can be seen from Figure 2-2, the production floor is divided into distinct area 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.

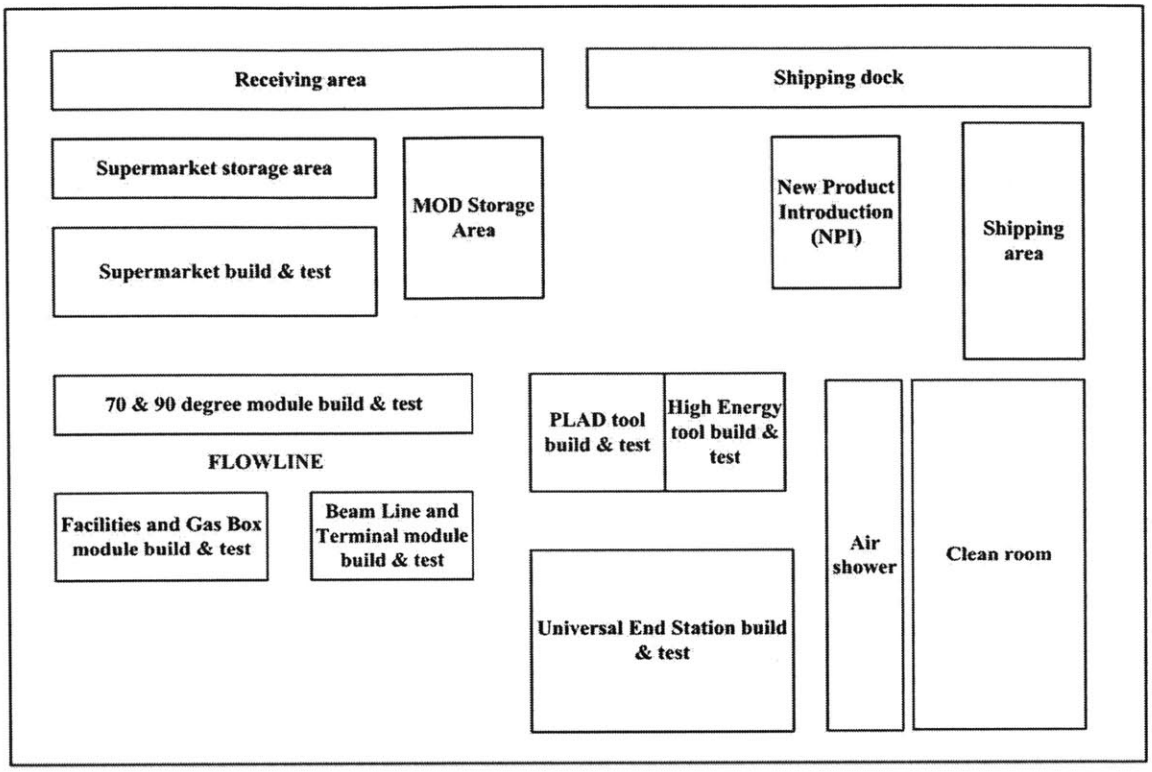


Figure 2-2: Production Floor Layout at Varian (not to scale)

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

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 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.

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.

2. Supermarket

The supermarket[3] 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 (MOD) 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.

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

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.

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 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 Squares. 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.

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 beam line module. The End Station is further made up of many sub modules. The UES Line functions like a flow line.

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 selects 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.

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.

Table 2-2: Inventory Locations at Varian

Location	Part Types
Building 80	Small parts required in supermarket or downstream assembly lines
Building 5 & 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 made to stock policy
Machine Racks	Stores all parts made by supermarket for downstream assembly except those on Gold Squares. Managed on made to order policy.

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.

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 5.

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 shown in Section 6.2.

2.3 Labor Management

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

Table 2-3: Work Shift Timings at Varian

Shift	Days	Duration
I	Monday - Friday	07:00 – 15:30
II	Monday - Friday	15:00 – 23:30
III	Monday - Thursday	23:00 – 07:30
IV	Fri-Sat-Sun; Sat - Sun-Mon; Sat- Sun- Wed.	07:00 – 19:00

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[4], 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 solving of the problem presented.

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

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[5] 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.

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.

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

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

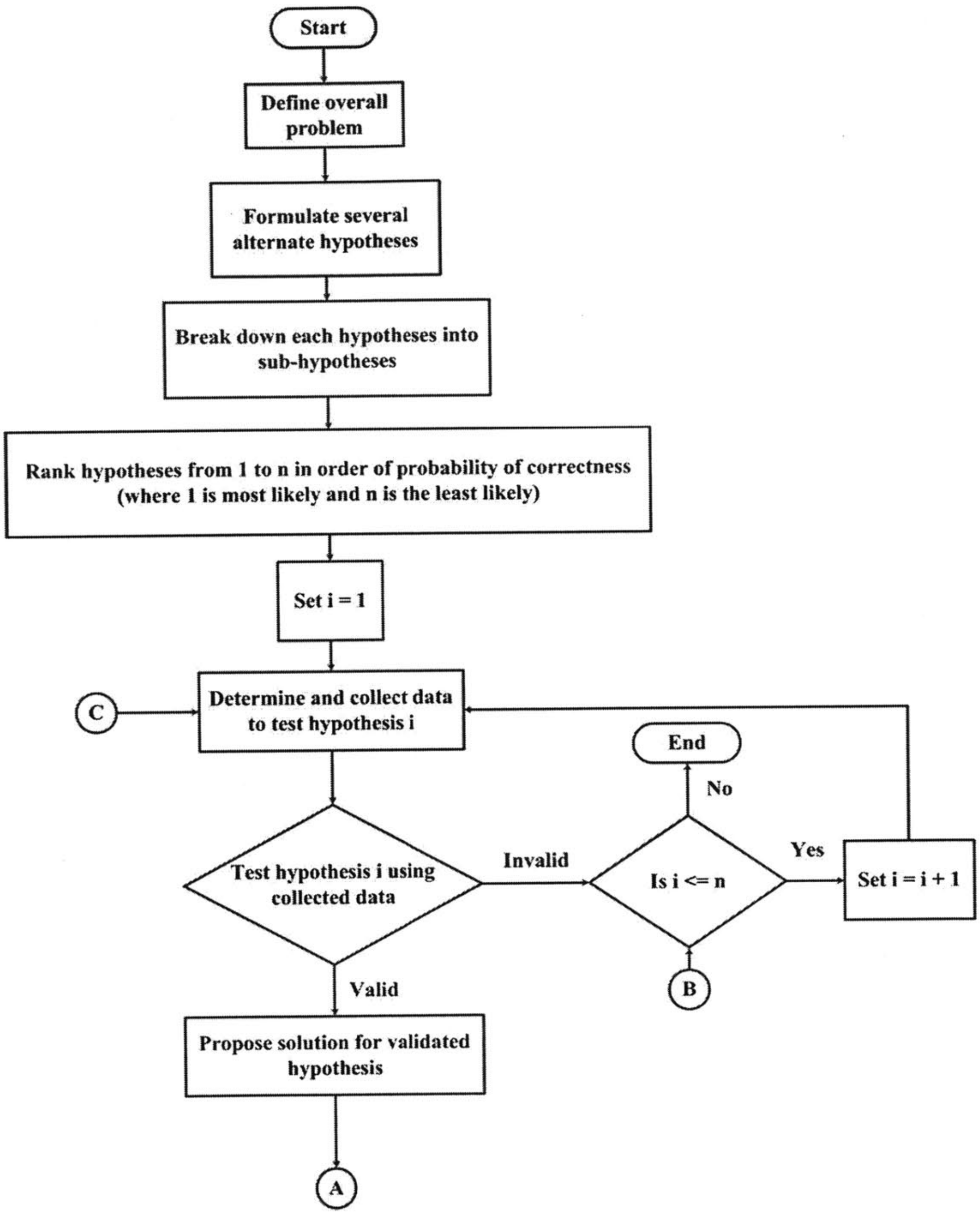


Figure 3-1: Hypothesis-driven Methodology (Part 1)

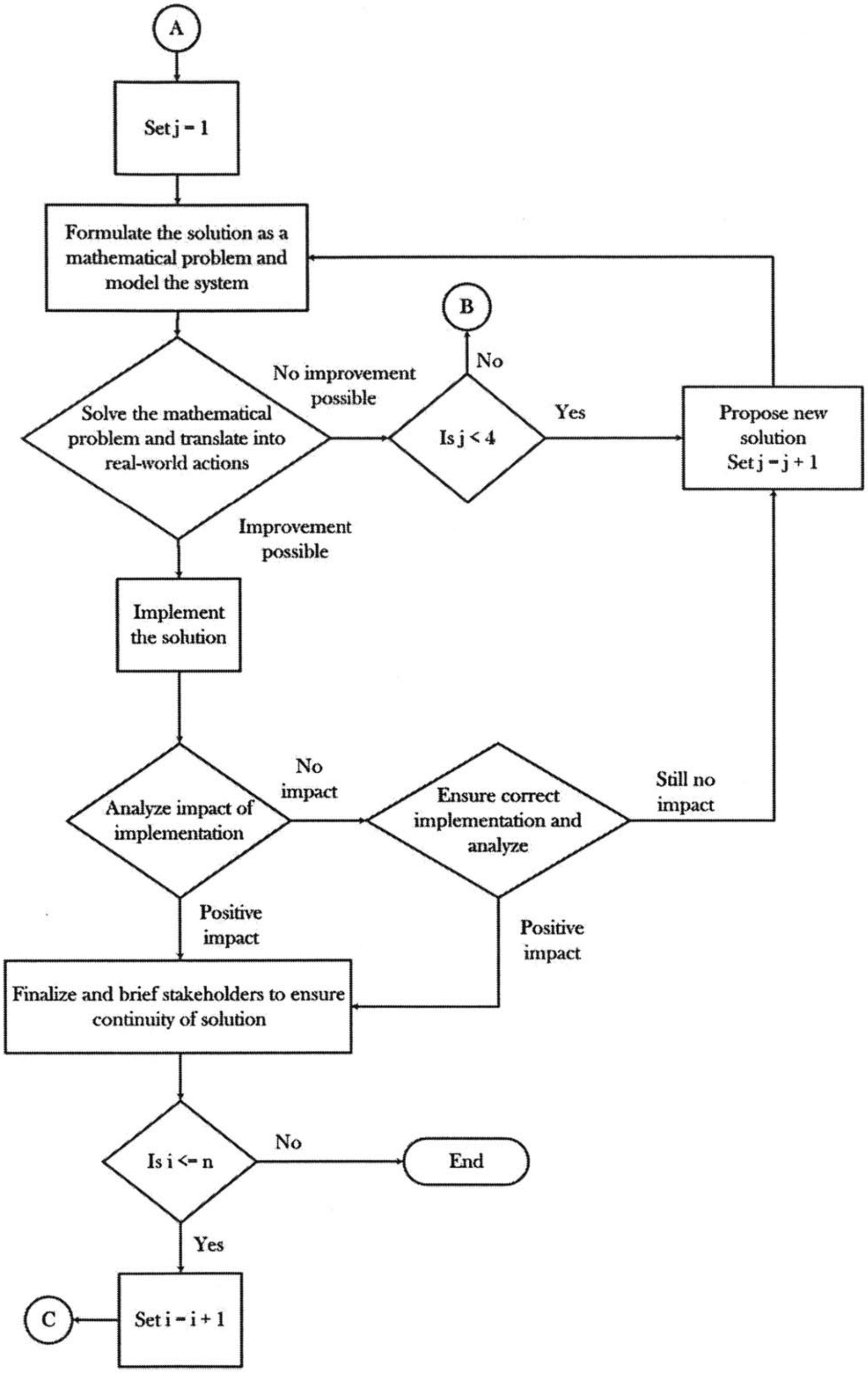


Figure 3-2: Hypothesis-driven Methodology (Part 2)

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.

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.

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.

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.

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.

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.

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 2, 3, and 4 under Section 3.1.2, 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.

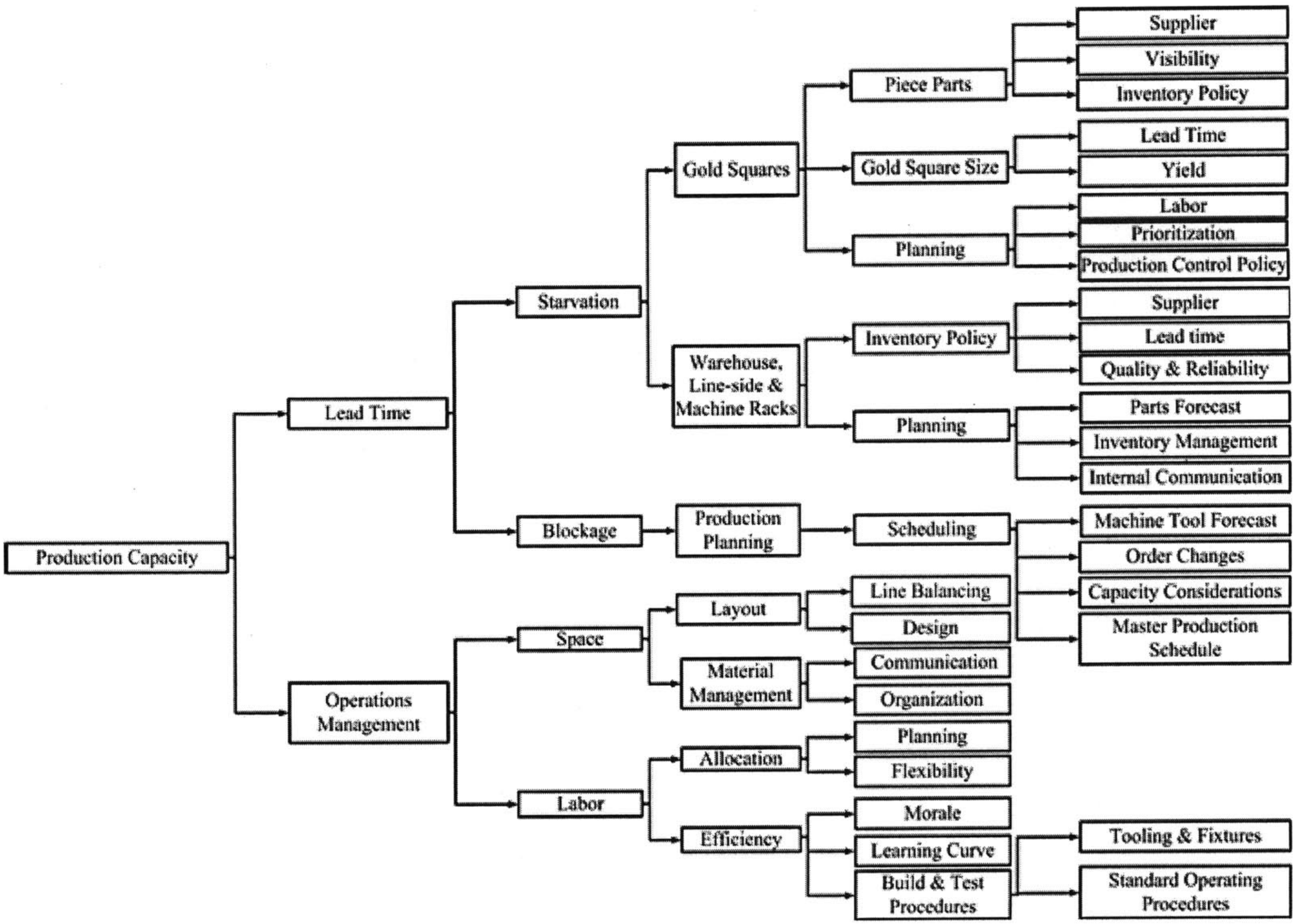


Figure 3-3: Hypothesis Tree

3.2.1 Excess Lead time [6]

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.

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

[6] 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.

- **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.

➢ **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.

➢ **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.

➢ **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.

- **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.

- **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.

- **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.

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.

- **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.

➢ **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.

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.

- **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.

- **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.

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.

- **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.

- **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. 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 5.

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 visibility and inventory policy sub-hypotheses of the piece parts branch of the gold squares hypothesis branch in Chapter 6. Chengappa [1] explores and presents solutions for the space and labor sub-hypotheses of the cycle time branch. Ramachandran [2] 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.

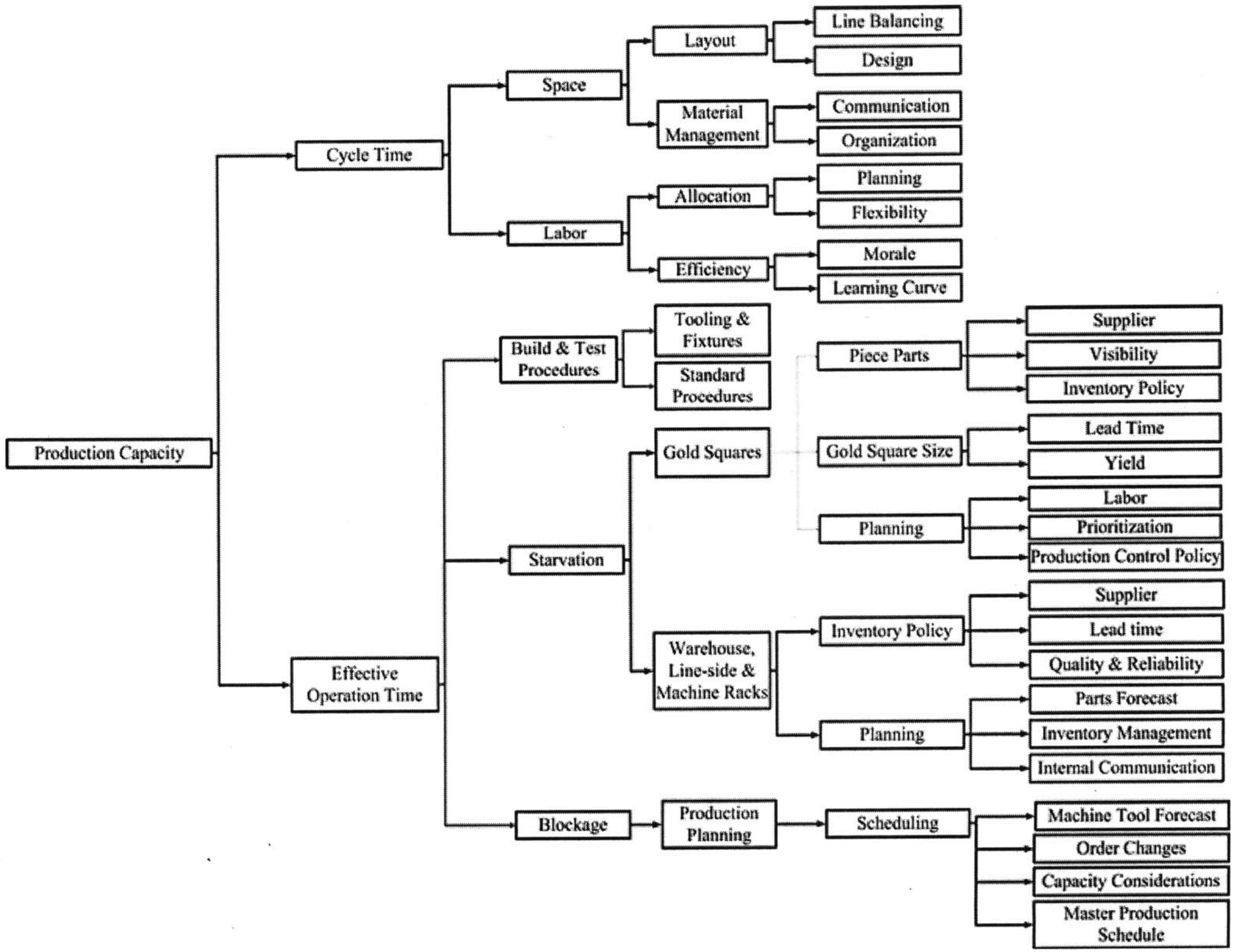


Figure 3-4: Updated Hypothesis Tree

3.5 Summary

In this chapter, we present 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

Review of Theoretical Background

In this chapter[7], we outline the various literature topics that were reviewed over the course of the work at Varian.

4.1 Inventory Policies

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 5.

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

4.1.1 Cycle Stock and Safety Stock

Cycle Stock refers to the quantity of inventory that needs to be kept on hand in order 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 [10].

4.1.2 Periodic and Continuous Review Policies

One of the major topics addressed in this thesis is the inventory management at the level of Gold Square Assemblies and piece parts. The Gold Square system is set up to function as a pull system as described in Chapter 5. A review of the two commonly used inventory strategies – the

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

Continuous Review Policy (also called Q-R policy) and the Periodic Review policy (also called base stock policy) as explained by Simchi-Levi et al is presented below [10].

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 shown as,

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

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

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

The base stock policy is a pull policy, where the inventory level is reviewed periodically and replenished back to the base stock level. Both the review period and the base stock level are fixed and can be reviewed to change after a certain period of time.

The base stock level is given by

$$B = \mu(r + L) + z\sigma\sqrt{(r + L)} \tag{4-3}$$

The average inventory level is given by,

$$E[I] = \frac{\mu r}{2} + z\sigma\sqrt{(r + L)} \tag{4-4}$$

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

r – the fixed reviewing period

4.2 Summary

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

Chapter 5

Assembly Level Inventory Management – Gold Square Assemblies

In this chapter[8], we describe the assembly level (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 they system currently implemented are presented, and the issue that arise due to the current implementation of the Gold Squares are outlined in Section 5.1. The methodology used to address these issues and the analysis to identify the operating parameters of the recommended inventory system is presented in Section 5.2. 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 5.3 and 5.4 respectively.

5.1 Overview of the Current Gold Square Inventory Policy

The Gold Square inventory management system is utilized at Varian in order to effectively manage the high-volume assemblies that are produced by Varian's supermarket build area. The high-volume assemblies are standard assemblies that are required by almost all the ion

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

implantation machines manufactured by Varian and hence are needed with high frequency. A Gold Square is a finite buffer to store the assemblies so that the workers can pick them for use.

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 system 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.

5.1.1 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 5-1 and explained below.

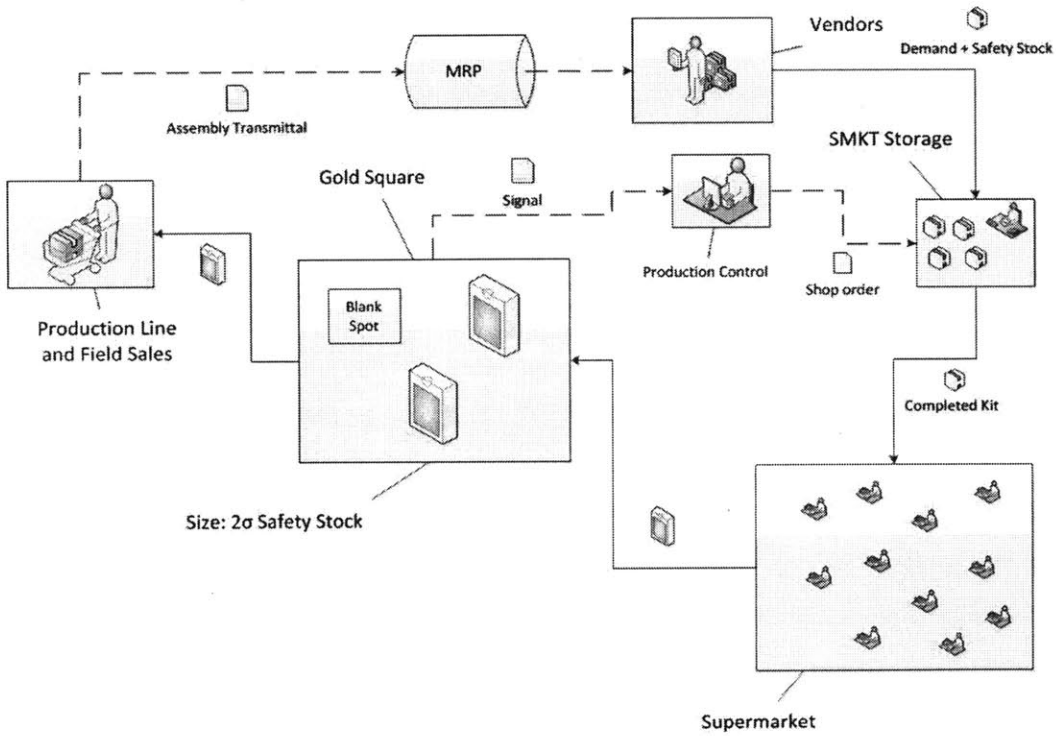


Figure 5-1: Planned Gold Square System at Varian

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, $2*\sigma*L^{1/2}$, 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 management personnel in charge of updating Varian's MRP[9] system that the assembly has been consumed. This causes the inventory management 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 as a pull

[9] MRP stands for Materials Requirement Planning

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

5.1.2 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 illustrated in Figure 5-2 and explained below.

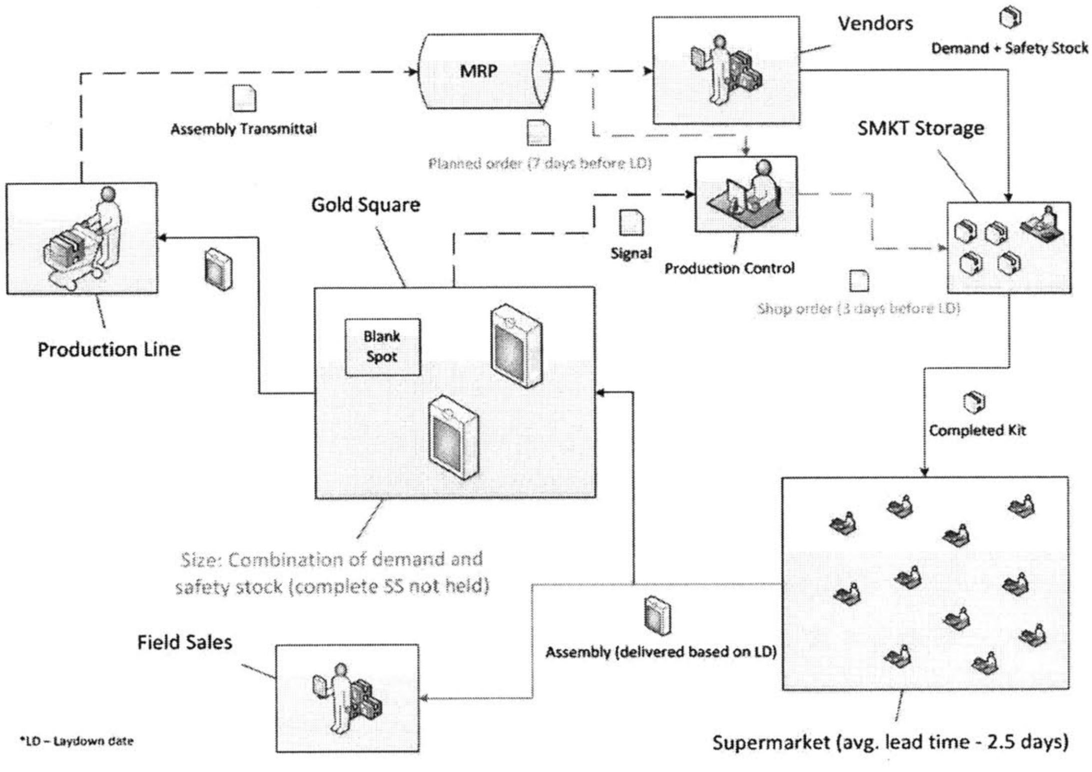


Figure 5-2: Currently Implemented Gold Square System

In the current system, each Gold Square shelf is still sized using the same formula (2σ) 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 shelf 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 the safety stock level of certain assemblies if there is 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.

5.1.3 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 to 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. Production control personnel had to refer to MRP to ensure that demand from the production line could be met, since the size of the Gold Squares was not adequate to meet the lead-time demand for that assembly. In the case of assemblies with low demand, production control would often not build assemblies to fill the complete Gold Square shelf. This resulted in inadequate safety stock on the shelf to cover for demand variations.

5.1.4 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 Square.

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 art 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 the 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 an instance when an assembler is forced to follow non-standard build procedures due to the lack of parts/assemblies needed to proceed with the standard build procedure.

There are problems caused by both line stoppages and work-around. A line stoppage would increase the operation time of the build process which 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 operation time of the build process by forcing the assembler to follow non-standard procedures that are longer and more complex than the standard procedure. The work-around could cause a further increase in operation 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 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 a chance that the assembler might make a mistake in the build process thereby 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 the test operation 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 of Ramachandran's thesis [2].

If there are no inventory shortages, the throughput of the UES line is found to increase by about 7%. 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 5-1. In the period from April to June 2012, the overall service level for the UES Gold Square assemblies was around 93% but was as low as 40% to 50% for certain assemblies.

One assembly, E11349360 was seen to have 100% shortage during the observation period. The team believes that this could be attributed to lapses in record keeping by shop floor personnel and thus the percentage of shortages for some assemblies could be slightly lower than shown in Table 5-1. However, this exercise was helpful in quantifying the severity of the problem.

Table 5-1: Shortage History for UES Gold Square Assemblies (Apr-Jun 2012)

Part Number	Instances present	Instances of shortage	Percentage of Instances of shortage
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%
E11292640	24	0	0.00%
E11300130	8	0	0.00%

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%
E11327270	11	0	0.00%
E11327290	9	0	0.00%
E11341910	15	3	20.00%
E11347360	1	0	0.00%
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%**

The practice of having a separate location for field sales in a different building caused confusion about the actual quantity of assemblies on hand.

5.2 Proposed Assembly Level Inventory Management System

We propose a consumption based planning systemto 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.

5.2.1 Inventory Mechanism

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 described below.

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.

$$P = B - H - W \tag{5-1}$$

Where

P in the number of assemblies to be built.

B is the base-stock level.

H is the number of assemblies on hand.

W is the number of assemblies in WIP (work in progress).

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 and the machine number where it was 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 5.1.1 in operation, but importantly, this system differs in the inventory parameters that are used.

5.2.2 Inventory Parameters Calculation

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

$$B = \mu(L + r) + z\sigma\sqrt{L + r} \tag{5-2}$$

The expected inventory level E[I] is given by

$$E[I] = 0.5 * \mu * r + z\sigma\sqrt{L + r} \tag{5-3}$$

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 (5-2) is commonly referred to as cycle stock or, in some cases, as 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.

Lead time

This is 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 observation over all assemblies built in the supermarket, the metrics shown in Table 5-2 were calculated for the lead time.

Table 5-2: Supermarket Lead Time Data (Based on a One-month 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, it was not feasible 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 2.5 days.

Mean Demand

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

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.

Standard deviation of weekly demand

This is the standard deviation of the weekly demand over the forecast horizon.

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

$$z = Normsinv\ (service\ level)$$

(5-4)

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 5-3.

Table 5-3: 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	90	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 are above are summarized in Table 5-4.

Table 5-4: 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	99% for Class A assemblies

Level	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 5-5. The assemblies are classified as described in Table 5-3. The mean and standard deviation of weekly demand of each assembly is obtained from the three month forecast in the MRP system. The cycle stock, safety stock, base-stock level and average inventory level are calculated using equations (5-2) and (5-3).

Table 5-5: Recommended Gold Square Inventory Parameters

Part No.	C[10]	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

[10] C stands for classification, please refer to Table 5-3.

Part No.	C[10]	Cycle Stock	Safety Stock	Base-Stock Level	Current Safety Stock	Expected Inventory Level
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
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 5-5 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 (5-3). The total expected inventory is the sum of the expected inventory level for each assembly as presented in Table 5-6.

From Table 5-6 we see that the consumption based planning system using a base-stock policy has lower total safety stock levels than the existing system by approximately 30%. However, due to the deviations in implementation from the planned system explained in section 5.1.2, there is an increase of 40% in the maximum shelf inventory. It is not feasible to 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.

Table 5-6: 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	93 assemblies

As detailed in section 5.1.3, 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 function of the planned system.

5.2.3 Implementation of the Proposed System

The inventory levels recommended in Table 5-5 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 5-3.

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 5-5). 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.

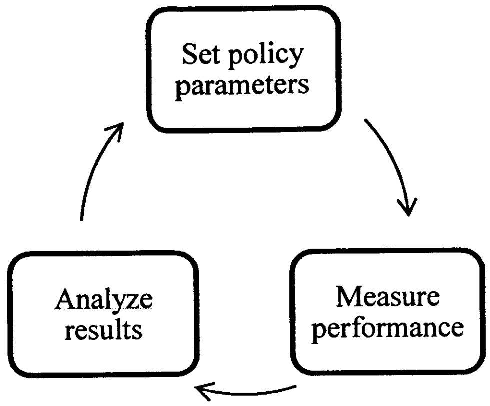


Figure 5-3: Proposed Inventory Policy Implementation Guideline

5.3 Implementation Challenges

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 up to the recommended base-stock level, 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.

5.3.1 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 Section 6.2.

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.

Chapter 6 of this thesis particularly covers detailed reasons of piece part shortages, investigates unknown shortages and proposes an inventory management roadmap for reducing unknown shortages. Chapter 7 in Ramachandran's thesis [2] discusses the solutions to optimize the inventory policy of MRP driven piece parts to reduce known shortages while achieving savings on inventory holding cost.

5.3.2 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.

5.3.3 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 3 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.

5.4 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 to the current system. It will, thus, improve the service level of Gold Square assemblies for UES line and reduce stock-out which may affect capacity.

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.

5.5 Summary

Gold Square assemblies were observed to have frequent stock-outs. Since these are high-volume fast moving assemblies, a flawed inventory management system can cause chronic stock-outs which can significantly inflate the cycle time on the assembly line and adversely affect plant capacity. In order to improve their service level, a consumption based planning (pull) system is proposed to manage the finished goods inventory of these frequently used assemblies on a make-to-stock basis. This requires production control to issue shop orders for assemblies daily to only bring the quantity on shelf and WIP up to the base-stock level. The base-stock level for each assembly is computed using a standard periodic review policy. We found that it is possible to significantly reduce safety stock quantity while improving the service level. Challenges in implementing the proposed policies are identified and solutions proposed. Thus a comprehensive inventory strategy is presented which can reduce safety stocks, improve service levels of Gold Square assemblies thereby preventing quality issues and inflated UES operation times, which adversely affect the overall plant capacity.

Chapter 6

Component Level Inventory Management – Supermarket Piece Parts

In this Chapter, the current supermarket piece part inventory management is studied to understand piece part shortages and the reasons. In Varian, supermarket piece parts are the component used to build Gold Square assemblies. Both short/middle term and middle/long term solutions are proposed to improve inventory accuracy in order to reduce piece part unknown shortages, please refer to Figure 6-1 for description of unknown shortages.

This chapter is organized as follows. The problem statement and motivation is presented in Section 6.1. The piece part inventory management system is introduced in Section 6.2. The piece part shortages are studied in Section 6.3, including both known shortages and unknown shortages. The impact of piece part shortages is broken down and discussed in Section 6.4, including both known shortages and unknown shortages. The causes for unknown shortages and the most problematic process are investigated in Section 6.5. The proposed solutions for piece part inventory management to reduce unknown shortages are detailed in Section 6.6. For causes and proposed solutions for piece part known shortages, please refer to Chapter 7 of Ramachandran's thesis [2], Component Level Inventory Management.

6.1 Problem Statement and Motivation

In Chapter 5, we investigate assembly level inventory management for Gold Square assemblies and propose a new policy to increase the service level of Gold Square assemblies. Supermarket piece parts are the components used to build those assemblies; therefore, the service level of piece parts has a direct and positive effect on the service level of Gold Square assemblies.

Piece part shortages cause assembly shortages on production line and longer average lead time in building assemblies. Besides, piece part shortages also lead to increased Gold Square size for accommodating supply variability, additional internal efforts and logistics cost for expediting piece parts to fulfill shortages, and lower efficiency in supermarket build area.

In order to solve these problems and make the implementation of the proposed policy for inventory management discussed in Chapter 5 possible, piece part shortages need to be reduced.

6.2 Piece Part Inventory System

Varian's supermarket storage area holds inventory of piece parts required to build Gold Square assemblies. There are 4 types of piece part inventory systems.

1. **Materials Requirement Planning (MRP) system**

Piece parts under this inventory management system are driven by SAP. Based on customer demand forecast and production schedule, SAP drives in piece parts for certain quantity at certain time. SAP keeps track of on hand inventory level of those piece parts and place corresponding replenishment orders for required quantity considering the lead time for delivery.

2. **Two Bin Kanban System**

This is a pull system. Demand is forecasted every 3 months and the Kanban bin is sized to hold two weeks' average demand. Additional piece parts driven by safety stock of Gold Square assemblies are also counted for bin size calculation. Whenever the first bin is empty, the Kanban card will be sent to trigger replenishment from vendors and the second bin will used. The second bin is expected to hold enough inventory to satisfy demand until the first bin is replenished. Most Kanban piece parts are supplied by domestic vendors and their lead time is around 5 business days.

3. Vendor Managed Inventory (VMI)

Piece parts from VMI system are managed directly by vendors' employees at Varian. They review those piece parts inventory level periodically and place orders for replenishment when it is necessary. VMI is the only inventory system not tracked by SAP, and VMI piece parts are always considered available.

VMI piece parts are those common components which are inexpensive and consumed in large volumes, such as nuts, screws, etc.

4. Consignment System

Consignment system holds piece parts that Varian pays for them only if they are actually consumed. Varian would however partially compensate the vendors if the piece parts were to go unused.

6.3 Piece Part Shortages

6.3.1 Shortage Overview

1. Shortage Detection

Piece part shortages comprise 'known shortages' and 'unknown shortages'. Known shortages can be detected through SAP system by supermarket production control, while unknown shortages are invisible through SAP system and can only be detected during piece part picking stage. Figure 6-1 presents the flowchart of current information flow and materials flow happened in supermarket area and this flowchart highlights when known and unknown piece part shortages are detected.

In Figure 6-1, following the flowchart from 'Start', supermarket production control does daily check of Gold Square inventory level, work in progress at supermarket build area, and demand request through SAP to make decision whether it is required and how much is required to build for each individual assembly.

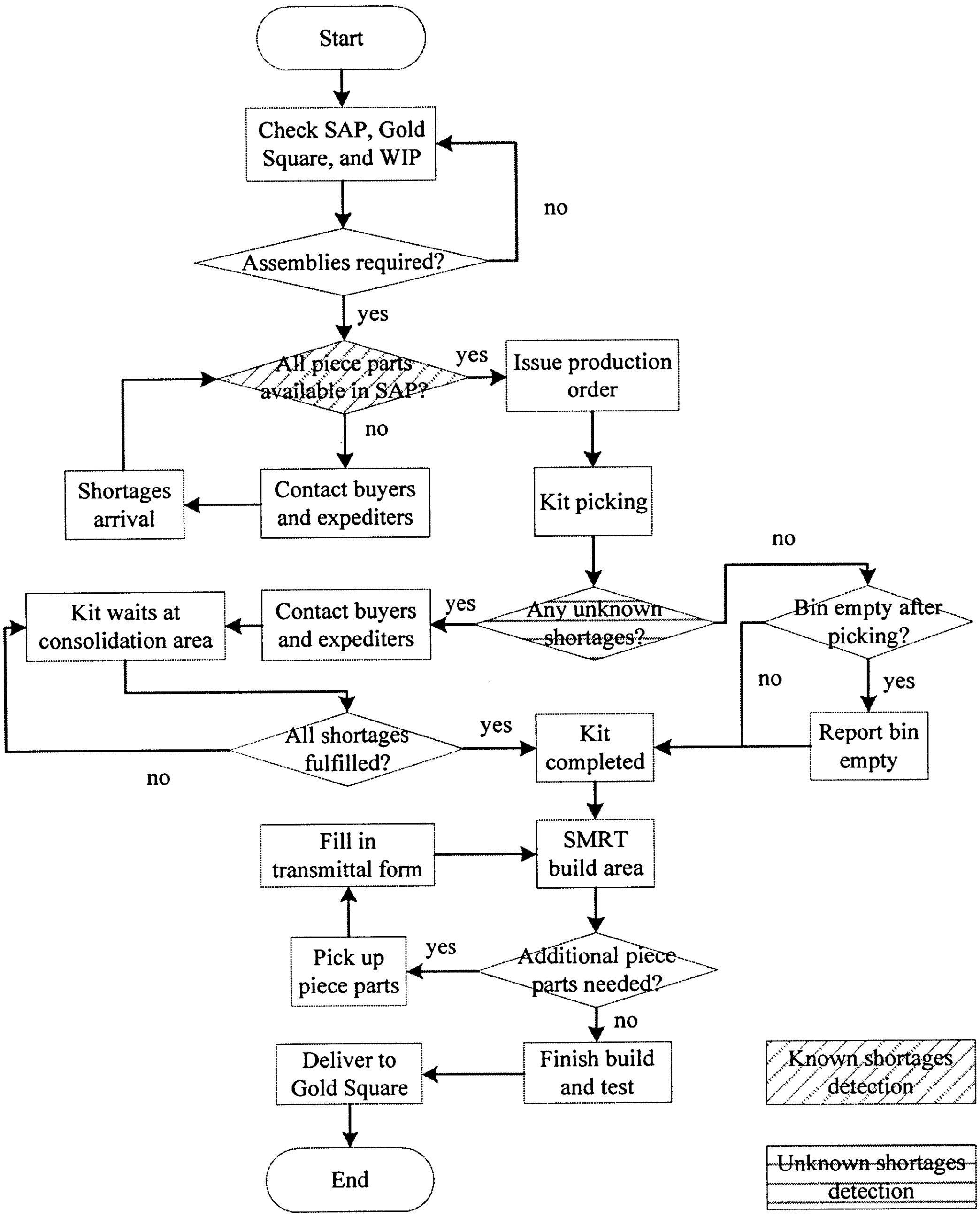


Figure 6-1: Supermarket Information and Materials Flow

If it is required to build a certain assembly, then production control checks piece part availability through SAP. At this stage, known shortages are detected and reported to internal buyers and expediters at Varian to check the next arrival date, and the production order request is suspended until those known shortages are fulfilled. If the piece parts required are needed before the next arrival date, buyers and expediters will contact vendors for expediting. After all the known shortages are fulfilled, production order for this assembly is created and sent to kit picker for kit picking.

During kit picking, unknown shortages are detected while those piece parts appear to be available in SAP initially. Kit picker continues checking through all the piece parts required, notes down all the unknown shortages, and puts kit wait at supermarket consolidation area. Similarly, requests are sent to buyers and expediters by production control to check the next arrival date. If the piece parts required are needed before the next arrival date, buyer and expediters will contact vendors to expedite those piece parts. After all the unknown shortages are fulfilled, the completed kit is sent to supermarket build area. If there are no unknown shortages detected during the kit picking process, the kit will be sent to supermarket directly after kit picking. If any bin becomes empty after kit picking, a replenishment request will be created and reported by the kit picker.

During the assembly building and testing stage at supermarket build area, if any additional piece parts are needed due to various reasons, assemblers will pick up those piece parts required directly and fill in the picking information on a 'transmittal form[11]' which will be updated into the SAP system periodically. Currently, the update happens on a daily basis; therefore, there is a lag between SAP and real inventory level.

After the assembly is complete with building and testing, it is delivered to Gold Square for temporary storage, and it will go to either production line or field sales afterwards.

[11] Please refer to Section 1 under Section 6.5.3 for detailed description of 'transmittal form'.

2. Untracked Known Shortages

Known shortages are detected during piece part availability check stage, and requests for checking and expediting are corresponded through emails between production control and buyers' side. Currently, historical known shortages have not been tracked and analyzed to investigate known shortages' influence on manufacturing operations. In Section 6.4.1, historical known shortage data is analyzed to study its impact in increasing assembly lead time.

3. Tracked Unknown Shortages

Unknown shortages are detected during kit picking process and recorded on a 'SMKT (supermarket) Pick List Cover Sheet' attached to the kit. Unknown shortages have been tracked on each business day by Varian's Materials Group since May 2011. Those shortage data is analyzed in to study its impact in increasing assembly lead time in Section 6.4.1 and the dominate cause for unknown shortages in Section 6.5.

6.3.2 Shortage Analyses

1. Known Shortages

- **Data Collection**

During business days, supermarket production control checks daily to decide whether a production order is required to be issued for an assembly. If there is known shortages detected and the known shortages cannot be fulfilled during that day[12], the corresponding assembly is highlighted in yellow on the 'Daily Production Control Sheet'. The yellow highlight remains on the next day's production control sheet until the known shortages are fulfilled. If there are no known shortages for a given assembly during piece part availability check, a production order is issued for this assembly and the production order number is recorded on the 'Daily Production Control Sheet'. Therefore, the assemblies highlighted in yellow on the 'Daily Production Control Sheet' represent piece part known shortages detected for those assemblies on that particular date.

[12] Sometimes known shortages can be fulfilled during that day due to scheduled delivery from vendor.

'Daily Production Control Sheets' for Gold Square assemblies of UES line, from March 2012 to May 2012, have been collected to analyze known shortage percentage in each month, know shortage percentage is described in equation (6-1). UES line is the bottleneck of Varian's production; therefore only known shortages related to UES Gold Square assemblies are analyzed here. The analyses and results of known shortages related to MOD Gold Square assemblies are similar.

- **Known Shortage Percentage**

Known shortage percentage is calculated by using the following formula

$$Known\ shortage\ percentage = \frac{Sum\ of\ shortages}{Sum\ of\ demands} \tag{6-1}$$

Where

$Sum\ of\ shortages$ – the total amount of assembly shortages during the given period of time. For example, if 6 identical assemblies are needed on a 'Daily Production Control Sheet', it is counted as 6.

$Sum\ of\ demands$ – the total amount of assemblies needed during the given period of time.

Known shortages percent for March, April and May is presented in Figure 6-2.

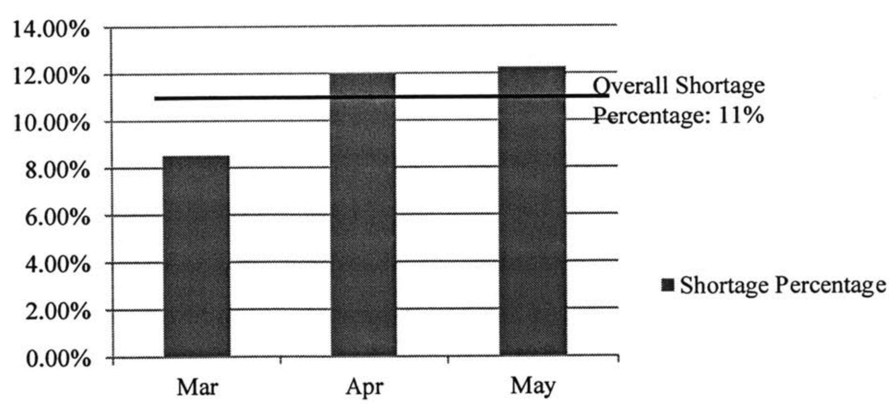


Figure 6-2: Known Shortage Percentage (March-May 2012)

In March 2012, known shortage percentage was 8.5%. In April and May 2012, known shortage percentage was 12%. By comparing monthly throughput with monthly known shortage percentage, it shows that there is no direct correlation between them.

On average, known shortage percentage was 11% during the period of time.

2. Unknown Shortage

- **Data Collection**

After the production order is released, unknown shortages are detected during kit picking stage. Unknown shortages are recorded on the 'SMKT Pick List Cover Sheet'. If there is no unknown shortage for a kit, the unknown shortage section is leaved blank on the 'SMKT Pick List Cover Sheet'.

Similarly as known shortages, only kits data related to UES Gold Square assemblies was collected and analyzed. UES line is the bottleneck of Varian's production; therefore only unknown shortages related to UES Gold Square assemblies are analyzed here. The analyses and results of unknown shortages of MOD Gold Square assemblies are similar. Due to limited data availability, 4 weeks' kits from March 26th to April 20th were used to analyze unknown shortage percent in each week.

- **Unknown Shortage Percentage**

Unknown shortage percentage is calculated by using the following formula

$$Unknown\ shortage\ percentage = \frac{Sum\ of\ short\ kits}{Sum\ of\ kits} \tag{6-2}$$

Where

$Sum\ of\ short\ kits$ – the total amount of kits with unknown shortages during the given period of time.

Sum of kits – the total amount of kits during the given period of time.

Unknown shortage percentage for Week 3.26-3.30, Week 4.2-4.6, Week 4.9-4.13 and Week 4.16-4.20 is presented in Figure 6-3.

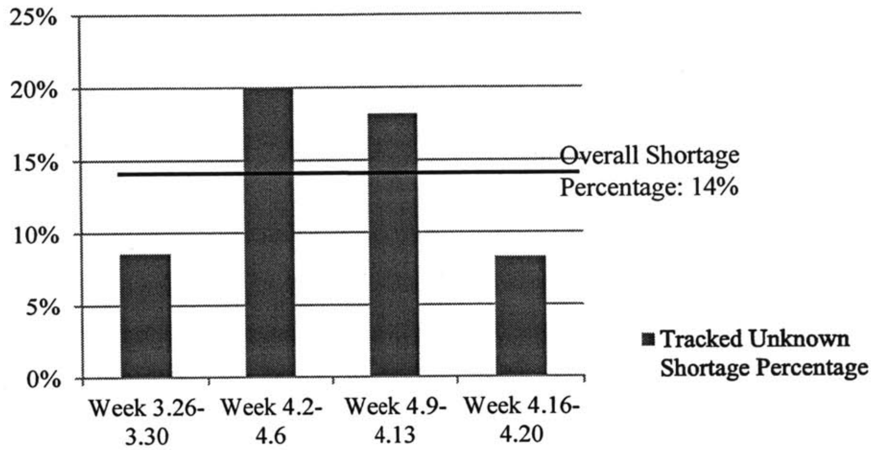


Figure 6-3: Unknown Shortage Percentage (Year 2012)

Over these four weeks, unknown shortage percentage varied from 8% to 20%. On average, unknown shortage percentage was 14% during the period of time.

3. Tracked Unknown Shortage Percentage vs. Combined Shortage Percentage

In Section 6.3.1, it is described that known shortages are note tracked inside Varian. By consolidating both known shortage data from the 'Daily Production Control Sheet' and unknown shortage data from the 'SMKT Pick List Cover Sheet', the combined shortage percentage was calculated and compared with currently Varian tracked unknown shortage percentage for the four weeks from March 26th to April 20th. Combined shortage percent is calculated by using the following formula

$$Combined\ shortage\ percent = 1 - (1 - Known\ shortage\ percent) * (1 - Unknown\ shortage\ percent) \quad (6\text{-}3)$$

Where

Combined shortage percent – the combined shortage percent for that week.
Known shortage percent – the known shortage percent for that month.
Unknown shortage percent – the unknown shortage percent for that week.

The comparison between Varian tracked unknown shortage percentage and combined shortage percentage are shown in Figure 6-4.

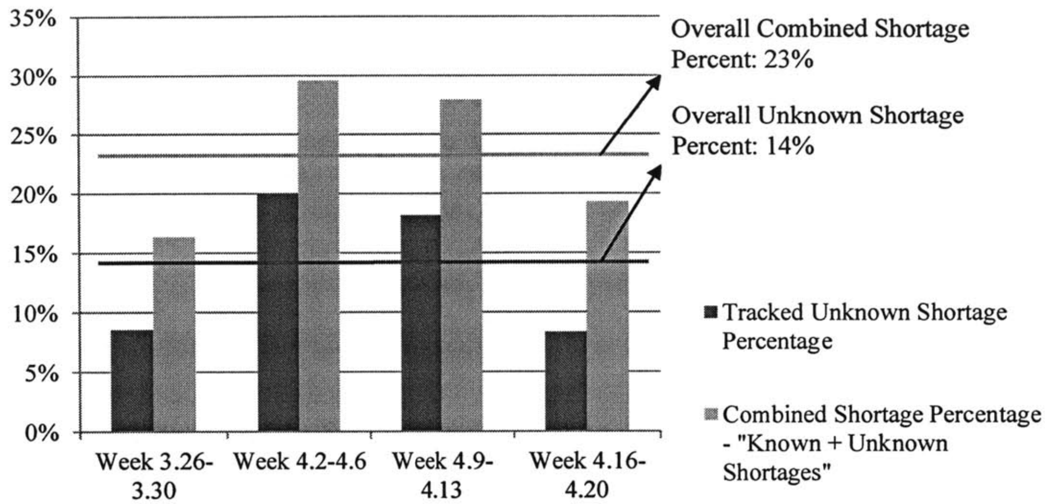


Figure 6-4: Tracked Unknown vs. Combined Shortage Percentage (Year 2012)

As can be seen from Figure 6-4, the overall combined shortage percentage is 23%, while the overall unknown shortage percentage is 14% over the 4 weeks. The overall combined shortage percentage is 64% higher than the overall unknown shortage percentage; therefore, it shows that the known shortages which are currently not tracked have significant influence on piece part availability.

6.4 Impact of Piece Part Shortages

6.4.1 Increase Assembly Lead Time

1. Known Shortages

In the Section 'Data Collection' of 'Known Shortages' under Section 6.3.2, it mentions that a known shortage is highlighted in yellow and the yellow highlight remains on the next day's production control sheet until the known shortages are fulfilled, and then a production order is created and the production order number is recorded. Therefore, the number of times of consecutive highlights happening for a given assembly is equal to the number of days the known shortages last, and it directly increases the assembly lead time.

'Daily Production Control Sheets' for Gold Square assemblies of UES line, from March 2012 to May 2012, have been collected to analyze assembly lead time increase caused by known shortages. Only known shortages related to UES Gold Square assemblies are analyzed here because UES line is the bottleneck of Varian's production, and the analyses and results of known shortages related to MOD Gold Square assemblies are similar.

Table 6-1: Assembly Lead Time Increase Caused by Known Shortages

Metric	Lead time increase (days)
Mean	2.42
Standard Deviation	1.82
Minimum	1
Maximum	9

Lead time increase varies for each assembly. Given the time limitation of the project, it was not feasible to observe lead time increase for each assembly over a sufficiently large sample space. Therefore, for the purpose of analysis the lead time increase is taken to be 2.6 days, which is slightly higher than the mean value to partially account for the variability.

2. Unknown Shortages

On the 'SMKT Pick List Cover Sheet', it records the start date when the production order is issued and the end date when the assembly is delivered to Gold Square.

The lead time after the production order is issued can be calculated by this formula

$$Lead\ time = end\ date - start\ date + 1 \tag{6-4}$$

Similarly as known shortages, only kits data related to UES Gold Square assemblies was collected and analyzed. Only unknown shortages related to UES Gold Square assemblies are analyzed here because UES line is the bottleneck of Varian's production, and the analyses and results of unknown shortages of MOD Gold Square assemblies are similar. Due to limited data availability, 4 weeks' kits from March 26th to April 20th were used to analyze assembly lead time increase caused by unknown shortages.

Table 6-2: Assembly Lead Time Increase Caused by Unknown Shortages

Metric	Lead time without unknown shortages (days)	Lead time with unknown shortages (days)
Mean	3.07	3.75
Standard Deviation	1.74	1.34
Minimum	1	2
Maximum	11	7

Lead time varies for each assembly. Given limited data availability, it was not feasible to observe lead time for each assembly over a sufficiently large sample space. Therefore, for the purpose of analysis, the lead time for kit without unknown shortages is taken to be 3.07 days, and the lead time for kit with unknown shortages is taken to be 3.75 days.

The average lead time of production order with unknown shortages is 3.75 days, while the average lead time of production order without unknown shortages is 3.07 days. The difference between the average lead times appears to be small because that supermarket assemblers work over time to build those assemblies once the unknown shortages are fulfilled in order to meet on time delivery; however, assembly shortages happen when they are not able to deliver on time.

3. Impact of Assembly Lead Time Increase

- **Impact on Current Gold Square System**

Assembly lead time increase, caused by both known shortages and unknown shortages of piece parts, leads to assembly shortages in the production line.

In order to reduce assembly shortages, the currently implemented Gold Square system run by supermarket production control deviates from the planned Gold Square system. This is a major reason why the currently implemented Gold Square system is a combination of a signal-based, pull system and an MRP-driven, push system as presented in Section 5.1.2.

However, assembly shortages are not effectively reduced by currently implemented Gold Square system, the assembly service level is not satisfactory especially during high throughput period.

- **Impact on Proposed Gold Square System**

In Section 5.2.2, a consumption-based planning system, which is a pull system, is proposed to manage the Gold Square assembly inventory on a make-to-stock basis. The base stock level B is given by

$$B = \mu(L + r) + z\sigma\sqrt{L + r} \tag{6-5}$$

The expected inventory level E[I] is given by

$$E[I] = 0.5 * \mu * r + z\sigma\sqrt{L + r}$$

(6-6)

Where

$\mu = mean\ weekly\ demand\ (quantity/week)$

$L = lead\ time\ (weeks)$

$r = review\ period\ (weeks)$

$z = safety\ factor$

$\sigma = standard\ deviation\ of\ weekly\ demand$

$\mu(L + r)$ is commonly referred to as cycle stock or pipeline stock. The second term, $z\sigma\sqrt{L + r}$, is referred to as safety stock.

If μ, r, z and service level are given, lead time increase will lead to base stock level B increase as well as the expected inventory level E[I] increase.

Table 6-3 presents the cycle stock and safety stock level increase due to shortages. As presented in Table 6-3, a 'production request' means when there's a request for assembly production, and known shortages are detected during this stage; after there's no known shortages, a production request will turn into a production order, and unknown shortages are detected afterwards. The percentage shown in Table 6-3 represents the service level of production request at each individual condition. For the data from March 26th to April 20th 2012, there was nearly no production request that had both known shortages and unknown shortages, which is similar as the calculated 1.5% as presented in the table.

As presented in Table 6-3, unknown shortages increase cycle stock by 17% and safety stock by 8%, while known shortages increase cycle stock by 64% and safety stock by 28%.

Table 6-3: Cycle Stock and Safety Stock Level Increase Caused by Shortages

Production request	without shortages	with unknown shortages	with known shortages	with known and unknown shortages
% of production request	73.5%	14%	11%	1.5%
lead time (days)	3.07	3.75	3.07 + 2.6	3.75 + 2.6
lead time % increase	0%	22%	85%	107%
L + r (days)	4.07	4.75	4.07 + 2.6	4.75 + 2.6
cycle stock % increase	0%	17%	64%	81%
safety stock % increase	0%	8%	28%	34%

6.4.2 Additional Internal Efforts and Logistics Cost

1. Additional Internal Efforts

Supermarket production control, kit picker, buyers and expediters, and Materials Group spend plenty of efforts daily to deal with both known and unknown piece part shortages.

As shown in Figure 6-1, once a shortage is detected, either known or unknown, production control needs to contact corresponding buyers and expediters. Buyers and expeditors first check the next scheduled delivery, if it is later than the request date, buyers and expeditors will send an expediting request to vendors to expedite the piece parts. After the piece parts arrive, production order will be issued or kit picking process will be resumed. Besides, Materials Group does unknown shortages tracking every business day through 'SMKT Pick List Cover Sheet' in order to keep reducing unknown shortages which is detailed in Section 6.5.

Furthermore, piece part shortages cause lower efficiency and effectiveness at supermarket build area and UES production line. Waiting for kits at supermarket build area, starvation and workaround on UES production line caused by piece part shortages are one of the driving reasons that piece part service level needs to be improved.

2. Additional Logistics Cost

Whenever an expedited inbound delivery is requested other than the normal delivery, additional logistics cost is spent to fulfil the shortages. This applies to both domestic and international vendors.

Given the time and data limitation of the project, inbound expediting data of January 2012 was collected and only those shipments with bill weight less than 200 pounds were considered to calculate the average logistics expense per piece part expediting.

In January 2012, total expense spent on inbound transportation from all over the world to Varian was around $ 600K, out of which only $ 35K were spent on expediting 448 shipments with bill weight less than 200 pounds, which is $ 80 per expediting for logistics expense on average.

- **Data Collection**

Unknown shortage data was collected from Materials Group for the time period from the week of May 26, 2011 to the week of June 21, 2012. There were 788 unknown shortage instances in total, and the shortage breakdown is shown in Figure 6-4.

Table 6-4: Piece Part Unknown Shortage Instances Breakdown

Inventory System	Percentage of Shortage Instances
MRP System	82%
Two Bin Kanban System	14%
Consignment System	2%
Other	2%

- **Cost Estimation**

Kanban expediting usually doesn't generate additional logistics expense, as most Kanban piece parts are supplied from local vendors and expediting is just to pull in the next order as replenishment faster. While MRP and Consignment piece parts come in batches with orders being driven by SAP, those piece parts need additional logistics expense occasionally.

Table 6-5 presents the estimated expediting cost associated with unknown shortages under three different assumptions, where 100%, 60% or 20% of those piece parts with unknown shortages need to be expedited. In the table, 84% refers to 82% unknown shortages from MRP driven piece parts and 2% unknown shortages from Consignment system.

Table 6-5: Expediting Cost Estimation for Unknown Shortages

Percentage of unknown shortages need additional logistics expense for expediting	Expense
84%*100%	$ 53 K
84%*60%	$ 32 K
84%*20%	$ 11 K

As mentioned earlier in Section 6.3.1, known shortages are not tracked; therefore, known shortage percentage and unknown shortage percentage were used to estimate the amount of known shortage instances over the same period of time, and we estimated that there were around 700 known shortage instances. Following the similar calculation as Table 6-5, the overall logistics expense over the week of May 26, 2011 to week of June 21, 2012 is presented in Table 6-6. In the table, 84% refers to 82% unknown shortages from MRP driven piece parts and 2% unknown shortages from Consignment system.

Table 6-6: Expediting Cost Estimation for Overall Shortages

Percentage of overall shortages need additional logistics expense	Expense
84%*100%	$ 100 K
84%*60%	$ 60 K
84%*20%	$ 20 K

According to the additional logistics cost analyses, piece part shortages do have a direct impact on the transportation expense generated during expediting. The cost for expediting is only a small percentage of the entire expense, which is less than 1% of the overall annual transportation cost including both inbound and outbound transportation.

6.5 Investigation of Unknown Shortages

6.5.1 Unknown Shortages Breakdown

As presented earlier, there were 788 instances of unknown shortages happened over the week of May 26, 2011 to the week of June 21, 2012, and those 788 instances of unknown shortages were distributed amongst 605 various kinds of piece parts. Out of these 605 various types of piece parts, 77.4% of them only went short once during the one year period of time, which represent 59.4% of the total shortage instances, and 94.8% of them went short either once or twice during that period, which represent 86.0% of the total shortage instances, as shown in Table 6-7.

Table 6-7: Unknown Shortages Breakdown

# of times of shortage instances happened for a particular piece part type	**6**	**5**	**4**	**3**	**2**	**1**	**Sum**
Count of piece part varieties which have that particular times of shortage instances	1	3	5	23	105	468	605
Percentage of the above	0.2%	0.5%	0.8%	3.8%	17.4%	77.4%	100%
					94.8%		
Total count of shortage instances	6	15	20	69	210	468	788
Percentage of the above	0.8%	1.9%	2.5%	8.8%	26.6%	59.4%	100%
					86.0%		

This reveals that unknown shortages don't follow a clear pattern, appear to be random and usually don't reoccur; therefore, a more in-depth study of the causes leading to unknown shortages needs to be conducted to identify where the problem is.

6.5.2 Causes for Unknown Shortages

Materials Group continuously identifies and improves unknown shortages. From January 2012 to July 2012, Materials Group studied the reasons for unknown shortages taking every Thursday as a sample, and the consolidated Pareto Chart in present in Figure 6-5.

As shown in Figure 6-5, the top 4 reasons for supermarket unknown shortages are presented here with their corresponding strategies to mitigate shortages which are developed and implemented by Materials' Group, and continuous improvements have already been witnessed since January 2012.

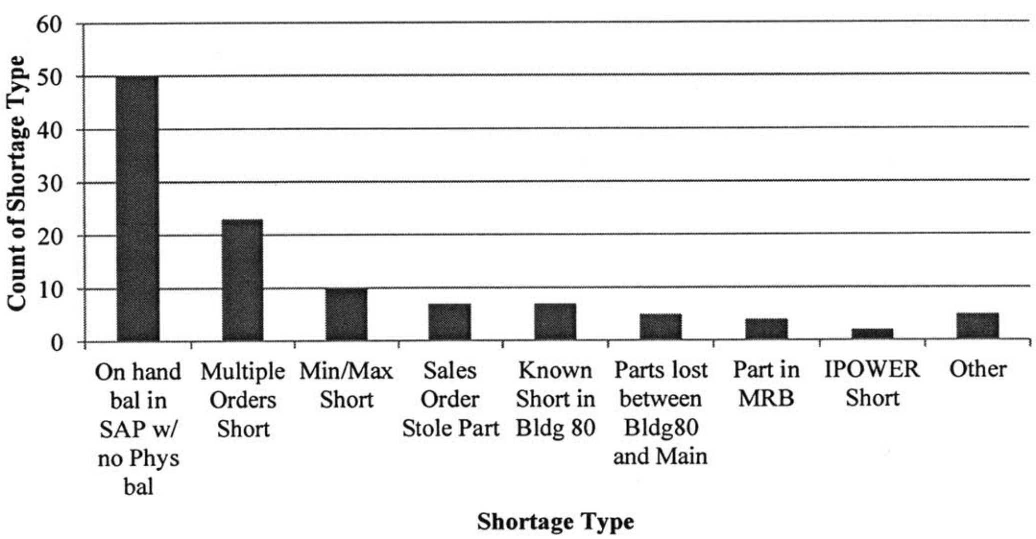


Figure 6-5: Reasons for Supermarket Unknown Shortages (Jan-Jul 2012)

1. Available on hand balance in SAP, but with no physical on hand balance

This is the typical unknown shortage type, 'bad on hand balance'. It means that when SAP shows there is available on hand balance while there is actually no physical on hand balance. Bad on hand balance, the dominant reasons for supermarket unknown shortages, leads to 42% of the entire supermarket piece part unknown shortages.

The current and ongoing solutions for bad on hand balance will be discussed in Section 6.5.3 and Section 6.6.

2. Multiple Orders Shortage

Multiple orders shortage happens when there are multiple production orders requesting for the same piece parts which have less on hand balance than the request, it doesn't show up as shortages on SAP initially during availability check but it shows up as shortages for those who pick the kit last.

The multiple orders shortage categorized here will be solved by Electronic Warehouse Management system (EWM) which is capable of tracking all materials transactions, including receiving, putaway, shop order issuing, consolidation waiting stage, and finished goods assembly at Gold Square.

3. Min/Max Shortage

Min/Max stands for open storage inventory which are free to take at any time for anyone. Min/Max inventory is not tracked by SAP and it is being monitored periodically and replenished when it is necessary.

In order to reduce Min/Max shortage, quarterly reviews are conducted to capture requirements not adequately depicted in forecasting and safety stocks are put up to deal with shortages.

4. Sales Order Stole Part

If an unexpected sales order comes in, it 'steals' piece part driven by SAP, hence causing piece part unknown shortages.

6.5.3 Bad on Hand Balance – Transmittal Process

1. Transmittal Process

The flow chart presented in Figure 6-6 shows the current transmittal process.

The left flowchart shows the piece parts picking process. Currently, the supermarket storage area is an open storage area, as shown in Figure 6-7, where anyone can enter to pick up any piece parts they want. When there is a piece part request not driven by SAP, such as piece parts is required due to break and loss, the transmittal form is required to be filled out in order for data entry into SAP system by production control to keep accurate on hand balance. However, occasionally the transmittal form filling is skipped for certain piece parts, which eventually causes bad on hand balance for these piece parts. The right flowchart shows the data entry process. Transmittal forms are collected daily by production control and corresponding new requisition are created in SAP to update inventory level and drive additional demand request for those piece parts.

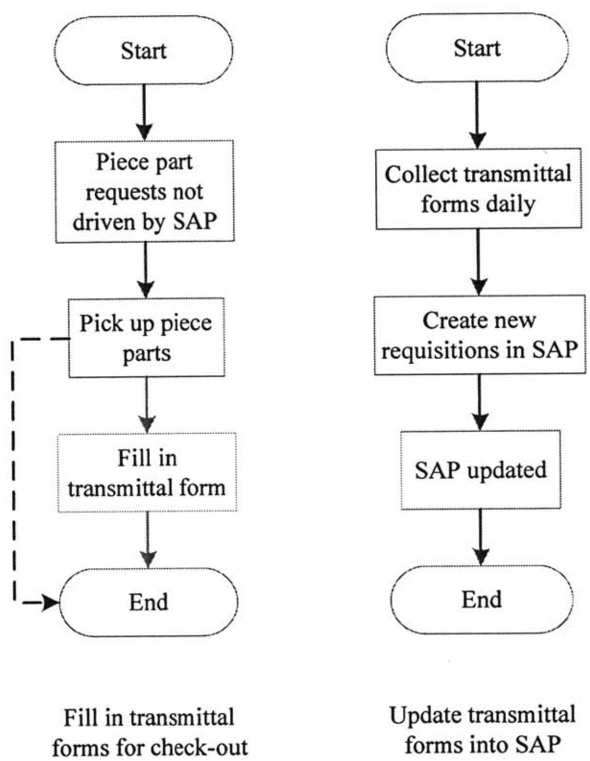


Figure 6-6: Current Transmittal Process

2. Current and Ongoing Solutions

Materials Group continuously identifies and brings in new ways to reduce bad on hand balance.

Currently, in front of the shelves of MRP driven, Two bin Kanban and Consignment piece parts, new supermarket signage and tapes on the floor are used to remind transmittal form filling, and transmittal forms are made available at more than 10 different places in supermarket material storage area, as shown in Figure 6-7. Min/Max shelves have been rearranged into designated areas, shown as free stock in Figure 6-7, in order for easy recognition and less confusion. Besides, audit cycles of transmittal forms are increased from daily to higher frequency to get more frequent data entry into SAP. Furthermore, kit pickers at supermarket area and Building 80 are both required to report bad on hand balances immediately to auditors when an unknown shortage is detected, and are required to use a 'Last Part Taken Sheet' to report last part taken in order to send out replenishment request immediately.

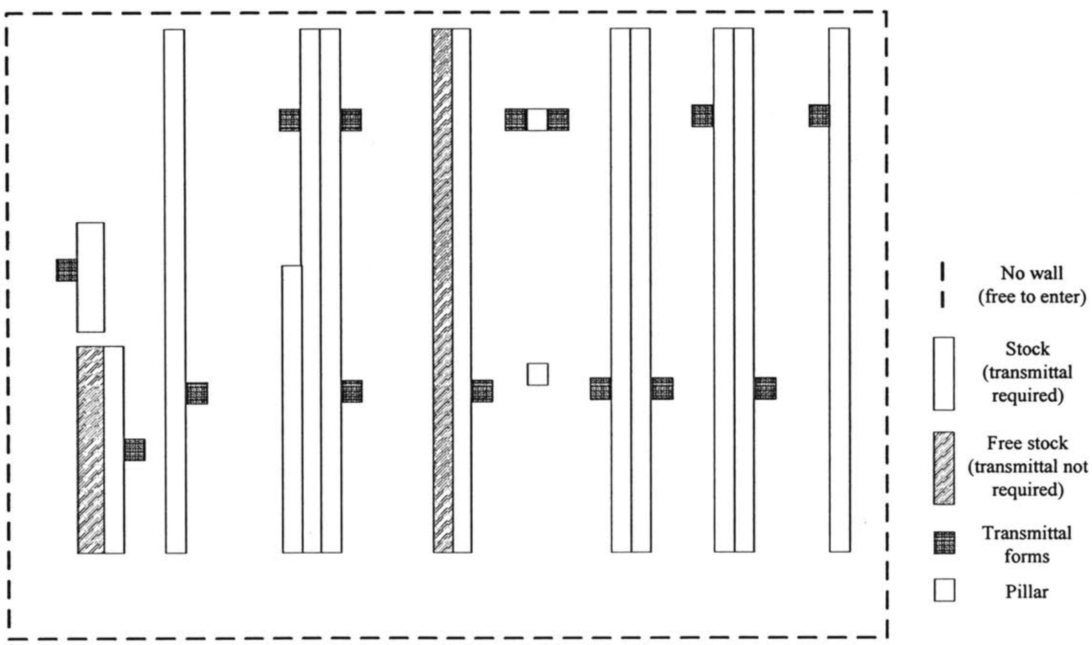


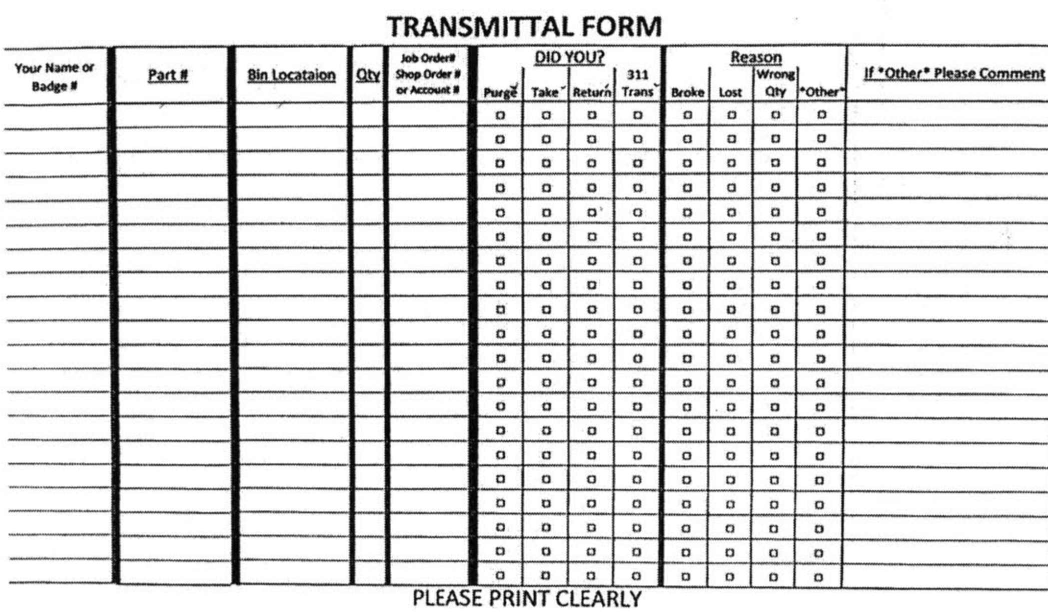
Figure 6-7: Layout of Supermarket Storage Area

Besides, EWM will be implemented at supermarket storage area in August 2012 to track the movement and storage of materials including piece parts between Varian's various storage locations and process all associated transactions, including receiving, putaway, picking and shipping [11]. However, the current transmittal form process will not be replaced by the EWM system process and Varian management has decided to remain this process to do data entry for additional piece parts requests that are not driven by SAP.

Both current and ongoing solutions are not effective in addressing the problem of the current transmittal process.

3. Investigation of Transmittal Process

Figure 6-8 shows the current transmittal form being used in the supermarket storage area and a couple of other locations as well. This transmittal form is used for SAP update of additional requests not driven by SAP.



TRANSMITTAL FORM

Your Name or Badge #	Part #	Bin Locataion	Qty	Job Order# Shop Order # or Account #	DID YOU? Purge	Take	Return	311 Trans	Reason Broke	Lost	Wrong Qty	*Other*	If *Other* Please Comment
					□	□	□	□	□	□	□	□	
					□	□	□	□	□	□	□	□	
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					□	□	□	□	□	□	□	□	

PLEASE PRINT CLEARLY

Figure 6-8: Current Transmittal Form

There are two situations when this transmittal process causes bad on hand balance. The first and dominant situation happens when the transmittal forms are not filled, especially during the working shifts when supermarket supervisors are not present. The second situation happens when the transmittal forms are not filled correctly which also causes bad on hand balance.

According to the observation of shop floor workers' usage of transmittal forms, we found out that after picking the piece parts, workers had to walk to a nearby transmittal form, take it off the rack, find a desk nearby, and then fill in the required information regarding 1) 'Your Name or Badge #', 2) 'Part #', 3) 'Bin Location', 4) 'Quantity', 5) 'Job Order #, Shop Order # or Account #', 6) 'DID YOU? Purge, Take, Return or 311 Trans', and 7) 'Reason? Broke, Lost, Wrong Quantity or Other'. After that, workers have to put the transmittal form back. The entire process takes around 2 minutes or longer for only 1 type of piece part picking.

The transmittal forms have a couple of disadvantages, thereby providing suboptimal user experience. Those disadvantages are discovered and validated through interviews and discussions with shop floor workers and engineers who use the transmittal form. First, there are no clear instructions on how to choose 'DID YOU? Purge, Take, Return or 311 Trans', so that workers usually choose 'Take'. Second, when engineers take or return piece parts, they often don't fill in the transmittal forms as there are no clear instructions as well. Third, 'Part #' and 'Bin Location' are duplicated information in the form which takes additional time. Fourth, currently, transmittal forms are collected and updated on a daily basis, so there is a discrepancy between SAP and physical on hand balance which again causes unknown shortages. Fifth, handwriting on the transmittal forms is difficult to recognize. All these above cause bad on hand balance.

Besides, it is inconvenient and time-consuming for production control to create new requisitions to update transmittal forms information into SAP.

6.6 Proposed Solutions for Piece Part Inventory Management

As presented in the unknown shortages Pareto Chart in Figure 6-5, all the unknown shortages caused by reasons other than bad on hand balance can be either reduced or completely resolved by EWM system or other methodologies developed by Materials' Group. While unknown shortages caused by bad on hand balance don't have an effective solution in the short term; therefore, this section presents a roadmap of two methods with associated piece part inventory management systems to reduce and then completely resolve unknown shortages caused by bad on hand balance.

Method One aims to provide solutions with better user experience to replace current transmittal process. As discussed under 'Investigation of Transmittal Process' in Section 6.5.3, most of these disadvantages are addressed here to in order to improve transmittal process adoption ratio, reduce unknown shortages and simplify the overall data entry process. Method One is recommended for short/middle term solution for piece part inventory management.

Method 2 aims to provide solutions which drastically or even completely solve the unknown shortages caused by bad on hand balance. Besides the major problem of bad on hand balance which is addressed here, there are also other important benefits of Varian management's particular interests which are discussed into details in this section.

6.6.1 Method One – Electronic Transmittal

Figure 6-9 shows the comparison between current paper transmittal process and proposed electronic transmittal process.

The current transmittal process shown in Box 1 was discussed in Section 6.5.3, Figure 6-6. The proposed electronic transmittal process shown in Box 2 uses electronic device for data entry instead of the current paper transmittal form.

The advantages associated with electronic transmittal process come with better user interface and user experience. Compared with the current paper transmittal form, first and most importantly, electronic transmittal process costs less time for workers, eliminates unnecessary information and provides clear instructions for each individual step which eliminates confusions. Unnecessary information here means that 'Part #' and 'Bin Location' are duplicated information in the paper transmittal form to ensure the handwriting can be understood, so that one of this unnecessary information can be eliminated in the proposed electronic transmittal process.

Besides, electronic transmittal process can be either updated into SAP system instantly or can be updated multiple times a day into SAP through production control if it is necessary.

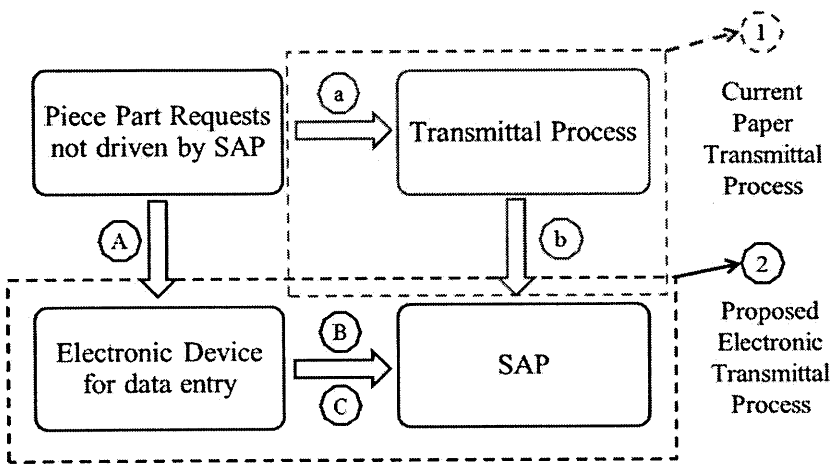

Figure 6-9: Comparison between Current and Proposed Transmittal Process

There are two types of electronic device solutions recommended to implement the proposed electronic transmittal process.

1. EWM Solution

- **Current EWM System**

The first electronic device solution comes together with EWM. Varian is going to implement EWM system in supermarket storage area in August 2012 to track the movement and storage of piece parts, and process all associated transactions, including receiving, putaway, picking and shipping [11]. Varian's EWM system to be implemented at supermarket area consists of barcode scanners as shown in Figure 6-10 for all the kit picking process that is driven by SAP, either for assembly build, direct sales or global material bank transfer.

While for those additional piece part requests not driven by SAP, whether they are parts broke, lost or wrong quantity, barcode scanners cannot be used to create new requisitions therefore the current transmittal form still remains.

Figure 6-10: EWM Barcode Scanner [12]

- **Proposed EWM solution**

The proposed EWM solution enables the function of creating new requisition directly through barcode scanner, and the requisition will directly goes into SAP system to update the real time inventory level.

Each time when non-SAP driven piece parts are requested, barcode scanning process is required for data entry into the SAP system as shown in Figure 6-11.

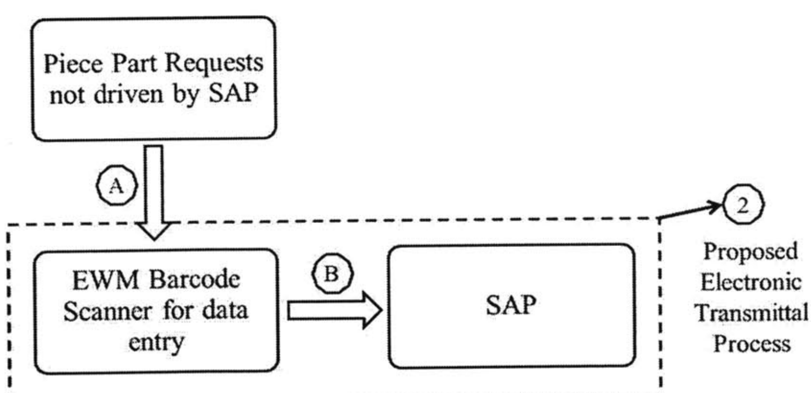

Figure 6-11: EWM Solution

The proposed EWM solution best leverages the facility of EWM system and only requires a little change to existing system.

- **Feasibility analysis**

With this EWM solution, anyone who may pick up non-SAP driven piece parts, including assemblers, engineers, contractors and etc., need SAP authorization in order to use barcode scanner. However, currently not everyone has SAP authorization, and additional SAP authorization is not cheap. Besides, management prefers not to make SAP accessible to everyone and only a few people are authorized to make changes to SAP system. Furthermore, additional expense is required for SAP training and maintenance for this EWM solution.

2. Tablet Solution

Besides the EWM solution, this tablet solution provides electronic terminals at multiple locations for self-check-out. Secured tablets are recommended as self-check-out terminals because they can provide superior user interface and user experience and they are consumer products with low price.

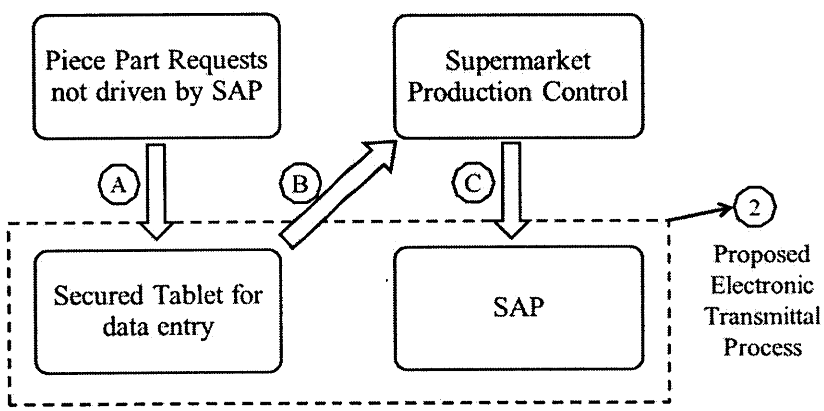

Figure 6-12: Tablet Solution

In Figure 6-12, it shows that non-SAP driven piece part consumption data is entered through secured tablets. After that, a request to create piece part requisition is sent to supermarket production control for confirmation and authorization. It ensures that only authorized people are able to make updates in SAP. Besides, it also provides production control with better user experience as requisition is created and updated into SAP automatically after authorization, and production control can authorize requisition request more frequently and easily compared with current transmittal form process.

The proposed tablet solution requires special software with an application developed for mobile devices, which is able to send requests to create piece part requisition, and a software installed on computer for production control to do confirmation and authorization. The software connects with SAP and creates new requisition in SAP after approved by production control. The application can be installed on various smartphone platforms as well so that each employee can log on the application from their own smartphones for data entry, this saves additional time on entering personal identification information.

- **Feasibility analysis**

Technically, the software can be developed either in-house by Varian's IT department or by outsourcing.

Financially, the investment on software development and a dozen of tablets can be easily returned within one year or even faster by savings from piece part expediting, internal efforts dealing with transmittal forms and unknown shortages.

Besides, the software is able to track employee's utilization of the electronic transmittal process; therefore, certain incentives can be given to increase the utilization of this solution to continuously reduce unknown shortage percentage and instances.

3. Comparison

As shown in Table 6-8, the tablet solution excels in all the dimensions compared with the EWM Solution; therefore, the tablet solution is recommended as a short to medium term solution to reduce bad on hand balance.

Table 6-8 presents the comparison between the EWM solution and the tablet solution.

As shown in Table 6-8, the tablet solution excels in all the dimensions compared with the EWM Solution; therefore, the tablet solution is recommended as a short to medium term solution to reduce bad on hand balance.

Table 6-8: Comparison between EWM Solution and Tablet Solution

	EWM Solution	**Tablet Solution**
User Experience	Medium	Easy to use
Accessibility	Limited access	Easy to access
Upgradable	Difficult	Easy
Investment	Medium	Low
Effectiveness in addressing bad on hand balance	Medium	More effective
Feasibility	Low – Medium	Medium – High
Recommend?	Not recommend	Recommend for short/mid term

One thing to notice here for Varian management, the tablet solution will gradually reach its up limit as supermarket storage area is still an open storage space where actually anyone is free to take any part at any time, it is nearly impossible to eliminate bad on hand balance by using the tablet solution. Therefore, in the middle to long term, a more effective solution is necessary to replace the table solution.

4. Implementation of Tablet Solution

- **Pilot Project**

We recommend to carry out a pilot project study before the fully implementation of the tablet solution. Pilot project is aimed to evaluate tablet solution's feasibility, effectiveness, time, cost, adverse effects, and etc. in an attempt to improve upon the pilot project's feedback prior to the implementation of the full-scale tablet solution [13].

Tablet solution has two key advantages over current transmittal form process. First, it provides piece part pickers with easier and better user experience to enter data through tablet terminals. Second, it makes requisition creation into SAP much easier for production control.

The pilot project will focus on providing piece part pickers with easier and better user experience as this directly reduce unknown shortages caused by bad on hand balance. In the pilot project, the user interface of the self-check-out tablet terminal should be carefully designed to make user experience as simple and as easy as possible in order to evaluate the effectiveness of the solution in addressing the bad on hand balance problem. While in the pilot project, it is not necessary to incorporate the function of automatic SAP requisition creation into the solution, and this process can still be conducted manually by production control. As shown in Figure 6-12, data entered through tablet can be updated to production control in real time through Step B, while Step C has to be done manually by production control in the pilot project stage.

- **Pilot Experiment Design**

In order to better study the effectiveness of the tablet solution, in the pilot project, we recommend fully replacing the transmittal forms in one or two storage passages (storage passage is the passage between two storage shelves as shown in Figure 6-7) with secured tablet terminals, and each individual selected storage passage should have comparable storage passage which still use the paper transmittal process for check-out. The storage passages with secured tablet terminals are experimental group, and the storage passages with paper transmittal process are control group. The storage shelves of the experimental group and control group should have comparable piece part varieties, bin quantities and bad on hand balance histories.

From historical unknown shortages, we observe that 4-week is an adequate length of time to eliminate unknown shortage fluctuations from week to week. Therefore, 4-week average of certain parameter is used to compare experimental group and control group. Week 0 is the starting week when the pilot project starts, while the comparison between experimental and control group only starts from Week 5 as there is a time lag effect between when bad on hand balance takes place and when the unknown shortages are detected.

Table 6-9 presents the comparison between experimental group and control group, the results column $P_n' - P_n''$ shows the relative percentage improvements in reducing unknown shortages caused by bad on hand balance for each week starting from Week 5 to Week 12.

Table 6-9: Results from Pilot Experiment

	Control group	**Experimental group**	**Results**
Adjusting factor	C'_{AF}	C''_{AF}	
Week 5	P'_5	P''_5	$P'_5 - P''_5$
Week 6	P'_6	P''_6	$P'_6 - P''_6$
Week 7	P'_7	P''_7	$P'_7 - P''_7$
Week 8	P'_8	P''_8	$P'_8 - P''_8$
Week 9	P'_9	P''_9	$P'_9 - P''_9$
Week 10	P'_{10}	P''_{10}	$P'_{10} - P''_{10}$
Week 11	P'_{11}	P''_{11}	$P'_{11} - P''_{11}$
Week 12	P'_{12}	P''_{12}	$P'_{12} - P''_{12}$

P_n represents the percentage of current 'unknown shortage instances caused by bad on hand balance per kit' divided by past year's 'unknown shortage instances caused by bad on hand balance per kit', the adjusting factor C_{AF} is used here to eliminate the possible differences between experimental group and control group. P_n' represents P_n for control group, while P_n'' represents P_n for experimental group.

$$P_n = \frac{C_n}{C_{AF}} \times 100\%, \qquad for\, n \geq 5$$

(6-7)

C_n is the 4-week average of 'unknown shortage instances caused by bad on hand balance per kit' for Week n.

$$C_n = \frac{a_j * \sum_{n-3}^{n} U_i}{\sum_{n-3}^{n} N_i}, \qquad for\, n \geq 5$$

(6-8)

Where

U_i is the total amount of unknown shortage instances for Week i for the given group.

a_j is the percentage of 'unknown shortages caused by bad on hand balance' out of 'the overall unknown shortages' during the time period of concern.

N_i is the total amount of kits picked in supermarket area for Week i.

C_{AF} is the adjusting factor for each individual group, it means 'count of unknown shortages caused by bad on hand balance per kit' for the past year.

$$C_{AF} = \frac{a_i * U_P}{N_P} \tag{6-9}$$

Where

U_P is the count of unknown shortage instances over the past year for the given group.

a_i is the percentage of 'unknown shortage instances caused by bad on hand balance' out of 'the overall unknown shortage instances' over the time period of concern.

N_P is the count of total kits picked in supermarket area over the past year.

- **Targeted Results and Discussions**

By the end of Week 12, the value of $P'_{12} - P''_{12}$ is targeted to reach 50%. It means generally that unknown shortages caused by bad on hand balance are reduced by 50%. If the value of $P'_{12} - P''_{12}$ reaches 50%, the savings on expediting cost are in the same scale as the total investment on the pilot project of the tablet solution, while the savings on expediting cost is only one small benefit out of the entire benefits from unknown shortages reduction which will be detailed later in this section; therefore, by reaching 50% target, Varian is able to obtain high return on investment out of the pilot project of this tablet solution.

Throughout the period of pilot project experiment starting from Week 0, user experience survey should be conducted to receive feedback in order to make continuous improvements on the pilot tablet solution. We recommend to start user experience survey from Week 0 because 1) user experience can be evaluated immediately by users starting from Week 0, and 2) the measurement of user experience improvements can only be reflected 4-5 weeks later through results of $\mathrm{P}_{\mathrm{n}}' - \mathrm{P}_{\mathrm{n}}''$ due to the time lag effect.

Potential directions for improvement include but not limit to number of available secured tablets at each storage passage, the locations of placement for those tablets, user interface of the self-check-out application on the tablet, and etc. User experience survey should be conducted on a weekly basis, and potential improvements should be made immediately whenever it is necessary.

The efforts of continuous user experience improvement will keep reducing unknown shortages caused by bad on hand balance, and the trend will be visible from the increase of the results. It is possible that improvement may meet certain bottleneck, focus group study and investigation is necessary to further improve the solution.

- **Full-scale Implementation**

By the end of the pilot project, the tablet solution has already gone through iterations of product improvements and development. $P_n' - P_n''$ trend shown through the pilot project will be an effective indicator of the effectiveness of the tablet solution in addressing the bad on hand balance problem. The benefits will be discussed in the following section, Section 5 of Section 6.6, for management to decide whether the full-scale implementation will benefit the operation of supermarket area. In general, unknown shortage reduction 1) reduces assembly shortages on UES line, 2) reduces Gold Square assembly lead time, 2) reduces Gold Square size, 3) reduces internal efforts for piece part pickers, production control, buyers and expediters, 4) reduces cost for expediting piece parts, and 5) increase efficiency of supermarket build area; while the investment on the tablet solution is one time and cost less than $10,000 for full-scale implementation as shown in Table 6-10, besides the tablet solution also brings additional benefits in simplifying production control's job in creating new requisition in SAP.

In full-scale implementation, secured tablets as self-check-out terminals are made available for each storage passages, and paper transmittal process is no longer available for supermarket storage area. Instead of temporary tablet application, fully functional software solution including both tablet application for piece part pickers and computer software for production control is developed, tested, improved and implemented. Upon the time of full-scale implementation, formal notifications are required for all relevant stakeholders, for example, new supermarket signage is required to replace the existing signage. Table 6-10 presents the comparison between pilot project and full-scale implementation.

Table 6-10: Comparison between Pilot Project and Full-scale Implementation

<table>
<tr><th colspan="2"></th><th>Pilot Project</th><th>Full-scale Implementation</th></tr>
<tr><td colspan="2">Implementation Scale</td><td>1 or 2 storage passages</td><td>Full scale</td></tr>
<tr><td colspan="2">Transmittal Process</td><td>Remains for other storage passages</td><td>Fully replaced</td></tr>
<tr><td colspan="2">Function 1: Step B, as shown in Figure 6-12
Data entry through tablet to production control</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Function 2: Step C, as shown in Figure 6-12
Automatic requisition creation into SAP</td><td>No</td><td>Yes</td></tr>
<tr><td colspan="2">Time to Develop Solution</td><td>2-4 weeks</td><td>4-8 weeks</td></tr>
<tr><td colspan="2">Total Investment</td><td>≤ $ 4,000</td><td>≤ $ 10,000</td></tr>
<tr><td colspan="2">Targeted Results</td><td>Gradually reduce unknown shortages caused by bad on hand balance by 50%</td><td>Reduce unknown shortages caused by bad on hand balance by 50% or higher</td></tr>
<tr><td rowspan="6">Benefits[13]</td><td>Reduce assembly shortages on UES line</td><td>Yes (partially)</td><td>Yes</td></tr>
<tr><td>Reduce assembly lead time</td><td>Yes (partially)</td><td>Yes</td></tr>
<tr><td>Reduce Gold Square size</td><td>Yes (partially)</td><td>Yes</td></tr>
<tr><td>Reduce internal efforts[14]</td><td>Yes (partially)</td><td>Yes</td></tr>
<tr><td>Reduce expediting cost</td><td>Yes (partially)</td><td>Yes</td></tr>
<tr><td>Increase efficiency of supermarket build area</td><td>Yes (partially)</td><td>Yes</td></tr>
</table>

[13] Benefits are discussed in details in Section 5 under Section 6.6.1.
[14] Internal efforts covers piece part pickers, production control, buyers and expediters.

As presented in Table 6-10, the full-scale implementation targets at reducing unknown shortages caused by bad on hand balance by 50% or higher, this will generate 6 various benefits for Varian as a whole, which is detailed discussed in the following section.

- **Benefits of Proposed Solution**

  - **Reduce Assembly Shortages on Production Line**

As presented in Figure 5-2, production control issues production order for required assemblies 3 days before machine lay down date. If a piece part is not available in supermarket storage area while available in Building 80, it takes at least half a day up to a full day to transport the required piece part from Building 80 to supermarket; while usually this doesn't cause assembly shortages. However, if there are any unknown shortages, it will take a couple of days in average to fulfil the shortages by expediting from either domestic or international vendors, and then this causes assembly shortages on production line.

By reducing unknown shortages caused by bad on hand balance, assembly shortages on UES line will be reduced. From historical unknown shortages data gathered from daily 'SMKT Pick List Cover Sheet', it shows that most kit with unknown shortages only have shortage for one type of piece part. By reducing unknown shortages caused by bad on hand balance by 50%; the assembly shortages on production line caused by bad on hand balance of piece part will be reduced by 50%.

  - **Reduce Assembly Lead Time**

The average lead time of Gold Square assemblies is increased by unknown shortages. The time spent between when a production order is issued and when a kit is fulfilled is increased by the time spent on unknown shortages detection, report and fulfillment. It is shown in Table 6-2 that unknown shortages increase lead time from average 3.07 days to 3.75 days, and it has been explained there why lead time increase caused by unknown shortages appears to be small.

➢ **Reduce Gold Square Size**

A pull system is proposed to manage Gold Square assemblies' inventory as shown in Section 5.2.2, and the base stock level B, presented in Section 3 of Section 6.4.1, is given by

$$B = \mu(L + r) + z\sigma\sqrt{L + r}$$

(6-10)

The expected inventory level E[I] is given by

$$E[I] = 0.5 * \mu * r + z\sigma\sqrt{L + r}$$

(6-11)

Where the units of L and r are weeks.

Therefore certain percentage of assembly lead time reduction will lead to even higher percentage of B and E[I] level reduction.

➢ **Reduce Internal Efforts**

By reducing unknown shortages, the additional internal efforts spent on dealing with those unknown shortages will be reduced, and the beneficial stakeholders include kit picker, production control, buyer and expediter, Materials Group and people from receiving.

As presented earlier, there are 788 instances of unknown shortages happened over the week of May 26, 2011 to the week of June 21, 2012. By effectively reducing those unknown shortages caused by bad on hand balance by 50%, the entire unknown shortages will drop by 20%. It means that the average weekly unknown shortage instances will be reduced by 3 from the original 14 shortages instances per week. This is based on the assumption that all the other unknown shortages not caused by bad on hand balance will still remain, while as mentioned earlier in Section 6.5.3, those other unknown shortages already have effective solutions.

> **Reduce Expediting Cost**

The additional logistics cost spent on unknown shortages caused by bad on hand balance can be reduced by 50%. Table 6-11 is presented here again to calculate the estimated annual savings on expediting cost. As shown in the table, 84% refers to 82% unknown shortages from MRP driven piece parts and 2% unknown shortages from Consignment system.

Table 6-11: Estimated Annual Savings on Expediting Cost

Percentage of unknown shortages need additional logistics expense	Expense	Savings on Expediting (Expense * 20%)
84%*100%	$ 53 K	$ 11 K
84%*60%	$ 32 K	$ 6.4 K
84%*20%	$ 11 K	$ 2.2 K

The savings on expediting cost are not significant; however, it can be seen that the savings on expediting are in the same scale as the total investment on the full-scale implementation of the tablet solution. Besides, the savings on expediting cost is only one small benefit out of the entire benefits from unknown shortages reduction; therefore, it further proves the financial feasibility of the tablet solution.

> **Increase Efficiency of Supermarket Build Area**

Unknown shortages make assemblers at supermarket build area wait until those shortages are fulfilled, so that the efficiency at this time is reduced. Besides, after those shortages are fulfilled, more production orders are accumulated and assemblers have to work overtime to accomplish those requests.

By reducing unknown shortages, production orders will be more balanced thereby enhancing the efficiency of supermarket build area.

6.6.2 Method Two – Enclosed System

For Method One, it provides solutions with better user experience, while the supermarket storage area is still an open storage space which is available to anyone at any time; therefore, Method 1 is not able to reduce unknown shortages caused by bad on hand balance by 100%, and the target of the tablet solution is around 50% reduction of unknown shortages caused by bad on hand balance or higher.

In short to middle term, Method One is sufficient to address bad on hand balance; however, in middle to long term, Method One is not sufficient enough as it will reach its limit in addressing this problem. Therefore, Method Two, an enclosed system is recommended here to effectively address the bad on hand balance problem. An enclosed system will completely eliminate unknown shortages caused by bad on hand balance.

1. **Enclosed SMKT Storage Solution**

Enclosed supermarket storage solution is presented in Figure 6-13. For this solution, the supermarket storage area is no longer an open storage place, it will be enclosed and all the transmittal forms will be removed. For all these non-SAP driven consumption, check-out is mandatory which is monitored by additional staff at each individual working shift. At the point of check-out, new requisition is created and updated into SAP to keep real time update of inventory level.

2. **VLM Solution**

Vertical Lift Module (VLM) is an inventory storage system comprises vertically arranged trays for storage, a delivery lift platform mechanism, and a computerized control system [14]. A tray can be requested by requesting a part either from the software or from the built-in control pad, and then the tray is automatically brought to the access point. After that, the operator picks or replenishes stock and then the tray is returned to home after confirmation [15].

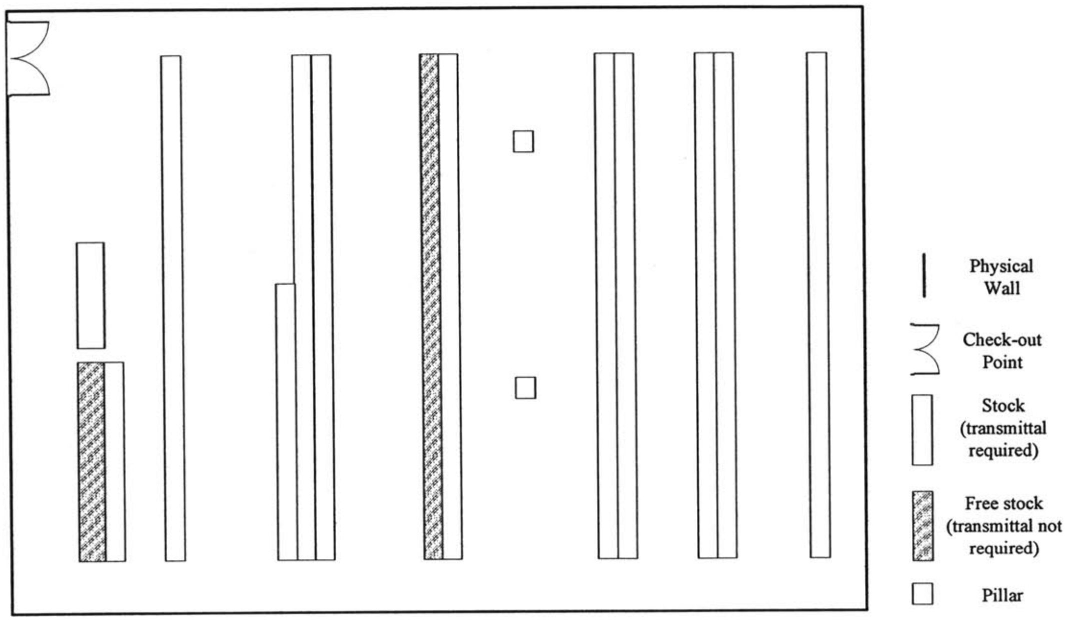

Figure 6-13: Enclosed SMKT Solution

Similarly as the enclosed supermarket storage solution, new requisition creation is mandatory when requesting piece parts not driven by SAP. Therefore, real time and accurate inventory update is achieved to eliminate bad on hand balance.

3. Comparison

Table 6-12 presents the comparison between the enclosed supermarket storage solution and the VLM solution.

As shown in Table 6-12, both solutions can completely eliminate unknown shortages caused by bad on hand balance. While the enclosed supermarket storage solution requires annual investment in the scale of 0.1 million USD on additional labor at the check-out point at each individual working shift, and the VLM solution requires one time investment in the scale of 1 million USD.

What's more importantly, from the management's point of view, an open and friendly working environment is of high importance at the shop floor. An enclosed supermarket storage solution conveys opposite information in this direction; therefore, Varian's management has less interested in this solution. Besides, VLM has already been implemented in Building 80, it has demonstrated its benefits in addressing bad on hand balance issues and it has increased the efficiency of material picking there.

Table 6-12: Comparison between Enclosed SMKT Storage Solution and VLM Solution

	Enclosed SMKT Storage Solution	**VLM Solution**
Effectiveness in addressing bad on hand balance	Completely eliminate	Completely eliminate
Investment	Annual investment in the scale of 0.1 million USD per year	One time, in the scale of 1 million USD
Feasibility	Low – Medium	Medium – High
Recommend?	Not recommend	Recommend for mid/long term

The implementation of the VLM solution in supermarket storage area will bring in the following benefits.

1. Completely eliminate bad on hand balance.
2. Reduce supermarket storage space significantly. Storage space can be reduced by more than 50% after implementing VLM solution. This is a very important decision variable in management's decision metrics as floor space is becoming the limiting factor of capacity increase at Varian.
3. Enhance efficiency and effectiveness of material picking. According to the current implementation of VLM in Building 80, material picking's efficiency has been significantly increased. However, the increase of material picking at supermarket storage area will not be as significant as the increase at Building 80 as the turnover in supermarket storage area is low.
4. Convey the information of a better working environment. VLM brings in the above benefits and meanwhile presents a better image of working environment.

Therefore, the VLM solution is recommended for supermarket storage area in the middle to long term.

4. **Benefits of Proposed Solution**

The VLM solution completely eliminate unknown shortages caused by bad on hand balance, it will lead to more benefits in the following directions mentioned earlier,

1. Reduce assembly shortages on production line.
2. Reduce assembly lead time.
3. Reduce Gold Square size.
4. Reduce internal efforts.
5. Reduce expediting cost.
6. Increase efficiency of supermarket build area.

6.7 Summary

The service level of supermarket piece parts directly affects the service level of Gold Square assemblies. Piece part shortages cause longer lead time and delivery delay for those Gold Square assemblies, and cause other problems and inconvenience as well. Piece part shortages consist of known shortages and unknown shortages. The shortages detection processes and impact of shortages have been studied, the root causes of unknown shortages have been investigated and the proposed solutions are focused on the leading reason of unknown shortages. Both short/middle term solutions and middle/long term solutions are discussed and compared to get the optimal solutions which accomplish the objectives. In the short/middle term, the tablet solution is recommended, and it is recommended to start from a pilot project and then move to the full-scale implementation. The target of the tablet solution is to successfully reduce unknown shortages caused by bad on hand balance by 50% or higher. The scale of investment on the tablet solution is small compared with the benefits it brings. In the middle/long term, the VLM solution is recommended not only because of the benefits it brings but also due to the management's considerations. VLM's initial investment is not small, while the overall benefits it brings make it worthwhile. The benefits originated from unknown shortages reduction include reducing assembly shortages on production line, reducing assembly lead time, reducing Gold Square size, reducing internal efforts, reducing expediting cost, and increasing efficiency of supermarket build area.

Chapter 7

Recommendations and Future Work

In this chapter, we present the recommendations developed in this thesis work and the future work going forward.

7.1 Recommendations for Assembly Level Inventory Management – Gold Square

- Adopt the pull based inventory system modelled on the periodic review policy detailed in Chapter 5 to manage the finished goods inventory of fast moving high-volume assemblies made by the supermarket.
- Use the spread sheet based tool presented to the inventory management group which calculates the base-stock and safety stock quantities for the required service levels, demand parameters and review period desired by the user.
- Constantly refine the parameters of the policy based on continuous monitoring of performance indicators like service level, yield and criticality of the assembly.

In order to realize the capacity potential it is important to minimize stock-outs of assemblies which may lead to line starvation or increased labor hours. The most frequently used assemblies on the line are managed on a make-to-stock basis. However the operating policy for these assemblies is a major cause for their frequent shortage. The team recommended a periodic review policy to manage the finished goods assemblies. The parameters of the periodic review policy were computed for the assemblies feeding the UES line. The proposed policy has lower total safety stock value than the current policy while ensuring a high service level and being simpler to execute.

7.2 Recommendations for Component Level Inventory Management – Supermarket Piece Part

1. **Pilot Project – Tablet Solution**

   - Implement a pilot project of the tablet solution to evaluate its feasibility, effectiveness, time, cost, adverse effects, and etc. in an attempt to improve upon the pilot project's feedback prior to the full-scale implementation. We recommend fully replacing the transmittal forms in one or two storage passages with secured tablet terminals, and using Table 6-9 to track the effectiveness of this pilot project. By the end of the pilot project period, we target to reduce unknown shortages caused by bad on hand balance by 50%.

In the pilot project, the user interface of the self-check-out tablet terminal should be carefully designed while it is not necessary to incorporate the function of automatic SAP requisition creation into the solution.

2. **Full-Scale Implementation – Tablet Solution**

   - Implement the full-scale tablet solution. We will make secured tablets as self-check-out terminals available for each storage passages at supermarket storage area. Instead of temporary tablet application, fully functional software solution including both tablet application for piece part pickers and computer software for production control is developed, tested, improved and implemented. The full-scale implementation targets at reducing unknown shortages caused by bad on hand balance by 50% or higher.

Upon the time of full-scale implementation, formal notifications are required for all relevant stakeholders, for example, new supermarket signage is required to replace the existing signage.

3. **VLM Solution**

   - Implement Vertical Lift Module to replace the current supermarket storage shelves.

VLM solution completely eliminates bad on hand balance, reduce supermarket storage space significantly, enhance efficiency of material picking, and convey the information of a better working environment.

7.3 Future Work

We follow the hypothesis-driven methodology for our team work and individual work throughout the thesis project. Following the updated hypothesis tree in Figure 3-4, it presents a guideline for potential future work to further increase Varian's capacity. One of the promising areas is to simplify build and test procedures at UES line to reduce the effective operation time. Effective operation time reduction of build and test procedures will reduce the cycle times at those procedures, and then factory layout and line balancing is required to further reduce the overall cycle time and increase the capacity. Besides, shortages reduction of warehouse, line-side inventory and machine racks is another promising area to reduce effective operation time.

7.3.1 Assembly Level Inventory Management

Currently the proposed base-stock inventory management is for UES Gold Square, the methodology and analyses here can be extended to the Mixed Module Gold Square assemblies to reduce shortages while reducing finished goods safety stock.

The proposed base-stock inventory levels are calculated using average lead times of the entire supermarket assemblies, there is potential to refine the base-stock inventory levels by calculating lead time for each individual assembly over a enough long period of time.

7.3.2 Component Level Inventory Management

1. Tablet Solution

- **Apply to Other Open Storage**

As discussed earlier in Section 1 of Section 6.6.1, SAP requisition creation function is not enabled for EWM barcode scanner for supermarket storage area as this is an open storage place where piece parts are available to everyone. For other open storages, including MOD storage area and line side inventories, paper transmittal form is currently used for non-SAP driven consumption and this process will not be replaced by EWM process.

The problems associated with paper transmittal form for supermarket storage area exist for those open storages as well. Bad on hand balance causes unknown shortages for those open storages, and it's even more difficult for production control to collect and update those transmittal forms as they are located at different places in the shop floor.

After the benefits are demonstrated through either the pilot project or full-scale implementation, we recommend implementing the tablet solution to other open storage areas. The tablet solution will use exactly the same software solution as the one implemented at the supermarket storage area, so that only investment on tablets are required, which is only 40% of the initial investment required for the same scale of project.

While implementing tablet solutions at other open storages may require different number of available secured tablets at each storage passage and different locations of placement for those tablets in order to provide superior accessibility of these self-check-out terminals.

The potential benefits received from implementing the tablet solution will be reducing unknown shortages caused by bad on hand balance and simplify production control's work in new requisition creation.

- **Apply to Other Areas**

The tablet solution proposed above is used to replace the current transmittal process. Besides this, there are also a couple of other areas where tablet solution is able to simplify the communication process.

1. Bin Empty Report

In supermarket storage area, during the kit picking process, if a bin goes empty after the kit picker takes out the final parts, kit picker will use a ticket to report bin empty, as shown in Figure 6-1. With tablet solution implemented, bin empty can be potentially reported through tablet terminals so that production control can be notified immediately.

2. Unknown Shortage Report

In supermarket area, during the kit picking process, if an unknown shortage is detected, it will be recorded on the 'SMKT Pick List Cover Sheet' and then production control will be informed in person of those unknown shortages. With tablet solution implemented, unknown shortage can be potentially reported through tablet terminals so that production control can be notified immediately.

2. VLM Solution

The VLM solution may not be adequate for other open storage areas in shop floor, for those open storages, the tablet solution will remain to be used to help reduce unknown shortages caused by bad on hand balance and improve internal communication.

Bibliography

[1] Chengappa, L., 'Operational Improvements in a Semiconductor Capital Equipment Manufacturing Plant: Resource Optimization, Labor Flexibility and Inventory Management', Graduate Thesis, 2012, Massachusetts Institute of Technology

[2] Ramachandran, V., 'Operational Improvements in a Semiconductor Capital Equipment Manufacturing Plant: Capacity Management and Inventory Policies', Graduate Thesis, 2012, Massachusetts Institute of Technology

[3] Ch. Hollauer, 'Modeling of Thermal Oxidation and Stress Effects', Institut für Mikroelektronik, 2007, http://www.iue.tuwien.ac.at/phd/hollauer/node6.html

[4] Daneshmand, M., 'Lean Manufacturing in a Mass Customization Plant: Improved Efficiencies in Raw Material Presentation', Graduate Thesis, 2011, Massachusetts Institute of Technology

[5] Semiconductor Equipment and Materials International – Market Information, http://www.semi.org/en/MarketInfo/EquipmentMarket

[6] An Introduction to Plasma Source Ion Implantation – University of Wisconsin, Centre for Plasma Aided Manufacturing, http://silver.neep.wisc.edu/psii

[7] 'Semiconductor Manufacturing Equipment Sales Rose 9% in 2011', March 13, 2012, Solid State Technology, http://www.electroiq.com/articles/sst/2012/03/semiconductor-manufacturing-equipment-sales-rose-9-in-2011.html

[8] Chen, W., 'Lean Manufacturing in a Mass Customization Plant: Improvement of Kanban Policy and Implementation', Graduate Thesis, 2011, Massachusetts Institute of Technology

[9] Discussions with Dr Stanley B Gershwin, Thesis Advisor and Sr. Research Scientist, MIT, March 2012.

[10] Simchi-Levi, D., Kaminsky P., Simchi-Levi E., *Designing and Managing the Supply Chain: Concepts, Strategies, and Case Studies*, McGraw Hill Professional, 2003.

[11] ERP with a Fully-Integrated Warehouse Management System – Technology Group International, http://www.tgiltd.com/contact-us/contact-us.html

[12] Barcode Scanner Symbol mc9090 – Barcode Scanner, http://barcodescannerx.com/barcode-scanner-factors-in-picking-a-barcode-scanner/barcode-scanner-symbol-mc9090/

[13] Hulley, Stephen B., *Designing Clinical Research*, Lippincott Williams & Wilkins, 2007, p.168-169.

[14] Vertical Lift Shuttles Storage | Vertical Lift Modules (VLM) – Southwest Solutions Group, http://www.southwestsolutions.com/equipment/kardex-remstar-vertical-lift-modules-shuttles-storage

[15] Automated storage and retrieval system – Wikipedia, http://en.wikipedia.org/wiki/Automated_storage_and_retrieval_system#Vertical_Lift_Module

[16] HBS Toolkit – Basic Operations Self Instructional Workbook, http://hbswk.hbs.edu/archive/146.html

Appendix A

Glossary

General Terminology [16]

Bottleneck: The production resource which limits the overall capacity. It is usually the production resource with the longest cycle time.

Capacity: Maximum output rate of a process measured over a period of time

Cycle Time: Average length of time between the completion of two successive units on the assembly line.

Manufacturing Lead Time: Time spent by each unit in the complete manufacturing or assembly process.

Operation Time: Expected time required to complete a particular operation.

Varian Semiconductor Equipment Specific Terminology

Labor Utilization: Varian calculates labor utilization as the percentage of total available labor hours that are 'billed' to some machine. Whenever a worker does any build or test work on a machine, it gets billed to that machine number. Activities like team meetings, training and shop floor maintenance do not get billed to a machine and account for the complement of the labor utilization percentage.

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 has 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 subassemblies may be shipped separately with the machine.

Piece Parts/Components: The individual parts which are assembled together at the Supermarket Area to make the subassemblies. These constitute the lowest levels of the bill of materials.

Laydown: The act of setting up the frame, which is the basic structure on which the module is built, on the designated bay. It is a common practice at Varian for all the modules for a particular machine to have the same laydown date.

Gold Square: The storage location for a high-volume fast moving assembly made in the supermarket for the Universal End Station or Mixed Module line. These assemblies are typically managed on a make-to-stock policy.

Supermarket: The production cells which build and test the subassemblies used downstream.

MOD Storage Area: Stores parts needed on the Mixed Module line.

Kit codes: To simplify the pulling of parts from different storage locations, the parts 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 Kit Codes: Codes used for pulling parts stored in external warehouses, Buildings 5 and 80.

Z Pick Lists: Kits of parts stored in the locations on the shop floor in building 35. Ex: in the MOD storage area.

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

Known Shortage: Shortages of piece parts which show up on 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 present on the shelf.

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 for replacement in their fabs or shipped to inventory banks across the world managed by Varian.

Options: Additional assemblies beyond the basic configuration which can be chosen by the customer to be installed on the ion implantation machines.

Selects: An assembly which is selected by the customer among many options to be installed on the ion implantation machine.