Material Shortage Reduction at a Semiconductor Equipment Manufacturing Facility through the Re-evaluation of Inventory Management Strategies

By

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B.E. Engineering Product Development, Mechanical Engineering Track
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Submitted to the Department of Mechanical Engineering
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Abstract

This thesis addresses the material shortage problem in the Supermarket section of the production floor at the Varian Semiconductor Equipment business unit of Applied Materials. Through efforts in shortage data collection and subsequent analysis, it was ascertained that the inventory management strategies currently adopted by Varian are the dominant causes of shortages. This document serves as a guide on how to evaluate the performance of current inventory systems. A method of computing Theoretical Service Levels for current Re-order Points of inventory bins is proposed which relies only on the statistical distributions of daily demands for parts. Comparing computed Theoretical Service Levels with Observed Service Levels, allows for the inference on causes of shortages to be made. A criticism on a commonly advocated formula to determine bin sizes/re-order points is presented and the inappropriateness of the same is exposed when demands are not normally distributed. An unbiased formula for sizing bins/ setting re-order points to achieve Desired Service Levels is introduced which is accurate, regardless of the statistical distribution of demand. Using this technique, correct bin sizes/ re-order points of frequently short parts were computed to achieve desired performance during the replenishment period of the parts. The use of simulation software packages allowed for the validation of corrected bin sizes. The ineffectiveness of present inventory review methods for certain part types is also highlighted. The implementation of a FIFO policy for processing Shop Orders is recommended which has the potential to further reduce 21% of shortages while possibly lowering inventory levels. Lastly, the concept of setting desired On-time Delivery goals for sub-assemblies through the storage of completed/picked-to-complete sub-assemblies is explored.

Thesis Supervisor: Dr. Stanley Gershwin
Title: Senior Research Scientist

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Chapter 1

Introduction

The work documented in this thesis focuses on the reduction of material shortages at the Applied Materials facility in Gloucester, MA. This is division of Applied Materials, formerly known as Varian Semiconductor Equipment Associates Inc, is responsible for the manufacture of Ion Implantation Tools used extensively in the semiconductor industry. The shortages of interest are those of parts stocked in the Supermarket section of the production floor. This section is responsible for the delivery of sub-assemblies that are essential in the manufacture Modules that make up Tools. These sub-assemblies are built using the parts stocked in the Supermarket. The recent ramp up in production at Varian has increased the occurrences of material shortages in the Supermarket. As a consequence of the unavailability of parts when required, the completion of sub-assemblies is often delayed and hence are not delivered to the production floor when needed. This forces assemblers on the production floor to work out of sequence which results in additional rework costs. Over the first quarter of 2017, Varian incurred nearly $157,000 in rework cost due to all types of material shortages. A proportion of this total cost is attributed to the untimely deliveries of sub-assemblies resulting from material shortages in the Supermarket. The implementation of the recommendations proposed at the end of this paper has the potential to reduce over 90% of late sub-assembly deliveries due to material shortages.

1.2 Thesis Objectives

The objective of this thesis is to provide a detailed account on the diagnosis of the material shortage problem at Varian and highlight the techniques employed to identify the causes leading to instances of shortages. It aims to provide a means to evaluate the performance of the current inventory management strategies at Varian and addresses shortcomings that contribute to the occurrence of shortages.

1.3 Thesis Organization

The work presented in this thesis is a combination of individual and team efforts. Between February and August 2017, four graduate students from MIT (henceforth referred collectively

by 'MIT Team'), worked in the Manufacturing Department at Varian to resolve inefficiencies on the production floor. The MIT Team worked together at the beginning of the project, to determine the sources of material shortages in the Supermarket as well as to quantify the financial impact of these shortages. Following the analysis of shortage data gathered, different strategies were explored by each of the individuals to resolve the problem. The names and summaries of the work of individuals who were part of this team are listed below.

- Ruolin Xu: Evaluation of trucking capacity needed and overall cycle time reduction observable from the relocation of material from the Supermarket to the Warehouse. [1]
- Yadunund Vijay (author): Evaluation of shortcomings of present inventory management strategies and discussion on correct methods to manage inventory in the Supermarket to alleviate occurrences of shortages.
- Yuwen Zhang: Evaluation of floor space requirements and other challenges involved in the relocation of material from the Supermarket to the Warehouse. [2]
- Zongying Xu: Evaluation of capacity needed to meet on-time delivery requirements of Supermarket sub-assemblies and the development of an algorithm to assign jobs to assemblers in the Supermarket. [3]

Chapter 2 of this thesis provides a background of the company, an overview of manufacturing operations, shortage data collection efforts of the MIT Team and insights from the data collected that motivated the work of this thesis. The contents of this Chapter are likely to be similar in all the theses cited above. The work presented in subsequent Chapters reflect the author's individual efforts.

Chapter 3 covers techniques utilized in the identification of causes of material shortages and discusses the several strategies to reduce the occurrences of shortages.

Chapter 4 evaluates the proposed strategies from Chapter 3 and highlights viable recommendations for Varian.

Chapter 5 concludes the work presented in this thesis.

The Appendix contains a flowchart of material movements at Varian. It also presents the various MATLAB [4] scripts written by the author that are referenced throughout this document.

Chapter 2

About Varian Semiconductor Equipment Associates, Inc., Status Quo and Problem Statement

2.1 Company Background

Varian Semiconductor Equipment Associates, Inc. (henceforth Varian) design, build, supply and service ion implantation equipment used in the manufacture of semiconductor chips. Ion Implantation is a method of doping semiconductor wafers with elements that alter the physical properties of the substrate. [5] The company was acquired by Applied Material in 2011, which is the global leader in materials engineering solutions. Applied Materials carries expertise in the following products & technologies: Semiconductor, Display, Solar, Roll-to Roll WEB Coating, Emerging Technologies and Products and Automation Software. [6] The addition of Varian under the Applied Materials umbrella, filled the void in the required capabilities for the company.

The products at Varian, called Tools, are highly customizable and often have designs specific to customer needs. Tools produced by Varian fall into four unique product lines: High Current (HC), Medium Current (MC), High Energy (HE), New Product Initiative (NPI). While Varian has the capacity to produce twelve different Tools, the bulk of the demand is for five or so models. Out of these five, two are part of the High Current product line and rest, Medium Current product line. A description of the Tools is beyond the scope and intention of this thesis.

The Tools are assembled in the production floor inside the Main Building (BL35) at Gloucester. The process is extremely complex given the sheer volume and number of components that make up each machine. Table 1 summarizes the list of Tools that are built at Varian along with the total number unique components per Tool.

Tool Description	Product Line	Number of Unique Components
VIISTATRIDENT	HC	18,558
HCPLATFORM	HC	17,794
VIISTA900 3D	MC	15,182
VIISTAXSERIES	MC	16,253
VIISTAXTSERIES	MC	17,199

Table 1: List of Tools commonly built at Varian

Each Tool can be decomposed into a set of Modules (MODs) and some Modules are present in every Tool. Each module can be customized to meet customer requirements. Varian builds & tests modules separately and ships all the modules together without combining them to form the Tool. This is part of their "Smart Ship" policy that was implemented to achieve shorter cycle times and prevent contamination of the modules during assembly and dis-assembly for testing.

Table 2 below summarizes the Modules present in the two commonly built product lines of Varian.

Module	High Current	Medium Current
Analyzer Magnet 90°	■	
Corrector Magnet 90°	■	
Facilities	■	■
Gas Box	■	■
UES	■	■
Beam Line		■
Terminal		■

Table 2: Summary of Modules in High and Medium Current Tools

Modules are fabricated using pre-built subassemblies and piece parts. The pre-built subassemblies (henceforth Supermarket Sub-assemblies) are built in the Supermarket section of the production floor. The piece parts arrive at the assembly site, in kits termed Mod Kits.

The Supermarket Sub-assemblies are built by Assemblers on one of sixteen workbenches in the Supermarket. The parts required to build these sub-assemblies are consolidated into 'kits' and delivered to the Assemblers. Most of the parts required for a kit are 'picked' by Material Pickers from inventory bins in the Supermarket. There are 5,480 unique part types stocked in

the Supermarket. Section *2.2.3 Supermarket Shop Orders and Picking* provides a detailed overview of the operations within the Supermarket.

The inventory of nearly half of the part types stocked in the Supermarket are replenished from stock bins in the Warehouse (BL80)- A primary repository for most of the parts required at Varian to produce their Tools. It is located half a mile from the Main Building. Material is driven to the Warehouse from a variety of suppliers based on MRP requirements. A description of the MRP system is presented in *Section 2.2.2 Inventory at Varian*. Materials are transferred from the Warehouse to other stock locations, including the Supermarket, via trucks. These trucks are owned and operated by Varian. Trucking, which is the process having trucks transfer parts between the Warehouse and the Main Building, begins at 7:00 AM. Subsequently, a truck arrives at the Main Building once every hour, till about 4:00 PM each day.

2.2 Overview of Operations

This purpose of this chapter is to familiarize the reader of this document, with an overview of the operations at Varian. This allows for the work that follows this Chapter to be interpreted in the right context.

2.2.1 Order Fulfilment at Varian

Varian follows an 'Assemble-to-Order' fulfilment strategy where the assembly of components into tools in only commissioned once a Customer Order has been confirmed. A document called the Production Schedule, which is updated weekly, contains a list of both confirmed and forecasted Customer Orders, due in the upcoming months. The forecasted orders are usually converted to confirmed ones, at least a month before the Ship Date (date the tool needs to be shipped to reach the customer on time) for a Tool. With the Ship Dates, Tool Laydown Dates or build start dates, are assigned for each customer order. Overall, all the Modules for a Tools require 9-12 build days for completion. The parts required for Day 1 of the build are transferred over to the Main Building, the night before Laydown. All the Supermarket produced sub-assemblies that are required for a Module, are due on the Laydown Date. Hence the Need Date as defined as the date on which a Supermarket Sub-assembly is required on the production floor, is equivalent to the Laydown Date.

To allow for ample time for Supermarket Sub-assemblies to be picked, assembled and tested, Shop Orders, which are documents authorizing the build of Supermarket Sub-assemblies are

released five days prior to the Laydown Date. A detailed discussion on the operations of the Supermarket is presented in *Section 2.2.3 Supermarket Shop Orders and Picking.*

2.2.2 Inventory at Varian

The Warehouse (BL80) at Varian, is the primary stock location for majority of the parts required to build both Modules and Supermarket Sub-assemblies. The Secondary Warehouse (BL70) serves as a storehouse of bulky piece parts only. Most of the inventory stored at these locations are driven by MRP (Materials Requirements Planning) Software. Parts are driven to the Warehouses from Suppliers to satisfy both Production Demand as well as Sales Demand. To determine the demand quantity for Production, the system relies on the Production Schedule. For confirmed orders, the exact BOM (Bill of Materials) of the Tool is known and hence the MRP system drives the exact quantities required. For unconfirmed orders, a 'Standard Configuration BOM' is referenced by MRP. This BOM is for the core tool along with the most likely selections and options that a customer is expected to order. The Sales demand which is forecasted, is provided by the AGS Team. The Production Schedule is updated once a week and loaded into the MRP system at the same time. The Sales demands are updated only once a month. When the demand for a part is within its lead time, the MRP system will drive the required quantity to the Warehouse from the Supplier.

BL80 has several stocking areas or 'Racks' for inventory: RK, GL, Vertical Lift Module (VLM) and Vendor Managed Inventory (VMI). Large parts are stored in RK Racks while smaller ones in GL and VLM Racks. The VMI area houses consumables that are required for building Modules. When parts arrive at the Receiving Dock at BL80, from Suppliers, they are 'put away' into their respective stock locations as highlighted above. Some parts require special inspection before they are put away. If parts fail the inspection, they are sent back to the Suppliers. When parts are required for Tool Laydowns, they are consolidated into kits in the Warehouse and transferred to the production floor in the Main Building.

The Supermarket stocks both piece parts as well as a limited number of completed sub-assemblies (termed Gold Square Sub-assemblies). The piece parts can be categorized into two broad categories- Supermarket Bin Parts and Free Stock Parts. The inventory levels for the former are tracked on Varian's systems while they are not for the latter. Among Supermarket Bin Parts, some, categorized as Transfer (or EWM REPL) Parts, are also stocked and replenished from the Warehouse. The remaining Kanban and Primed Parts are replenished

directly from Suppliers. The Free Stock Parts, which are akin to consumables, are of two types. Those whose quantities are monitored by Varian and replenished from the Warehouse, are termed MinMax while the parts whose quantities are monitored and replenished by external vendors are MinMax VMI (or VMI) Parts. The stocking quantities of these parts in the Supermarket, is determined differently for each of these Part Types. A detailed discussion on the stocking quantities and replenishment methods of the inventory stocked in the Supermarket is presented in *Section 3.1.1 Present Replenishment Strategies & Bin Sizing Techniques.*

'Shortage' as defined for the context of this thesis, is the event that a part is not available for consumption when needed, at a given stock location. When a part that has been previously short in all of Varian arrives from the Supplier to the Warehouse, it skips the 'put away' process and is immediately, 'cross-docked' or trucked to the Supermarket or other stock location where demand is yet to be fulfilled.

Lastly, SAP is the enterprise software at Varian that is employed to automate and track a variety of operations. The Extended Warehouse Management (EWM) platform in SAP, provides additional inventory management solutions.

An overview of this section in the form of a block diagram depicting material storage locations and movements, can be referenced in *Appendix B. Material Movement Block Diagram*

2.2.3 Supermarket Shop Orders and Picking

A Shop Order is a printed document that authorizes the pick and build of a Supermarket sub-assembly. It consists of a Cover Sheet and subsequent sheets containing a list of line items and corresponding quantities of each item required for the build. Every Shop Order is assigned a unique Shop Order Number. This number along with Sub-Assembly Number, Sub-assembly Description, 'Order Type' and Due Date are printed on the Cover Sheet. The Cover Sheet also has a section for any shortages encountered during the pick process to be noted down. The other sheets of the Shop Order consist of a table with rows listing the parts required to build the sub-assembly. The columns provide information on the Bin Location, Part Number, Part Description, Quantity Required, On-hand Balance (bin level in Supermarket) and GL Balance (inventory level in Varian), for each part.

Every Shop Order is built to satisfy a requirement and hence has a 'Type of Order'. These types include:

a. Production- Requirement of sub-assembly to build Modules of Tools

b. Gold Square- Requirement of sub-assembly to replenish Gold Square Bins

c. Transfer- Requirement of sub-assembly at another Applied Materials facility

d. Customer- Requirement of sub-assembly at Customer Site (spare)

The parts for a given Shop Order are 'picked' into kits by Material Pickers. These parts are mostly housed in bins within the Supermarket. Some bulky and less frequently used parts are stocked only in the Warehouse and are transferred over to the Supermarket once the Shop Order listing the part, is released in EWM. These parts are categorized as CO27 parts.

Success for the picking operation is defined as the outcome where all the parts required to complete a kit, are picked on the first attempt, by the Picker. When picking is successful, the kit is said to be 'picked-to-complete'. On the other hand, if any part is unavailable, the item is said to be 'short' and the kit is then 'picked-to-short'. On average, it takes around forty minutes for a kit to be picked, provided no shortages are present.

The Shop Order to be picked is chosen by the Picker on shift, from a pile of Shop Orders in the Supermarket. The Shop Order Pile contains Orders in decreasing priority, with the topmost Order in the Pile being required the soonest. However, Pickers do not necessarily chose to pick the Orders on top of the pile. This decision might be influenced by factors including:

1. Convenience of Picking

2. Whether the Shop Order can be picked in the time remaining in the shift

While there is a form of priority in the Shop Order Pile, the processing sequence of the Orders does not conform to any strict policy. The Production Lead on shift routinely adjusts the position of Orders in the Pile based on changes in requirements. Moreover, a newly printed Shop Order can be placed directly on top of the pile, if its requirement is immediate. This happens especially in the case of Gold Square Shop Orders. An Order can spend anywhere between a day to a week in the Pile, before it is picked.

It is important to note that while the On-hand Balance and GL Balance values are accurate on the print date of the Shop Order, they are meaningless on the actual pick date. The inaccuracy arises from the time spent in the Shop Order Pile during which parts might have been consumed for other Orders requiring the same parts. Given that the time spent in the Pile is not consistent and the fact that Orders are not selected based on a fixed sequence, it is difficult estimate the

quantities on the actual Pick Date. Hence, the Picker has no way to determine whether a Shop Order will be picked to a short, prior to his/her selection.

Once a Shop Order is selected from the pile, the Picker then 'releases' the Order in EWM and is provided with a set of reference codes. These codes provide information on the locations of the bins of the parts required to complete the pick as well as the required quantities of the respective parts. The codes are inputted into the RF Gun equipped by the Picker. A digital screen on the RF Gun provides the Picker with the location of the bin containing the next part to be picked along with the required quantity. The Shop Order contains parts that are either stored in Supermarket Bins, MinMax Bins or only stored in the Warehouse. Most often if a Shop Order contains CO27 parts, it will be picked-to-short give that these parts are not stored in the Supermarket to begin with.

Once the Picker reaches a specific bin location and picks the required quantity of the part, he/she then scans the barcode on the bin with the RF Gun. A transaction for the withdrawal of the part is then recorded in EMW. For Supermarket Bin Parts, as the inventory level is continuously monitored, the transaction updates the real-time level appropriately. However, for MinMax parts, while the transactions are recorded, their inventory levels are not updated as the initial quantity is unknown.

2.4 Material Shortage Problem

Majority of the Spring Semester was spent by the MIT team in scoping the various projects at Varian. The team ultimately decided to make the Material Shortage Problem in the Supermarket, a priority. The decision was influenced by several factors including the severity of problem, depth of the project to allow for four theses, and Varian's desire to have the problem solved as soon as possible. The goal of this section is to formally describe the shortage problem and delineate the MIT Team's efforts to uncover the causes of the shortages and to quantify the impact the shortages have on production.

2.4.1 Overview of Supermarket Shortage Problem

The Supermarket as noted earlier stocks majority of the parts required to assembly sub-assemblies at Varian. When a sub-assembly is required, the parts in its BOM are consolidated into kits from their respective bins, by Pickers. The problem as presented to the MIT Team was the increasing occurrences of picked-to-shot kits in the Supermarket. The Team was informed

at the time that, one out of every three kits that were picked, had experienced a shortage. This statistic was determined by a Manufacturing Engineer at Varian, who was also tasked with investigating the shortage problem. The Engineer began looking into the problem about a month before the MIT Team decided to focus on shortages. A dynamic spreadsheet, 'SMKT BuildLog', contains a list of Shop Orders along with their current state within the Supermarket. It is updated irregularly throughout the day and hence viewing this document at any time provides information on the state of the Shop Orders at that instance. The five possible states include-

1. In Que- If a Shop Order is still in the Shop Order Pile
2. Pick Complete- If a Shop Order has been picked-to-complete and is waiting to be assembled
3. Picked W/ Shorts- If a Shop Order has been picked-to-short and is waiting for short parts to arrive
4. In Process- If a Shop Order is currently being assembled by an Assembler
5. Done- If a Shop Order has been assembled.

Over a few weeks, the Manufacturing Engineer recorded the number of Shop Orders with states 'Picked W/ Shorts' and 'Pick Complete', at the end of each day. With these numbers, the average picked-to-short percentage was computed to be 30%. Given that the data was observed at the end of each day, the absolute percentage of picked-to-short kits is expected to be higher. This is plausible as shortages encountered can be fulfilled on the same day. During the same time, the number of unique short part types per Shop Order was also recorded. Further, these numbers per Shop Order were divided into 3 categories as decided by Varian. These categories were-

1. GL- If the short parts were available in some other stock location at Varian. (GL stems from Gloucester which is the location of the Varian facility)
2. Actual- If the short parts were unavailable throughout Varian.

Beyond this, no further information was available on the parts that were short. With no other insights on the problem at hand, the MIT Team sought to first understand the cause of shortages. To obtain this information, a new template was for data collection was drafted as discussed in the next section.

2.4.2 Shortage Data Collection by MIT Team

The template as proposed by the MIT Team is seen in Table 3. The Team decided to group part shortages into the broad GL and Actual categories as done so earlier. The word 'Actual' however was changed to 'Real'. Hence, the broad categories are now GL and Real. Columns to collect further details about the shortages were included. For each of the broad categories, information fields for the part number, the quantity of units short as well as the cause for the shortage were included. A description of each column is presented below.

1. Date- Date when Shop Order was Picked
2. Type of Order- As described in *Section 2.2.3 Supermarket Shop Orders and Picking*
3. Assembly Number- Unique identification number of the sub-assembly
4. Description- Name of the sub-assembly
5. Shop Order No.- Unique serial number of the Shop Order
6. Due Date- Date when completed sub-assembly is required (same as Need Date)
7. S/o Created- Print date of the Shop Order
8. GL Shorts Qty- Number of parts of the part type listed in the 'GL Short Part No' that were short
9. GL Short Part No.- The unique identification number of the part that is a GL short
10. GL Short Cause- The possible categories of GL Short Causes are listed below
    a. Transfer- If the short part is a Transfer (or EWM REPL) Bin part and if stock is available in the Warehouse
    b. MinMax- If the short part is a MinMax part and if stock is available in the Warehouse
    c. CO27- If the short part is a CO27 part
    d. Quality- If the part is short in the Supermarket and Warehouse but units of the part are present in the Quality Department for review
    e. Inspection- If the part is short in the Supermarket and Warehouse but units of the part are present in the Inspection Department for review
11. Real Shorts Qty -Number of parts of the part type listed in the 'Real Short Part No' that were short
12. Real Short Part No.- The unique identification number of the part is a Real short
13. Real Short Cause-The possible categories of Real Short Causes are listed below
    a. MinMax VMI- If the short part is VMI free stock part

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b. MinMax Actual- If the short part is a Varian free stock part and if stock is unavailable in the Warehouse

c. Actual- If the part is not of types listed in Points a & b

d. Sales- A special case of the shortage listed in Point c. This is when shortage of parts is a result of Sales depleting bins in the Supermarket. This in inferred by looking at the material movements (in SAP) that led to the depletion of the bin level

D at e	Type of Order	Assem bly No.	Descr iption	S/O No.	Due Date	S/O creat ed	GL Shorts Qty	GL Short Part no.	GL Short Cause	Real Shorts Qty.	Real Short Part No.	Real Short Cause

Table 3: Template of Shortage Data Collection as Proposed and Used by the MIT Team to Uncover Causes of Shortages in the Supermarket

The possible choices for the GL and Real Causes were decided based on the information gathered by the MIT Team on the different types of inventory in the Supermarket. For a given part, the cause was determined by looking at the inventory levels and movements in SAP as covered at the end of this Section.

The above template was used to collect data starting April 5th 2017. The Team relied on the help of the Manufacturing Engineer to collect this data while still attending classes at MIT. The Manufacturing Engineer collected this data at the end of each day and hence the entries are reflective of the kits that remained short at the end of each day. Thus, data on kits that were picked-to-short but fulfilled on the same day, was not recorded. Given the busy schedule of the Engineer, data collection was irregular. No data was recorded between 5th May and 1st June.

It should also be pointed out that when the template was initially proposed, a distinction between MinMax and MinMax Actual was not recorded. If a short part was of MinMax type, it was recorded under the GL column straightaway. This was due to the nativity of the team in thinking this distinction was not important during the early stage of this project. As the overall shortage picture became clearer, this information was deemed important and subsequently recorded. The same was the case with CO27 and CO27 Actual Causes. Both instances were recorded as CO27 under GL Short Causes.

To obtain more data points, the Team resorted to extracting data from the Cover Sheets of completed Shop Orders. These Cover Sheets which record part numbers of short parts, were obtained for assemblies completed between 15th May and 8th June. Cover Sheets prior to 15th

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May had been discarded and hence unavailable. By using Cover Sheets as the source of data, information on Shop Orders with shortages fulfilled on the same day were also recordable.

While the data collection process at Varian was both irregular and inconsistent, meaningful insights into the causes of shortages were obtained by combining information from the different data sets when applicable. Table 4 below summarizes the periods over which data was collected along with information on the individual/ entity that collected this data, the format used to log the data and the source of data.

Period of Collection	Collector	Format	Source of Data
Feb 2- Feb 10	Mfg. Eng.	Old	SMKT BuildLog
Feb 21-Mar 3	Mfg. Eng.	Old	SMKT BuildLog
Mar 8- Mar 31	Mfg. Eng.	Old	SMKT BuildLog+ SAP Movements
April 4- May 5	Mfg. Eng.	New	SMKT BuildLog+ SAP Movements
May 15- June 8	MIT Team	New	Cover Sheets + SAP Movements
Jun 1- Jun 26	MIT Team	New	Daily Inspection + SAP Movements

Table 4: Observed Timeline of Shortage Data Collection

SAP/EWM

SAP is the enterprise software at Varian that is employed to automate and track a variety of operations. The Extended Warehouse Management (EWM) platform in SAP, provides additional inventory management solutions. Among the numerous capabilities of this software package, the most relevant ones are listed below.

- View Bill of Materials (BOMs) for different Tools, sub-assemblies and piece parts
- Provide up-to-date/ for specified date- information on materials including and not limited to quantities at various locations, requirements for different applications and sourcing information of the material.
- View all the transactions of parts in Varian (or at specific stock location) and provide information including and not limited to date of transaction, purpose of transaction and quantity of transaction.

Different 'SAP Codes' when keyed into the software, allowed for the viewing for information described in the points above. The Team heavily relied on SAP during the shortage data collection phase, to correctly identify causes of shorts for parts on a given day. The categorization of shortages into GL or Real as defined by the Team was only possible after

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looking up relevant information for the part, on SAP. The process involves first identifying whether the part is of type Supermarket Bin, MinMan or VMI. If the part is VMI, it is directly recoded under the Real Cause column. If not, stock availability for the part in the warehouse is cross-referenced. If no stock is present in the Warehouse, the part is listed as either Actual or MinMax Actual respectively. However, if stock is available in the Warehouse, the shortage cause is either Transfer or MinMax respectively.

The data collected was analyzed and the results are presented in *Section 2.4.4 Results of Shortage Data Collection.*

2.4.3 Financial Impact of Shortages

As with any industry project, it is important to quantify the impact of the problem on the company's finances. If the implementation of a proposed solution requires an investment greater than the losses currently experienced, then it is meaningless.

The impact of picked-to-short kits on the Varian's bottom line is indirect. From discussions with production leads and senior managers at Varian, the Team learnt that the late deliveries of sub-assemblies to the production floor, often leads to additional rework on the Modules. When a sub-assembly does not reach the MOD Build Site by its assigned Need Date, the assembly of a Module does not usually halt. Instead, assemblers on the production floor would continue building around the vacancy created by the missing sub-assembly. However, when sub-assembly finally arrives, additional rework or labor, is required to undo some of the work and install the sub-assembly in its rightful place. This rework which causes additional labor costs, would have been avoided if the sub-assembly were delivered on time.

While delays caused by part shortages during the picking process do lead to late delivery of competed sub-assemblies, this is not the case for every picked-to-short Shop Order. In the month of April, only 72% of the 231 Shop Orders with recoded shorts were delivered late out of the Supermarket. This suggests that some of the delays caused due to part shortages are being made up for, during the build and test stages of the Shop Order. However, this is not true for majority of the short kits.

From a financial report, the MIT Team was able to obtain data on the rework costs incurred for Tools produced in the first quarter of 2017. The report provided cost figures for rework associated with 'Material Shortages'. The report does not distinguish explicitly between

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shortages of piece parts (termed Z-pick Parts) required for building Mods and late delivery of Supermarket Sub-assemblies. Hence, while the total rework cost is known, it is unclear what percentage of the cost is linked to late deliveries out of the Supermarket. Figure 1 below is a breakdown of the rework costs incurred by Varian due to material shortages for the different Tool models produced in the first quarter of 2017. During this period, which spans across a financial quarter, roughly $157,000 was spent in additional rework.

Total Material Rework Cost per Quarter
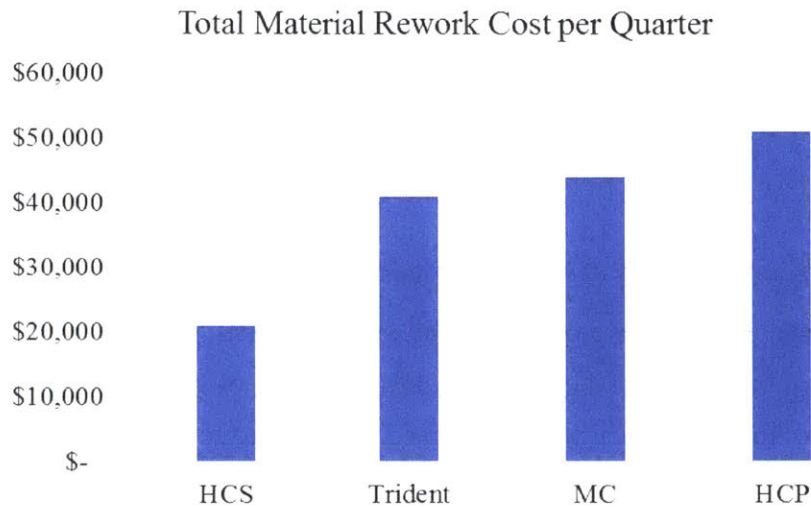
Figure 1: Total Rework Costs Incurred for Tool Models due to Material Shortages

To accurately quantify the financial cost due to late delivery of Supermarket Sub-assemblies, Varian will need to start recoding data each material that is short in the production floor.

2.4.4 Results of Shortage Data Collection

Over the data collection periods, 756 Shop Orders were picked-to-short. From the analysis of data gathered from Cover Sheets, roughly 40% of picked kits were picked-to-short. The data also reveals that shortages are more commonly observed on some days than others. As seen in Figure 2 below, over four weeks in June, higher number of picked-to-short kits were observed on Mondays than other days. This can be attributed to the reduced trucking of materials over the weekend. The number of picked-to-short kits over the weekend is significantly lower than other days as fewer kits are picked in total over the weekend than other days.

Number of Picked-to-Short Kits as Observed per Day in June
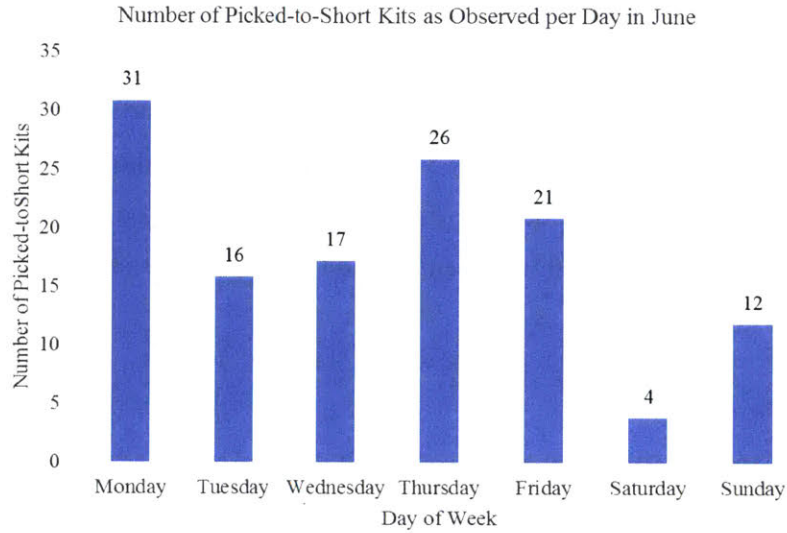
Figure 2: Number of Picked-to-Short Kits as Observed per Day

From the data gathered, there were 261 unique sub-assemblies that were picked-to-short. Figure 3 below, is a Pareto plot of the top 20 frequently picked-to-short sub-assemblies among the data set. These sub-assemblies when combined, contributed to 33% of all the picked-to-short kits.

List of Top 20 Frequently Short Sub-Assemblies
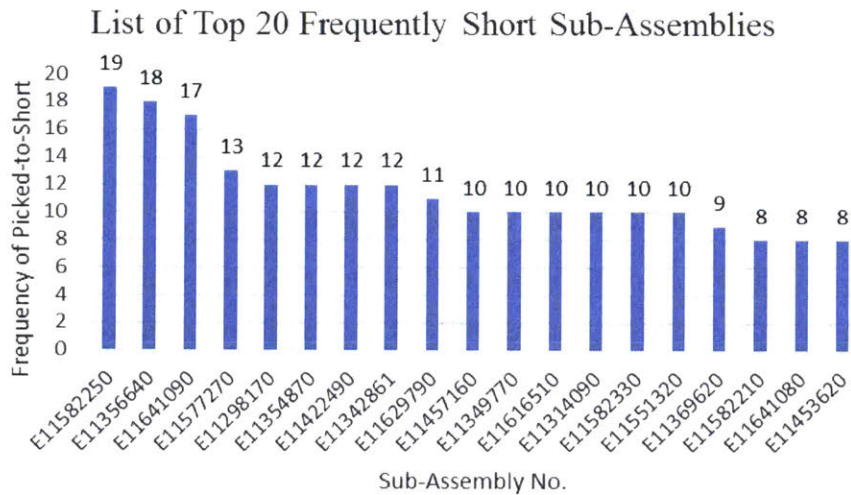
Figure 3: Picked-to-Short Frequency of Top 20 Most Commonly Picked-to-Short Kits

Over the period of data collections, nearly 300 unique part types were observed short. Figure 4 below is a Pareto plot of the top 20 frequently short parts from the data set. These parts when combined, contributed to 28% of all part shortages.

List of Top 20 Frequently Short Sub-Assemblies
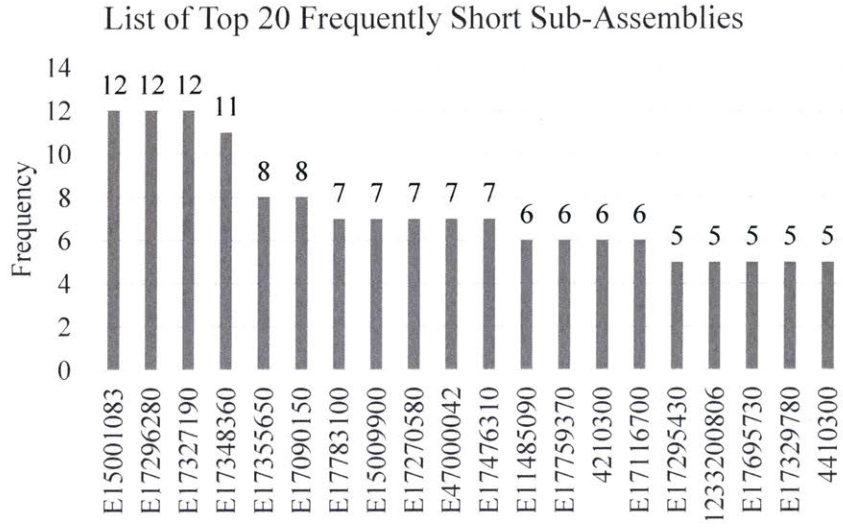
Figure 4: Shortage Frequency of Top 20 Most Commonly Short Parts

Among the part shortages observed, the proportion of causes of the shorts, as defined in Section 2.4.2 Shortage Data Collection by MIT Team is presented in Figure 5.

Proportion of Different Causes among Shorts
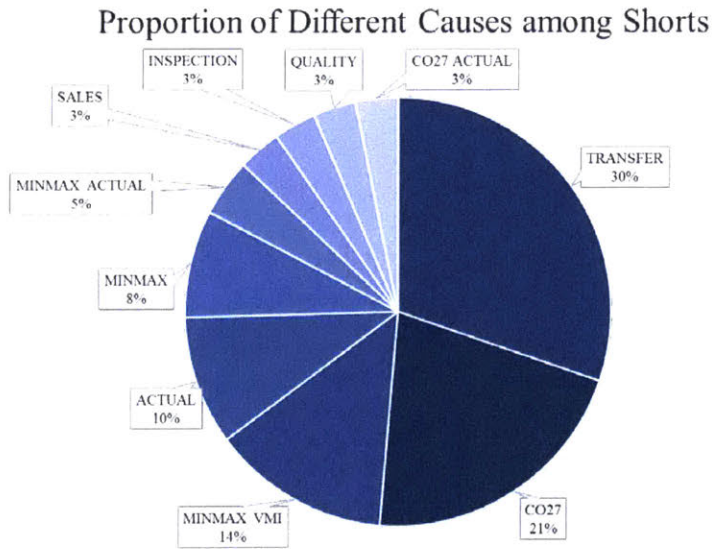
Figure 5: Pie Chart of Shortages by Cause of Short as Defined in Section 2.4.2

The Team was also able to track the average duration for the shortages to be fulfilled. Figure 6 below provides information on the mean and standard deviations of fulfilment durations for parts grouped by their assigned cause for shortage.
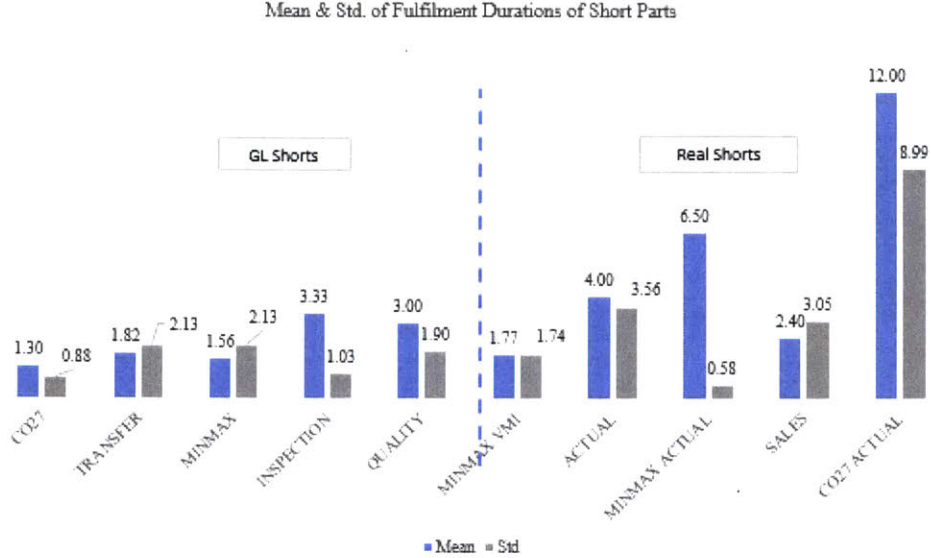
Figure 6: Mean and Standard Deviations of Fulfillment Durations for Short Parts

A discussion of the results of the shortage data analysis is presented in the next section.

2.4.5 Sources of Material Shortages in SMKT

A wealth of information, sufficient to diagnose the reasons for picked-to-short kits in the Supermarket can be obtained from Figure 5 and Figure 6.

From Figure 5, it is evident that 30% of the shortages (Transfer) were caused by parts in the Supermarket that are replenished from the Warehouse by an automatic replenishment system. An additional 8% of shortages (MinMax) came from MinMax parts with depleted stocks in the Supermarket but with quantities available in the Warehouse. Around 21% of the shortages observed were due to CO27 parts that are not stocked in the Supermarket to begin with. By combining these figures, it can be concluded that nearly 60% of the time a part was short in the Supermarket, it was available in the Warehouse. If Quality and Inspection shortages were also considered, then 65% (total percentage of GL Shorts) of the time a part was short, it was available at another stock location within Varian. The average fulfilment durations for CO27, MinMax and Transfer shorts are all within two days, which is the promised delivery time of

the Warehouse. This suggests that these shortages might be caused due to incorrectly sized bins as opposed to late delivery from the Warehouse. This was confirmed by observing material supply frequencies and is discussed in *Section 3.1.6 Part Demand & Distribution Fitting*. Thus, it can be concluded that majority of the shortages are self-inflicted by Varian based on their current inventory management strategies.

Among the 35% of shortages resulting from Real shorts, i.e. having no stock of the part anywhere at Varian, 14% are caused by VMI MinMax parts. The monitoring and replenishing stocks of these parts is the responsibility of an external Vendor. It is interesting to note that these shortages are usually fulfilled within 2 days of being recorded while the average lead time for these parts is 7 days. This strongly suggests that the re-order points for these parts are not adequately estimated such that the remaining quantities can satisfy demands over the replenishment duration.

While the percentage of MinMax Actual shorts (5%) is small in comparison to Transfer, VMI and CO27 shorts, the average fulfilment time for these shorts is nearly 5 days longer. Their impact is significant and thus cannot be ignored. This is also the case with CO27 Actual shortages which have an average replenishment time of 12 days. Further, these shortages highlight the shortcomings of the current MRP based replenishment system in the Warehouse.

Among the 13% of parts that suffered Actual shorts (Sales number included as Sales transactions are events that led to Actual shorts), some of these resulted from the depletion of stocks of Transfer parts in the warehouse. The remaining were caused by shortages of parts exclusively stocked in the Supermarket. In both cases, inventory management policies are to be blamed but the in the former, it is the MRP based replenishment system that is at fault and in the latter, it is the sizing method of the bins of these parts.

While it is impossible to eliminate all occurrences of shortages, it is certainly possible to eliminate most. This is especially true for GL Shorts which can be immediately prevented by correcting present methods of inventory management. For the Real shorts, recommendations can be made to alleviates shortages but these might require modification to inventory management systems such as MRP, at Varian.

2.4.6 Technical Problem Statement

From the results of shortage data that was collected and analyzed, it is clear that an inventory management issue is prevalent at Varian. Resolving this problem would have both tangible (financial savings from rework labor), and intangible (lower stress levels among employees) benefits. In light of this, the author decided to focus on material shortage reduction at Varian, through the re-evaluation of its inventory management strategies.

2.5 Literature Review

This work presented in this thesis is not the first attempt to review inventory management policies at Varian. A few MIT Teams in the past, have explored the sizing of bins and re-order points for parts stocked in the Supermarket. ([7], [8], [9], [10]) However, a fundamental assumption in these works has been the treatment of demand as a random variable of normal distribution. The subsequent formulations of bin sizes and re-order points has relied on this assumption. A commonly utilized formula to determine quantity of inventory to stock is presented below. [9]

$$Q = \mu * LT_{eff} + z * \sigma * \sqrt{LT_{eff}} \tag{1}$$

$where,$
$Q = Quantity\ to\ Stock$
$\mu = Mean\ of\ Demand\ over\ Time\ Period\ (eg.\ daily/\ weekly\ demand)$
$LT_{eff} = Effective\ lead\ time\ of\ replenishment$
$z = Z - score$
$\sigma = Standard\ Deviation\ of\ Demand\ over\ Time\ Period$

In the above expression, the Z-score (z) is the inverse of the cumulative distribution of the standard normal distribution evaluated at a desired Service Level. This Service Level is the percentage of times the demand is required to be satisfied. This equation is meaningful only in the case of a normal distribution because the Z-score as defined above, is not applicable for other distributions. The above formula has been employed previously without verification of the normality assumption of demand. When the demand is not normal, this expression will yield incorrect quantities to stock for the desired level. This thesis presents an alternative method to compute re-order points that is valid regardless of the distribution.

MIT Team at Varian last year showed a positive correlation between part shortages in the Supermarket and the First Pass Yield (FPY) of Tools. This led them to evaluate the bin sizes of parts leading to shortages. However, the Team did not collect data actively on the shortages observed in the Supermarket at did this year's Team. Instead, they relied on data in a 'Shortage Report' generated from SAP which only includes instances of 'cross-docked' items. [10] These cross-docked parts are the parts that were short everywhere in Gloucester and were immediately transferred over to the Supermarket when replenishment arrived from the supplier. These shortages are the equivalent of the 'Actual Shorts' as categorized by the MIT Team this year. As already presented in *Section 2.4.4 Results of Shortage Data Collection*, this type of shortage accounted for only 10% of all the shortages encountered. Further, among the 'cross-docked' parts, shortages of only those of 'KC' procurement type was investigated. Hence, only a small fraction of the overall shortage problem was addressed.

Last year's Team identified the demands for parts in the Supermarket to not follow a normal distribution and instead conform to geometric distributions. [10] The parameters of the distribution were obtained by fitting geometric distributions to the forecasted demand from MRP. However as discovered in *Section 3.1.6 Part Demand & Distribution Fitting*, the daily demand numbers from MRP does not reflect the observed demand of parts in the Supermarket. Hence distributions fit to MRP demands do not accurately capture the reality on the shop floor. A method of scaling observed demand distributions from a previous quarter, to estimate distributions of the same parts, in upcoming periods is proposed.

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Chapter 3

Solving the Supermarket Shortage Problem

The aim of this chapter is to highlight methods used by the author to reduce the occurrences of part shortages during the pick process of Supermarket Sub-assemblies.

The first section of this chapter is a description of the methods employed by the author to uncover the current state of the inventory system in the Supermarket. It explores the current replenishment practices and evaluates the consequences of the current bin sizes and re-order points of Supermarket Bins & Free Stock Bins. The accompanying sub-sections highlight the author's efforts to identify distributions of the demand of all the parts stocked in the Supermarket and subsequently estimate bins sizes & re-order points to achieve desired levels of service.

The second section of this chapter is dedicated to the elimination of the CO27 Shortages through the implementation of a priority policy for picking Shop Orders in the Supermarket. The FIFO policy is examined and its effect on inventory levels in Supermarket is evaluated.

The third section is an exploration of an alternative inventory management strategy where the Supermarket is no longer a stock location for parts but instead houses completed sub-assemblies. The author proposes a pull-based replenishment system of the sub-assemblies when one is consumed. In such as system, the parts required to build a sub-assembly will be driven from the Warehouse to the Assembler in the Supermarket directly.

3.1 Addressing Shortages of Inventory Stored in the Supermarket

From the results of the Shortage Data analysis, majority of shortages are self-inflicted by Varian, because of their present inventory management policies. Over 38% of total shortages, from the sum of Transfer and MinMax shortages, suggest that the Bin Sizes of parts in the Supermarket are not appropriately sized, to satisfy the demand over the replenishment period

of these parts. For these parts, the replenishment period is duration between respective inventory levels dropping below the respective re-order points and the arrival of replenishment stock from the Warehouse.

Around 35% of total shortages, from the sum of MinMax VMI, Actual, MinMax Actual, CO27 Actual and Sales shortages, reflect shortages of parts in the entire Varian facility at Gloucester. Some of these shortages result from parts that are exclusively stocked in the Supermarket while the rest come from parts with primary stock locations in the Warehouse. In both cases, inventory management is at fault. While the former part shortages can be resolved by correctly computing re-order points, the shortages of parts in the Warehouse is a non-trivial as material is driven to the Warehouse based on MRP.

The following section of this chapter will focus on correctly sizing the re-order points and bin sizes of all parts stored in the Supermarket. This includes those that are replenished from the Warehouse (Transfer & MinMax parts) as well as those that are directly replenished from the suppliers (Kanban & MinMax VMI parts). Collectively, these parts account for over 52% of total shortages encountered. The proposed changes for these parts would be the easiest to implement and therefore lead to the immediate reduction of shortages in the Supermarket.

3.1.1 Present Replenishment Strategies & Bin Sizing Techniques

An understanding of the current practices of computing the sizes of bins as well as replenishment methods is paramount to evaluate the current state of the Supermarket. Performance metrics such as Service Level and Inventory Cost of the system before and after recommendations can then be compared to evaluate impact of proposed changes.

The Supermarket is a stock location for 5,480 unique part types. As the focus is on evaluating bin sizes, it is most meaningful to categorize inventory based on their 'Type of Replenishment' given that Varian follows similar techniques for sizing and monitoring bins of parts with identical methods of replenishment. This categorization aligns with the classification of shortages into the various types described in preceding sections.

Table 5 below summarizes the inventory in the Supermarket based on Type of Replenishment as assigned by the Material Procurement Department. There are five different replenishment types as seen in the first column. These are: EWM REPL MIN/MAX, VMI, Free Stock DFT, Primed SMKT/MOD & Kanban SMKT/MOD. A description of inventory management

strategy as well as the replenishment strategy for the different replenishment types, is described below.

Type of replenishment	Replenishment Strategy	Inventory Management Formula	Count of Type	% of Type
EWM REPL MIN/MAX	Automatic request sent to WH when bin level drops below MIN value. Replenish up to Max policy	$Min\ Level = \mu_{M,1wk}$ $Max\ Level = \mu_{M,2wk}$	2159	39.4%
VMI	Vendor monitored. Once a week inspection. If bin level below "Re-order" point, fixed qty. reordered	$ROP = \mu_{LT}$ $ROQ = \mu_T$	1422	25.9%
Free Stock DFT	Varian Monitored. When picker notices bin level "about half" of bin size, reorder half the bin size	Max= Capacity of Bucket ROP= Half Bucket	808	14.7%
Primed SMKT/MOD	MRP driven		789	14.4%
Kanban SMKT/MOD	Two bin system. Reorder when first bin is depleted.	$Bin\ Size$ $= \mu_{DD} * LT * 2$ $+ \sigma_{DD}$	302	5.5%
Grand Total			**5480**	**100.0%**

Table 5: Overview of Present Replenishment Strategy and Bin Sizing Techniques of Inventory in the Supermarket

EWM REPL MIN/MAX

Parts in this category are the Transfer Bin parts described in previous sections of this document. Their primary stock locations are in the Warehouse. They are placed in bins on shelves in the Supermarket. The volume of these bins varies depending on the size and quantity of the part type they hold. Inventory level of these bins are continuously updated in EWM as and when parts are picked from these bins or transferred into these bins. The bins have Max and Min levels where Max of a bin corresponds to its Bin Size and Min is the Re-order Point. When the bin level falls below the Min level, a request is sent to the Warehouse to replenish the bin. The

number of parts transferred from the Warehouse is equal to the difference of Max level and inventory level at the time of request. Hence, the bins are set up on an 'Order Up to Max' policy. The lead time for the transfer is around two days.

Equations 2-4 below describe the formulae used to size the Transfer Bins. Currently, the Min Level $\mu_{M,1wk}$, equals the average of the Manufacturing Demand over one week. The Max Level $\mu_{M,2wk}$, equals the average of the Manufacturing Demand over two weeks. The replenishment quantity, $ROQ_{Transfer}$, is the difference between the maximum bin level and the current inventory level when the current inventory level drops below the Min Level.

$$Min\ Level = \mu_{M,1wk} \tag{2}$$

$$Max\ Level = \mu_{M,2wk} \tag{3}$$

$$ROQ_{Transfer} = Max\ Level - Current\ Level \tag{4}$$

$$where\ Current\ Level \leq Min\ Level$$

The Manufacturing Demand for a part is its three month, forward looking demand, to satisfy the needs of production. This demand includes the quantity required to build Supermarket Sub-assemblies and the quantity required to complete Mod Kits that go directly onto the production floor. The Manufacturing Demand is made available to the Materials Manager via a report generated by Rapid Response (another enterprise software). The report aggregates part requirements based on the Tools that have been added to the company's Production Schedule for the next three months.

VMI

VMI stands for "Vendor Managed Inventory" and as the name suggests, these parts are monitored and replenished directly from suppliers. At Varian, majority of the VMI inventory is managed by a single vendor (henceforth referenced by 'External Vendor'). This company serves as a distributor of parts from five different suppliers. This simplifies Varian's inventory sourcing challenges.

The MinMax VMI parts are consumables that are stocked in bins in the Supermarket, which is the primary stock location for these parts. The exact on-hand balance of these parts is not known kept track of in EWM as they are consumed freely by personnel on the production floor and by Supermarket Pickers. All the bins have the same volume. Their levels are monitored once a week, by an External Vendor representative. The bins have a predetermined Re-order

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Point corresponding to the bin level below which, a replenishment order is sent to the supplier of the part. The replenishment order is manually released by the External Vendor representative. Just as each bin has its unique Re-order Point, it also has a specified Re-order quantity. The lead times for replenishment of these parts range between five days and thirty-five days, while the average lead time is 7.3 days.

The ROP and ROQ are determined by External Vendor using the Equations 5-6 described below. ROP, which is the Re-order Point equals μ_{LT} which is the expected demand over the replenishment lead time LT. This is computed by multiplying the daily average demand, μ_{DD}, with the lead time if the part in days. The Re-order Quantity, ROQ, is based on the number of "Turns" the vendor has sent to achieve. A Turn as defined by External Vendor, is the event of replenishing inventory in the Supermarket. At present, External Vendor targets achieving no more than 12 Turns a year. This implies that each VMI bin is replenished thrice each quarter. Hence the ROQ equals a third of the quarter's remand, represented by μ_T.

$$ROP = \mu_{LT} \tag{5}$$

$$where\ \mu_{LT} = \mu_{DD} * LT \tag{6}$$

$$ROQ = \mu_T \tag{7}$$

External Vendor states that they regularly monitor the part demand which they obtain from the Sales & Forecasting Department. They claim to re-evaluate their Re-order Points every quarter.

Free Stock DFT

Parts in this category are the MinMax parts described in previous sections of this document. They are the Varian managed analogs of the VMI parts. MinMax parts are also consumables and their primary stock locations are in the Warehouse. Again, the exact on-hand balances of these parts are unknown for reasons identical to that of the VMI parts. The bins are of equal volume. Each part is assigned a single bin. Varian's strategy for stocking these bins is to fit as many parts of the same type as a possible into a bin. Replenishment of such a bin relies on Pickers noticing that the bin level has dropped below "half" its capacity. At this point, the Picker is required to "Wand" (scan barcode on the bin) the bin which then sends a request for replenishment to the Warehouse. The lead time for replenishment is the same as that for transfer bins, around 2 days.

The formulae of the bin size and replenishment quantity is summarized by Equations 8-10 below.

$$Max\ Level = Capacity\ of\ Bin \qquad (8)$$

$$Min\ Level = Half\ Capacity\ of\ Bin \qquad (9)$$

$$Wand\ Qty = Half\ Capacity\ of\ Bin \qquad (10)$$

Primed SMKT/MOD

These are special parts stocked exclusively in the Supermarket whose stocking quantities are MRP driven. There are no bins with re-order or max levels for these part types.

Kanban SMKT/MOD

The final category of parts based on Replenishment Type is Kanban SMKT/MOD or simply Kanban. Parts of this type are only stoked in the Supermarket and are replenished directly from suppliers. Inventory of this type is managed using a 'Two-Bin Policy' where parts are stored in two bins of equal size. Initially, parts are only drawn from one of the bins. When the bin is depleted, a replenishment request is automatically sent to the supplier. The second bin is consumed over the period of replenishment. The supplier then delivers one and a half bins worth of inventory. At present, the size of each bin is calculated using the Equation 11. where μ_{DD} and σ_{DD} correspond the mean and standard deviations of the Daily Demand. LT is the lead time of the part. The constant '2', serves as a 'safety factor'.

$$Bin\ Size_{Kanban} = \mu_{DD} * LT * 2 + \sigma_{DD} \qquad (11)$$

$$where,$$

$\mu_{DD} = Mean\ of\ Daily\ Demand$

$LT = Replenishment\ Lead\ Time$

$\sigma_{DD} = Standard\ Deviation\ of\ Daily\ Demand$

The lead time of Kanban parts varies between 5 and 15 days but is usually closer to 5 days.

3.1.2 Critique on Present Method of Inventory Management

This section serves as a critical examination of the formulae and policies employed currently at Varian, for sizing & reviewing bins of the different inventory types in the SMKT. While concerns specific to Replenishment Types are discussed under the respective subheadings, the

following paragraph presents a few fundamental errors that resonate across the different bin types.

Firstly, the concept of safety stock is either absent or not correctly accounted for in the respective formulae. Part demand, like any other process has some element of randomness to it. The standard deviation σ, or the second moment of the mean, of the demand is a good indicator of this randomness. Safety stock is a means of accounting for the variation and ensuring that parts are available, a certain percentage of the time. This percentage, called the Service Level, is usually set by the company deepening on the seriousness of stockouts. [11] At Varian, there is no target service level set for any of the parts. A detailed discussion of the correct methods to calculate bin sizes and re-order points is presented in *Section 3.1.5 Correct Bin Sizing Technique.*

Secondly, while demand figures are updated monthly, the bin sizes and Re-order Points are not. The Min and Max Levels of the Transfer Bins are re-calculated only twice each year. This is also the case for the Kanban Bins.

EWM REPL MIN/MAX

As described by Equation 2-4, the Min and Max Levels for these bins equal the one week average & two-week average of the Manufacturing Demand respectively. The Manufacturing Demand as currently defined, is the demand of parts for Mod Kits and Supermarket Kits. The demands from Sales and of parts to replenish the Gold Square bins, are not currently considered in the Manufacturing Demand. Hence, right from the get-go, the demand is not correctly accounted for. Given that Sales should not be picking from Supermarket Bins unless there are no parts available in the Warehouse, it is excusable to not factor in the Sales demand into the Manufacturing Demand. However, since Sales currently picks from these bins, it can be concluded that Demand is not properly accounted when material is driven to the Warehouse.

Furthermore, from the formulae used to size bins in the Supermarket does not account for variability in demand over the replenishment lead time. Examining the formula for Min Level again,

$$Min\ Level = \mu_{M,1wk}$$

If the demand were normally distributed, this formula would size bins to achieve stock outs, 50% of the time the bin level dropped to Min Level. Safety stock, which is an insurance against

demand spikes caused by demand variability, is lacking. A more detailed discussion on this is presented in *Section 3.1.5 Correct Bin Sizing Technique.*

VMI

Once again, demand variability is not factored in at all in the determination of the ROPs and ROQs of the VMI bins. Ideally, safety stock which covers this variability should be included the determination of the Re-order Points.

Further, as bins levels are only inspected once a week, there is a good chance replenishment orders are not sent when the bin level drops to the Re-order Point. The delay could be between a day to six days, during which parts are consumed from these bins. Hence there is a significant risk of stockout occurring before replenishment. The demand over the review period of 7 days is not accounted for.

Even if variation is not accounted for, the correct formula the Re-order Point should be as show in Equation 12 below.

$$ROP_{VMI} = (r + LT) * \mu_{daily} \tag{12}$$

where ,

$r = Review\ Period = 7\ days$

$LT = Replenishement\ Lead\ Time\ in\ days$

$\mu_{daily} = Average\ Daily\ Demand$

MinMax

The methods of currently sizing and reviewing the MinMax bins were the most surprising. The lack of automated review system or dedicated personnel to inspect the bin levels routinely, is appalling. Needless to state, demand variability is not considered in sizing the bins.

At present, as Pickers pick parts for Shop Orders, they are responsible for 'wanding' MinMax bins with bin levels less than half the capacity of the bin. This notion of 'half' is both arbitrary and highly subjective. What look like half to one Picker might not be the case to another. Also, since wanding is a collective responsibility among the pickers, there might be a tendency for a Picker to skip the wanding of a bin, if he/she is in a hurry, with the expectation for someone else to carry out the operation.

Kanban SMKT/ MOD:

While the formula for the bin size of Kanban Bins is the only one that factors demand variability, it is not set up correctly to improve the service level of the bin.

$$Bin\ Size_{Kanban} = \mu_{DD} * LT * 2 + \sigma_{DD} \qquad (13)$$

In the above formula, the constant 2 is a safety factor for the lead time, LT. While the mean correctly scales by a factor of $2 * LT$, the standard deviation does not scale appropriately. Hence, the formula does not account for the variation in demand over the entire $2 * LT$ number of days. To correctly account for variation, the standard deviation term, σ_{DD} should be multiplied by $\sqrt{2 * LT}$. The general form of this equation relies on the normality assumption of demand. Even if this is true, accounting for demand variation by adding multiples of the mean demand is not the right approach. Bins sized this way will still lead to stockouts if the standard deviation of demand is greater than the mean. Last year's Team voiced the same concerns. Back then, only a half multiple of standard deviation was used as opposed to adding a complete standard deviation as seen above. [10]

Primed SMKT/MOD:

The average lead time of this part type is 45 days. Since MRP drives material of this type directly to the Supermarket, there is a possibility that no stock for such parts exists in the Supermarket over a prolonged period. When a tool order is confirmed, and if the need date is before the replenishment lead time, shortages are inevitable.

3.1.3 Discussion on Demand Distribution

Demand for parts in the Supermarket is not deterministic. For any given part type, the exact quantity that will be consumed on each day cannot be ascertained. This results from the lack of pre-determined order to the Picking process as well as the fact that Production Demand and especially Sales Demand are updated regularly. Even if manufacturing demand was ascertained, events such as part breakages during assembly/testing, or emergency requirements by Sales would cause disruptions to the demand figures. Hence, demand is a random variable.

Random variables, including demand, have probability distributions which specify the probability that its value falls in any given interval. Specifically, daily part demand in the

Supermarket can be treated as a discrete random variable. This allows for estimations of probabilities of integer values of daily demand. Working with daily demand is appropriate for the following reasons:

1. Obtaining information at a finer resolution (eg. Hourly) is not accurate given delays in data logging.

2. Part lead times are available in days.

3. Data on Supermarket kit shortages were collected once a day. Hence, any attempts to link shortages to observed demands will make sense if the observed demands are on a per day basis.

The Probability Mass Function (PMF) is a function that describes the distribution of a discrete random variable. The PMF assigns a probability to each value of the random variable. In Equation 14 below, if X is a random variable, $f_X(x)$ describes its PMF for some value of X equaling x. [12]

$$f_X(x) = P(X = x) \qquad (14)$$

$$x \in Z^+$$

The Cumulative Distribution Function (CDF), for a discrete or continuous random variable, describes the probability that the random variable will be less than or equal to a certain value. The generic mathematical representation of a CDF function is as shown in equation 15. $F_X(x)$ if the CDF function of random variable X. [12]

$$F_X(x) = P(X \leq x) = \int_0^x f_X(x) dX \qquad (15)$$

$x \in R^+$, for continuous random variables, and

$$F_X(x) = P(X \leq x) = \sum_{X=0}^{X=x} f_X(x)$$

$x \in Z^+$, for discrete random variables

Some of the commonly encountered discrete distributions in the manufacturing context are Poisson, Binomial, Negative Binomial and Geometric distributions. Table 6 lists the PMF and the characteristics parameters of these respective distributions. The parameters in the last column are those that are required to define the PMF & CDF.

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Distribution	PMF	Parameters
Poisson	$\dfrac{\lambda^k e^{-\lambda}}{k!}$ x=0,1,2..., $\lambda > 0$	λ
Binomial	$\binom{n}{x} p^x (1-p)^{n-x}$ X=0,1,...,n, $0 \leq p \leq 1$	n, p
Geometric	$(1-p)^{x-1} p$ x=1,2,..., $0 \leq p \leq 1$	p
Negative Binomial	$\binom{x-1}{r-1} p^r (1-p)^{x-r}$ x=r,r+1,r+2...	r,p

Table 6: Commonly Observed Discrete Distributions along with PMF & Characteristic Parameters [12]

Daily demand which is a random variable, has an expected value usually termed 'mean' (μ) and a 'variance' (σ^2) which is the expectation of the squared deviation of the random variable from its mean. The variance term is a measure of how spread out the demand is from the central mean. [12] In sizing the inventory bins, it is important to account for the variance as this causes demand to spike. Bins should be sized such that there is enough material in them, to satisfy demand (including spikes), a specified percentage of this time. This percentage is often referred to as the Service Level (SL). Stockout is the situation where there is demand for a part but the bins are empty. The percentage of stocksouts (STO) occurring is related to the service level as shown in Equation 16 below.

$$STO = 100 - SL \tag{16}$$

The objective of inventory management should be to maximize service levels of part bins that have serious consequences to production if empty. The tradeoff between performance and cost needs to be evaluated. A discussion on service level is presented in the next section.

3.1.4 Discussion on Service Level

The service level is a quintessential concept in inventory management. As described above, it reflects the ability of a system to meet requirements. For the context of this thesis, the service level (SL) is the percentage of the time that a bin can satisfy part demand over its replenishment period. In other words, it is the percentage of time that a part will be found in its bin, given that the bin level has dropped below its re-order point. The Effective Service Level (SL_{eff}) as

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defined for the context of this thesis, is the percentage of time that a part is available in its bin at any time. To illustrate how the SL_{eff} and SL are related, consider the following example:

Let P be a part stocking in a bin with maximum level Q, re-order point ROP that achieves service level SL, replenishment lead time LT. Also, let T be the time between re-supply of inventory. When the bin level is above ROP, there is a 100% chance that a part will be found in the bin. Whereas when the bin level is below the ROP, there is SL % probability of the part being available.

$$SL_{eff} = \frac{T - LT}{T} * 100 + \frac{LT}{T} * SL \qquad (17)$$

$where,$

$SL_{eff} = Effective\ Service\ Level$

$T = Time\ between\ Orders$

$LT = Replenishment\ Lead\ Time$

$SL = Service\ Level\ of\ Re - order\ Point$

In the above expression, there are two ways to increase the overall effective service levels: Increasing T-LT or increasing SL. The former can be increased by increasing the difference between the max level Q and re-order point ROP. However, this would result in higher average inventory levels. Increasing the SL would increase the overall Service level of the bin while minimizing average inventory levels. The aim of this thesis is to achieve higher effective service levels by maximizing the service level SL.

The organization is responsible for setting this metric, based on its desired performance. In the case of Varian, the concept of service level is lacking. Most of the bin levels across the different replenishment types are determined using average demands only.

For inventory bins, service levels are achieved by setting re-order points appropriately. The re-order point needs to be set such that the contents of the bin can satisfy part demand over the replenishment lead time, i.e., between when a replenishment request is sent and when new stock arrives. If the re-order points are not correctly set, bins might become empty leading to stockouts. The re-order point required to achieve a certain service level is dependent on the probability distribution of demand of that part over its lead time. Specifically, the service level

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is the value of the cumulative distribution function of the demand when demand takes on the value of the re-order level. Mathematically, this can be expressed as shown in Equation 18.

$$SL = F_{X,LT}(ROP) \tag{18}$$

where,

$SL = Service\ Level$

$X = Demand\ Random\ Variable$

$LT = Replensihement\ Lead\ Time$

$F_{X,LT} = CDF\ Function\ of\ Demand\ \ Pooled\ over\ LT$

$ROP = Re - order\ Point$

The proof for this is intuitive. The CDF is the probability that a random variable takes on a value less than or equal to a specified number. If probability is thought of as the ratio of number of successes over total number of attempts, the CDF of demand evaluated at the re-order point, is the percentage of times the remaining parts in the bin will satisfy demand until replenished. This is the definition of the service level.

The graph below is a plot of CDFs of demands with equal means and variances but follow two different distributions: Normal and Poisson distributions. When the replenishment time is 1 day, the CDF of the daily demand is also the CDF of the demand over the lead time of the part. In this case, the CDF value at any re-order point X, represents the service level of this bin. As seen in the plot, for same value of re-order point, the service level is higher when demand is Poisson distributed than when Normally distributed. While this is true for this specific example, the larger message is that identifying the correct demand distribution is important to size bins levels to meet desired service levels.

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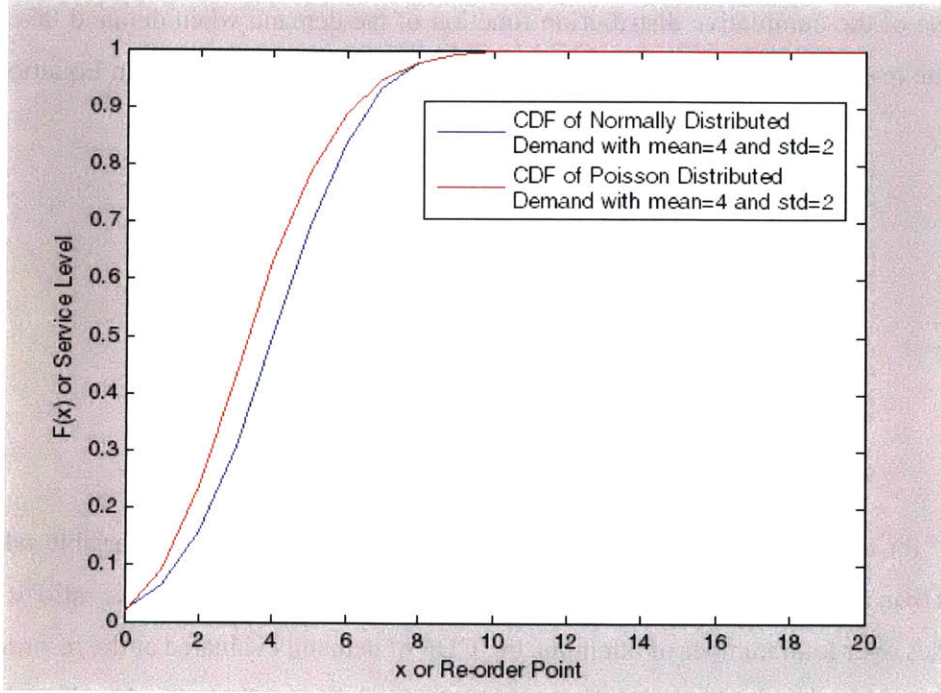
Figure 7: Plots of Service Levels vs Re-order Points for Normally and Poisson Distributed Demands with Equal Means and Variances

It is crucial to comprehend the distinction between the CDF of Daily Demand, $F_X(x)$, and the CDF of demand pooled over the lead time, $F_{X,LT}(x)$. For any part, the Pooled Demand Random Variable is the sum of LT number of Daily Demand Variables. This is represented mathematically in Equation 19 below. X is the Daily Demand Random Variable for a part type, that follows a statistical distribution '*dist*' with characteristic parameters '*params*'. The demand of the part pooled over LT number of days, is the random variable Y which has a distribution $dist_{pooled}$ with characteristic parameters, $params_{pooled}$.

$$X \sim dist(< params >) \tag{19}$$

$$Y = \sum_{i=1}^{LT} X_i \tag{20}$$

where X_i are independent and identically distirbuted demand random variables

$$Y \sim dist_{pooled}(< params_{pooled} >) \tag{21}$$

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The distribution of the Pooled Variable may or may not be the same as that of the Daily Demand. This highly depends on the distribution of X and number of days over which demand is pooled. In either case, the parameters of the distribution changes and it is important to estimate the parameters of the pooled distribution.

Equation 18 can be re-written as,

$$SL = F_Y(ROP) \tag{22}$$

$where,$
$SL = Service\ Level$
$Y = Variable\ of\ Demand\ Pooled\ over\ LT\ Days$
$LT = Replensihement\ Lead\ Time$
$F_Y = CDF\ Function\ Y$
$ROP = Re - order\ Point$

Hence, in order to size re-order points correctly, it is imperative that the right distribution of the pooled demand be identified along with the correct characteristic parameters.

3.1.5 Correct Bin Sizing Technique

Bin Sizing as defined for the context of this thesis involves setting the correct values of maximum bin levels as well as re-order points. Regardless of the replenishment strategy followed by Varian, all parts have a re-order point. For the Transfer, MinMax and VMI bins, it is the Min Level, Wand Qty. and ROP respectively. For the Kanban bins, which are managed by a two-bin system, the re-order point is the bin size of one of the bins. As highlighted in *Section 3.1.4 Discussion on Service Level*, the re-order point directly influences the service level of the bin. The primary objective of this section is to highlight the correct method to set re-order points for various part bins.

Setting the Max Level or Bin Size for Trasnfer, MinMax and VMI parts is dependent on the capacity to deliver parts to the Supermarket. The frequency of re-stocking is higher when the difference between the Bin Size and corresponding Re-order Point is lower, and vice versa. Lower average inventory levels can be achieved by minimizing the difference between the two levels. However, it is important to ensure that the increased frequency of trucking is financially

feasible. The objective of the work presented is to correctly set re-order points to minimize stockouts. The Max Levels for bins (where applicable) will be assigned such that the difference between the new Max Levels and new ROPs is equal to that of old Max Levels and old ROPs. However, this is not suggested as the optimal method to set Max Levels. The difference between the levels can be minimized if factors like trucking capacity are analyzed. This is beyond the scope of this thesis.

3.1.5.1 Setting Re-order Points to Achieve Service Levels

As briefly stated in preceding sections, re-order points should be set such that the contents of the bin at this point, can satisfy demand until the bin is replenished. The replenishment time or lead time (LT) is the number of days between the time a replenishment request is sent and the time when new stock arrives into the bins.

A commonly prescribed formula to stock inventory while protecting against demand variability, is presented in Equation 23. [11] Q, which is the amount of inventory to hold is equal to the sum of mean demand over the replenishment period ($LT * \mu_D$) plus some safety stock ($z * \sqrt{(LT)} * \sigma_D$). The safety stock term accounts for the variability in demand but adding a factor of the standard deviation of demand. This factor, termed Z-score and represented by z, is usually the inverse of the standard normal cumulative distribution evaluated at the desired service level.

$$Q = LT * \mu_D + z * \sqrt{(LT)} * \sigma_D \tag{23}$$

where,

$Q = Inventory\ to\ Stock$

$LT = Replenishment\ Lead\ Time\ in\ Time\ Scale\ units$

$\mu_D = Mean\ Demand\ /\ Time\ Scale$

$z = Z - Score$

$\sigma_D = Standard\ Deviation\ of\ Demand\ /\ Time\ Scale$

Table 7 below presents values of z corresponding to certain service levels.

Service Level (%)	Z-Score
84	1
85	1.04
90	1.28
95	1.65
97	1.8
98	2.05
99	2.33
99.9	3.09

Table 7: Service Level and Corresponding Z-Score

The objective of Equation 23 is cover enough area under the probability density curve of demand such that the cumulative distribution equals the desired service level. This is achieved by adding multiples of standard deviation to the mean demand. While the mathematical representation of this concept looks different, it is akin to Equation 22 which suggests that the cumulative distribution of demand evaluated at the re-order point equals the service level of the bin. Equations 24-26 below shows how they are related.

$$If\ ROP = Q = LT * \mu_D + z * \sqrt{(LT)} * \sigma_D \qquad (24)$$

$$then,$$

$$SL = F_Y(ROP) \qquad (25)$$

$$where\ Y \sim N\left(LT * \mu, \sqrt{LT} * \sigma\right) \qquad (26)$$

A fundamental assumption of Equation 23 is that demand is **Normally** distributed. The mean μ_D and standard deviation σ_D of most distributions do scale with LT and $\sqrt{LT}$ respectively. However, the values of Z factor corresponding to service levels is only accurate if demand distribution is normal. In fact, there are no standardized distributions of the commonly encountered discrete distribution listed in Table 6. Hence obtaining the Z-score which is the standardized cumulative inverse of the service level is not trivial. An invalid assumption to make would be that the pooling of demand would tend to a normal distribution. While this is true as per the Central Limit Theorem, in cases where a large number of variables are pooled together ($\geq$ 30), it may not be applicable when pooling a few number of variables. Given that replenishment lead time for bins in the Supermarket vary between 2-15 days in most cases, the

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normality assumption may not hold good. When a few number of variables are pooled, the result of the Central Limit Theorem is valid only if the individual distributions do not depart radically from a normal distribution. [12] Hence, it is erroneous to blindly apply this formula to any situation. A more robust formula for stocking inventory/sizing re-order points can be derived from Equation 22 as shown below.

$$SL = F_{X,LT}(ROP) = F_Y(ROP)$$

Taking the inverse of cumulative distribution on both sides,

$$ROP = F_Y^{-1}(SL) \tag{27}$$

The above formula is true regardless of the distribution. By knowing the distribution of pooled demand along with the characteristic pooled parameters, re-order points for any bin can be estimated this way. Consider demand random variable X which follows a certain Distribution with characteristic Parameters as show below.

$$X \sim Distribution(< Parameters >) \tag{28}$$

Random variable Y is the pooled demand variable such that,

$$Y = \sum_{i=1}^{LT} X_i \tag{29}$$

where X_i are independent and identically distirbuted demand random variables

In this case, Y will have a distribution- Pooled Distribution, with Pooled parameters as represented below.

$$Y \sim Pooled\ Distirbution(< Pooled\ Parameters >) \tag{30}$$

Table 8 below lists a few common distributions, their characteristic parameters, the corresponding pooled distribution, and the parameters of the pooled distribution.

Distribution	Parameters	Pooled Distribution	Pooled Parameters
Normal	μ, λ	Normal	$LT * \mu\ , LT * \sqrt{\sigma}$
Poisson	λ	Poisson	$LT * \lambda$
Binomial	n, p	Binomial	$n * LT\ , p$
Geometric	p	Negative Binomial	LT, p

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Negative Binomial	r, p	Negative Binomial	$r * LT$, p

Table 8: List of select distribution with characteristic parameters and distribution [12] [13] [14]

Depending on the distribution of the demand for a given part and knowing the lead time, the pooled parameters can be estimated as shown in Table 8. With this information, the re-order point for any part can be calculated using Equation 27.

3.1.6 Part Demand & Distribution Fitting

Determining the correct distribution and parameters of daily demand is imperative for two reasons:

1. To evaluate current service levels and diagnose causes of shortages of the commonly short parts

2. To set correct re-order points where required

3.1.6.1 Demand Data Collection

With the above points in mind, the focus shifted to characterizing the demand of all 5,480 part types stocked in the Supermarket. Historical data of the actual daily demand was required. The actual daily demand refers to the demand of parts from Supermarket bins on each day. Unfortunately, no readily available historical data of this demand for each part existed. While the MRP demand for parts is available, it is a forward-looking estimate that is inflated and not accurate. Further, when MRP drives parts, it does so in batches or 'lots'. The quantity of a 'lot' is an economic order quantity that is calculated by Varian. Figure 8 below is a plot of the MRP demand for Part E17296280, in the Supermarket on each day between 1st Feb 2017 and 30th June 2017. The spike in demand represent the 'lots' of parts that are needed for the period of interest. It must be noted that the data points of the daily demand visualized below
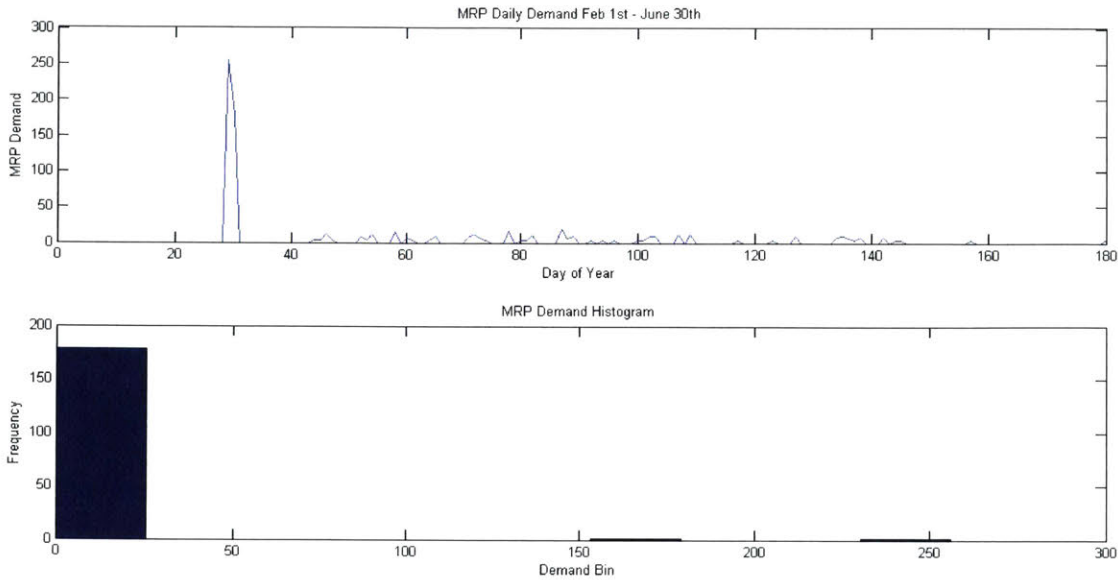
Figure 8: Example of MRP Demand of a Part Stocked in the Supermarket

For these reasons, it is not appropriate to fit distributions to the 'forecasted' MRP demand as it does not reflect the actual number of parts withdrawn from a bin each day. Hence, sizing bins based on this demand would be erroneous.

The actual daily demand numbers for parts stocked in the Supermarket, was obtained using the MATLAB Script '*PartDemand.m*' (refer Appendix), written by the author that extracts this information from a material movement report generated by SAP. This report, generated using the MB51 transaction code in SAP, contains information on the movement of every part, into and out of the Supermarket over a period of choice. For the purpose of fitting distributions to part demands, this report was generated with movements in the Supermarket, over the period of 1st January 2017 and 26th June 2017. A snapshot of the report as generated, is presented in Figure 9 below. The first column of the report, 'Sloc', contains the unique part numbers with rows of data specific to the movements of each part type separating one another. In Figure 9, the part numbers captured are 1117300 and 1264000. The 'MvT' column, which stands for "Movement Type", is a list of codes that corresponds to the nature of the transaction. Eg. MvT 811 signifies that the movement was a Transfer of parts from one stock location to another, while MvT 908/913 is when parts are picked for a shop order. The other two columns of interest are the 'Pstng Date' and 'Quantity' columns which list the date and quantity associated with each transaction. The quantity is positive when material enters the Supermarket and negative when material is picked.

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SLoc	MvT	S	Pstng Date	Quantity	BUn	Mat. Doc.	Batch	Order	PO	Reference	Vendor	Plant	Customer	Doc.Head	User
1117300															
SMKT	908		15.05.2017	-2	EA	4.92E+09					1.7E+08				IP0620
SMKT	811		15.05.2017	2	EA	4.92E+09					US1 00500	4030			IP0620
SMKT	908		03.05.2017	-2	EA	4.92E+09					1.7E+08				IP0620
SMKT	811		03.05.2017	2	EA	4.92E+09					US1 00500	4030			IP0620
SMKT	908		14.04.2017	-2	EA	4.92E+09					1.7E+08				IP0620
SMKT	811		14.04.2017	2	EA	4.92E+09					US1 00500	4030			IP0620
SMKT	908		06.01.2017	-2	EA	4.92E+09					1.7E+08				IP0620
SMKT	811		06.01.2017	2	EA	4.92E+09					US1 00500	4030			IP0620
1264000															
SMKT	908		26.05.2017	-20	FT	4.92E+09					1.7E+08				IP0620
SMKT	811		26.05.2017	20	FT	4.92E+09					US1 00500	4030			IP0620
SMKT	908		14.04.2017	-20	FT	4.92E+09					1.7E+08				IP0620
SMKT	811		14.04.2017	20	FT	4.92E+09					US1 00500	4030			IP0620
SMKT	908		17.03.2017	-20	FT	4.92E+09					1.7E+08				IP0620
SMKT	811		14.03.2017	20	FT	4.92E+09					US1 00500	4030			IP0620
SMKT	908		31.01.2017	-20	FT	4.92E+09					1.7E+08				IP0620
SMKT	811		31.01.2017	20	FT	4.92E+09					US1 00500	4030			IP0620

Figure 9: Snapshot of Material Movement Report Generated by SAP

The negative quantity transactions correspond to part quantities picked on the associated positing date and positive (mostly MvT 811) transactions are instances of re-stocking part bins. Negative MvT 811 transactions are instances where parts are transferred from the Supermarket bins to other stock locations. These usually occur when Sales requires parts from the Supermarket. These parts are transferred back to the Warehouse from where they are sent out on Sales orders (MvT 640).

The MB51 report generated contained movement information for 2,988 unique part types stocked in the Supermarket. The lack of data for the remaining 2,492 out of total 5,480 part types can be explained due to the following reasons:

1. Transaction for VMI parts are not recorded in SAP or EWM. These part bins are replenished directly by the on-site representative of External Vendor and hence information on material flow in not registered in Varian's systems. Also, pickers do not pick these parts using their RF Guns which records transactions. Instead they manually pick these by looking at the shop order. Hence, none of the 1,422 VMI part transactions are available. The Materials Manager at Varian also concluded that this information unobtainable.

2. There was no demand or supply for the remaining part types.

The MATLAB script, '*PartDemand.m*' reads the MB51 Report and generates a spreadsheet with daily demand numbers and daily supply quantities of the 2,988 part types. Running the

'*ExportDemand_Daily.m*' script, then writes these numbers to a spreadsheet in the format presented in Table 9.

Part Number	1st Jan 2017	2nd Jan 2017	3rd Jan 2017	:	26th July 2017
P_1	0	0	4	:	5
P_2	1	0	0	:	8
P_3	7	6	1	:	0
:	:	:	:	:	:
P_{2988}	0	4	2	:	2

Table 9: Format of Daily Demand as Exported by MATLAB Algorithm

Running the 'SearchPart_Daily.m' MATLAB script for part number specified by variable 'x', generates a four-in-one plot as seen in Figure 10. The top two plots are run charts of the daily demand and supply quantities each day from Day 1 (1st Jan 2017) to Day 177 (26th Jun 2017). The bottom two graphs are histograms of the daily demand and supply data sets of the part.
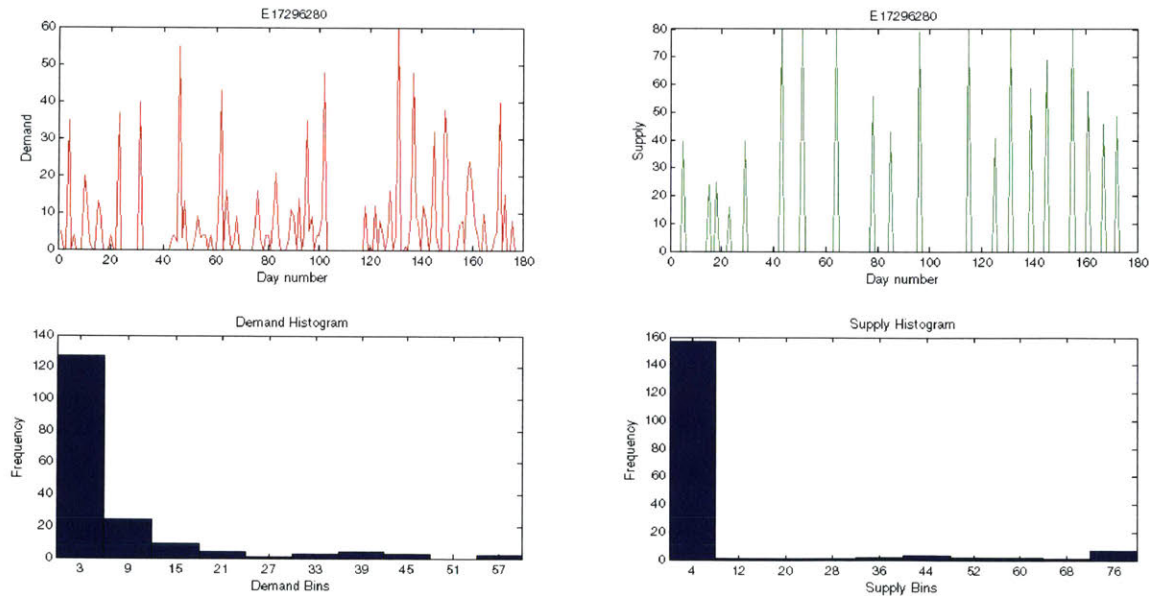
Figure 10: Clockwise from Top Left- Daily Demand Plot, Daily Supply Plot, Histogram of Daily Supply Data & Histogram of Daily Demand Data

Figure 11 below is a Normplot of the observed daily demand for Part E17296280. As evident, there is a strong deviation from normality suggesting that the pooled demand variable cannot be assumed as normally distributed.
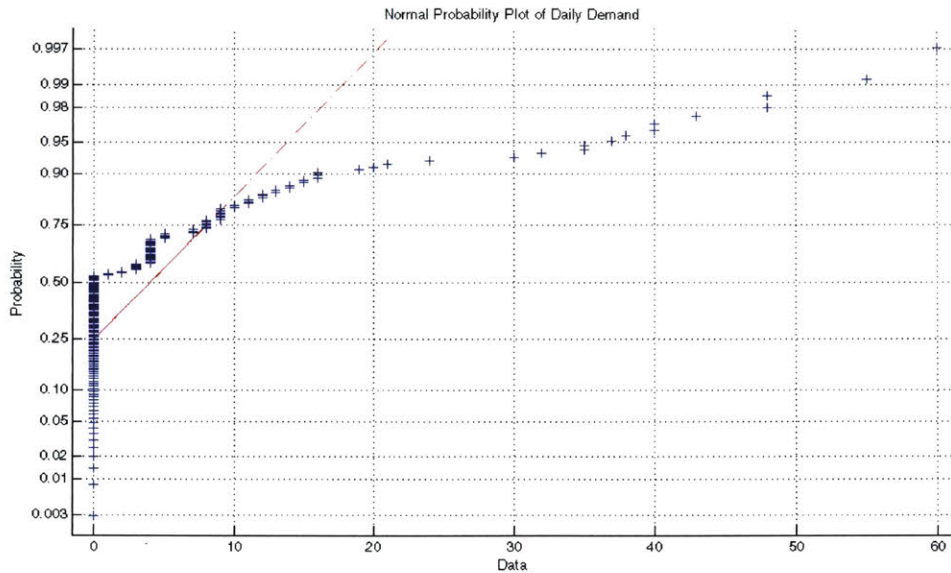
Figure 11: Normplot of Daily Demand for E17296280

The script also plots a graph as seen in Figure 12. This plot contains run charts of Daily Demand, Daily Supply and Daily Bin Levels, all superimposed on a single graph. The Bin Level plot is possible only when the initial quantity of the bin on 1st Jan 2017 is specified in the script. This information is readily available in SAP using the MB51 transaction. Additionally, the instances of shortages of the part, as recorded by the MIT team is also plotted. This script automatically reads the Shortage Data Collection Spreadsheet maintained by the MIT team in order to obtain this information. It is interesting to observe that the shortages recorded by the Team did occur whenever the bin was empty.
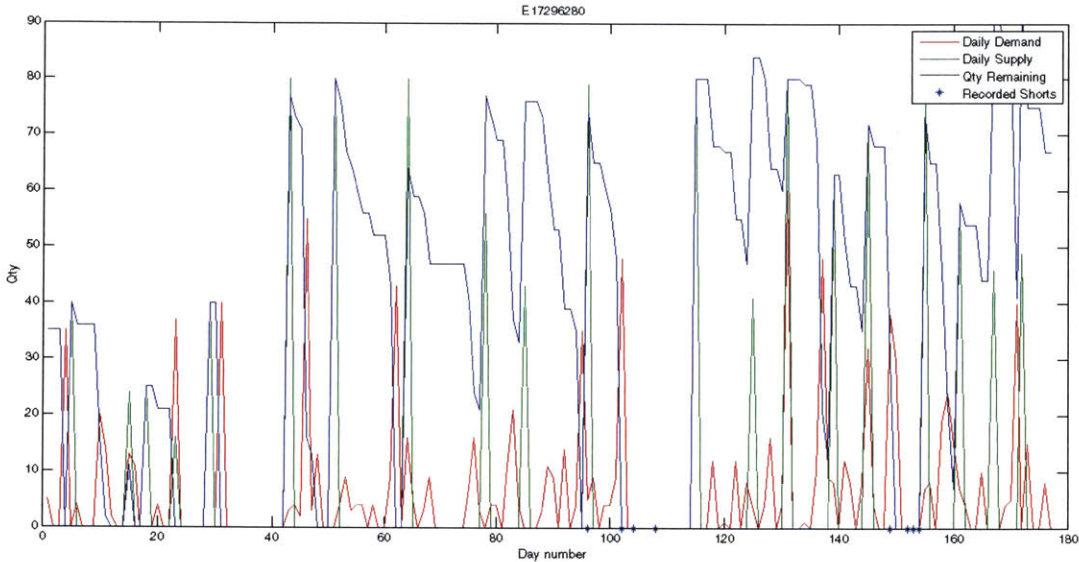
Figure 12: Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts Plot for Part E17296280

Plots like the ones in Figure 10 and Figure 12 can be generated for any of the 2,988 parts for which data is available. The only modification required to the script is changing the value of variable 'x' to the desired part number. Looking at the 'Daily Supply' and 'Qty. Remaining' curves in such plots confirm that the lead times for replenishment are within agreed values between Suppliers and Varian. For parts with primary stock locations in the Warehouse, peaks in the Daily Supply are observed within two days of the bin level (Qty. Remaining) dropping to the current Min/Wand Levels. The part whose plots are seen in Figure 12, the primary stock location is the Warehouse. For replenishment from the Warehouse, the lead time is about two days and for replenishment from the supplier, the lead time is 5 days. In the plot, a supply peak can be seen within two days of the Qty. Remaining dropping below 40, which is the re-order point for this part type. The instances where this is not observed (around the Day 35 & Day 100 mark) are when actual shorts of the part were experience at Varian. This observation is consistent across different part types. Hence, it can be concluded that variations in supply lead times (delivery time) is not a significant cause for shortages. Incorrect re-order points are responsible.

The plots in Figure 13 serve as comparison of MRP Demand as seen in Figure 8 and Actual Demand for part E17296280 as seen in Figure 10. The difference in the daily requirements is

glaring. Given these differences, it is clear that fitting distributions to MRP demands will not accurately reflect demand observed in the Supermarket.
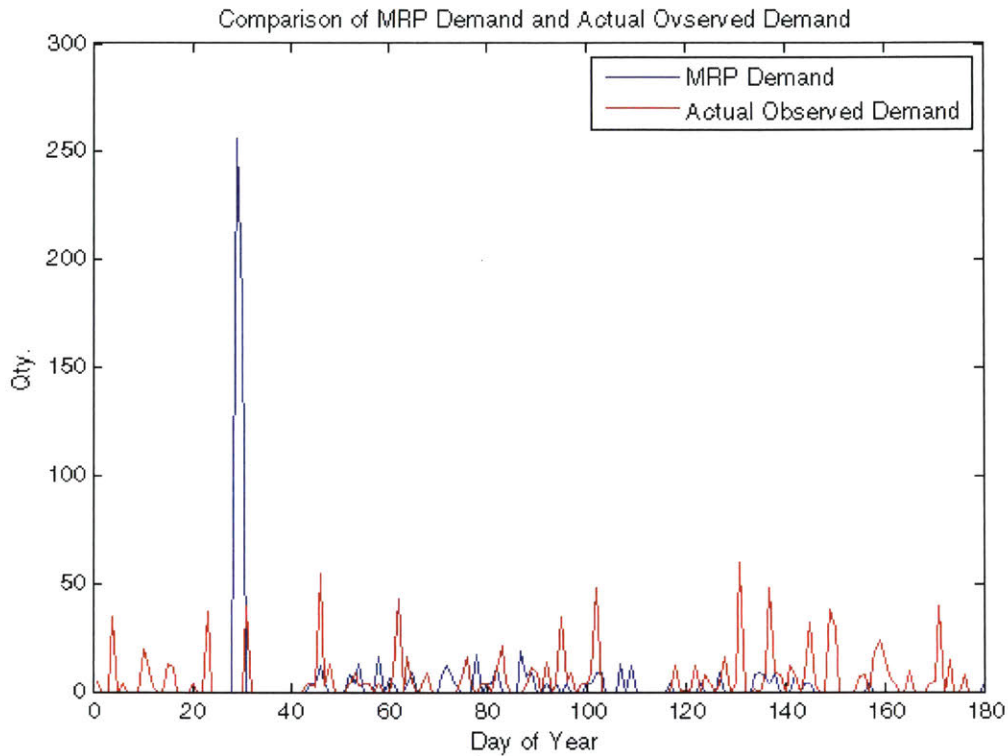
Figure 13: Comparison of MRP Demand and Actual Observed Demand between 1st Jan 2017 and 30th June 2017

One might argue that looking at MRP demand is required when sizing bins for upcoming quarters as actual demand for these periods is not yet observed. This does not have to be the case as covered in *Section 4.5 Scaling of Observed Demand for Future Quarters*. The magnitude of demand numbers may change from quarter to quarter, but since Varian builds the same proportion of different Tools each quarter, the type of distribution of demand might be constant. It might then be possible to scale the demand parameters to reflect the scaling of MRP demand from one quarter to another.

3.1.6.2 Fitting Distributions to Daily Demand Data

As stated earlier, identifying the correct distribution of the demand of parts is vital for sizing re-order points correctly. To identify the best fit distribution for each part demand, the *allfitdist* MATLAB function was utilized. This function can be downloaded from the MathWorks website and requires the Statistical and Machine Learning Toolbox to be installed. As demand

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is discrete, so should be the distributions fitted. The *allfitdist* function fits three discrete distributions to the demand data for a part. These distributions are namely Binomial, Negative Binomial and Poisson. The characteristic parameters of each model are estimated by maximizing the likelihood function. The likelihood function is the product of the probability mass functions evaluated at the observed data values. [15] Following this, the fits are ranked based on the NLogL statistic which is chi-squared distributed. The best fit, is the highest ranked among the three. Thus, the best fit distribution for demand along with the characteristic parameters were obtained for all 2,988 part types. The MATLAB script CharacterizeDemand Figure 14 is a pie chart of the proportions of the best fit distributions among all the part types. As evident, about 76% of the part demands are negative binomially distributed.

Proportion of Best Fit Distributions
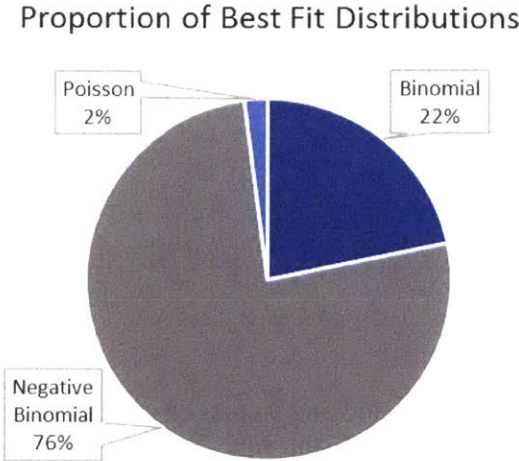
Figure 14: Proportion of Best Fitted Distributions for Part Demand among 2,988 Parts in the Supermarket

The quality of a fit can be visually inspected by comparing plots of the normalized demand histogram and the PDF of the fit distribution. The shape of a demand histogram is a good indicator of the distribution. This is true since a histogram, with bars normalized by its area, is the value of the PDF function [12]. Figure 15 below presents plots of normalized histograms, overlaid with corresponding best fit PDF plots for a few different parts.
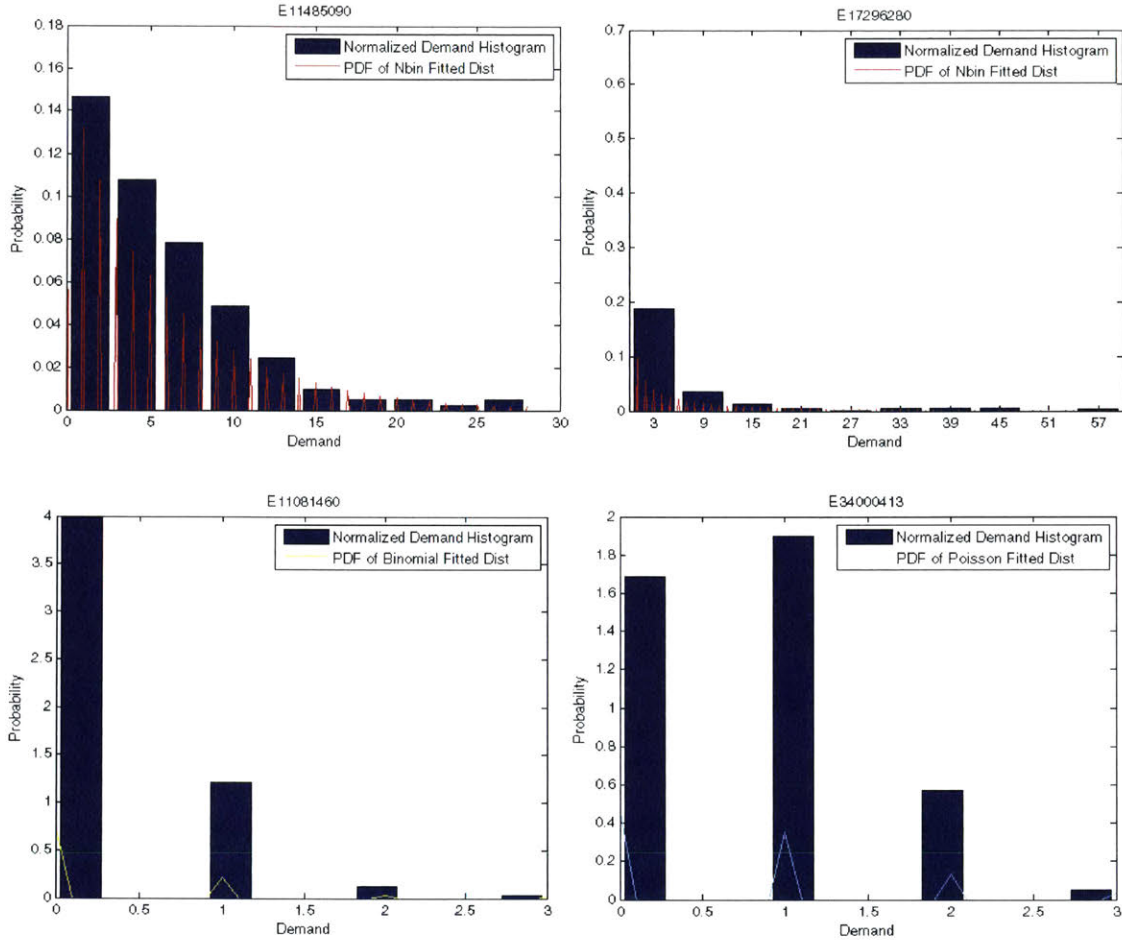
Figure 15: Comparison of Normalized Histogram of Demand Data and PDF of Fitted Distributions for Four Different Part Types

3.1.6.3 Evaluating Current Service Levels

At present, Varian does not set re-order points for bins in the Supermarket to achieve any desired service level over the replenishment period. However, given the current re-order points for the different Supermarket bins, the current Theoretical Service Levels can be calculated using Equation 22. This Theoretical Service Level is the service level that should be observed for a bin, given its demand distribution and lead time for replenishment. Identifying Theoretical Service Levels allow for the following deductions to be made regarding the causes of shortages:

1. If Theoretical Service Level is low, shortages are a result of incorrect re-order points

2. If Theoretical Service Level is high and yet shortages are persistent, it can be due to the following reasons:

   a. Depletion of stock in warehouse

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    b. Ineffectiveness of current replenishment methods

    c. Anomalies in demand

To compute the Theoretical Service Level of the bins of the commonly short parts, the parameters of the pooled demand distribution for the parts need to be estimated. Equation 22 can be re-written as presented below.

$$TSL = F_Y(ROP) \tag{31}$$

where,

$TSL = Theoretical\ Service\ Level$

$Y = Variable\ of\ Demand\ Pooled\ over\ LT\ Days$

$LT = Replensihement\ Lead\ Time$

$F_Y = CDF\ Function\ Y$

$ROP = Re - order\ Point$

The Lead Times of all the commonly short parts were gathered. For parts with primary stock locations in the Warehouse, the lead time equals the transfer time from the Warehouse to the Supermarket: 2 days. For parts driven directly to the Supermarket from respective suppliers, the lead times are the Supplier Lead Times as negotiated by Varian. Knowing the lead times of all the parts, the characteristic parameters of the demand pooled over the respective lead times can be estimated, depending on the distribution, as seen in Table 8. As per the summarized results in this table, if daily demand X follows a negative binomial distribution with parameters r &p, then the pooled demand Y will also follow a negative binomial distribution but with parameters $r * LT$ and p. This result was empirically verified in the following way:

1. The r & p parameters for parts with negative binomial daily demands were identified.

2. Weekly demands of the same parts were generated by modifying the 'ExportDemand_Daily' MATLAB script. The modification bins the demand into weeks based on the Posting Date in the MB51 Report.

3. Distributions were fit to the weekly demands and new parameters were identified. (The weekly demands were also Negative Binomial distributed for all the parts)

4. Scatter plots for each parameter with its daily distribution value along X axis and weekly distribution value along the Y axis were plotted.

5. Trendlines were fit and equations were compared to respective expected theoretical values:

   For the 'r' parameter, $r_{weekly} = LT * r_{daily} = 7 * r_{daily}$

   For 'p' parameter, $p_{weekly} = p_{daily}$

The scatter plot for the 'r' parameter is presented in Figure 16 below. The trendline fitted has an equation $r_{weekly} = 7.12 * r_{daily}^{0.97}$ which can be approximated to $r_{weekly} \sim 7 * r_{daily}$. This resembles the theoretical formula.

Weekly Demand r vs Daily Demand r

$y = 7.1219x^{0.9669}$
$R^2 = 0.8897$
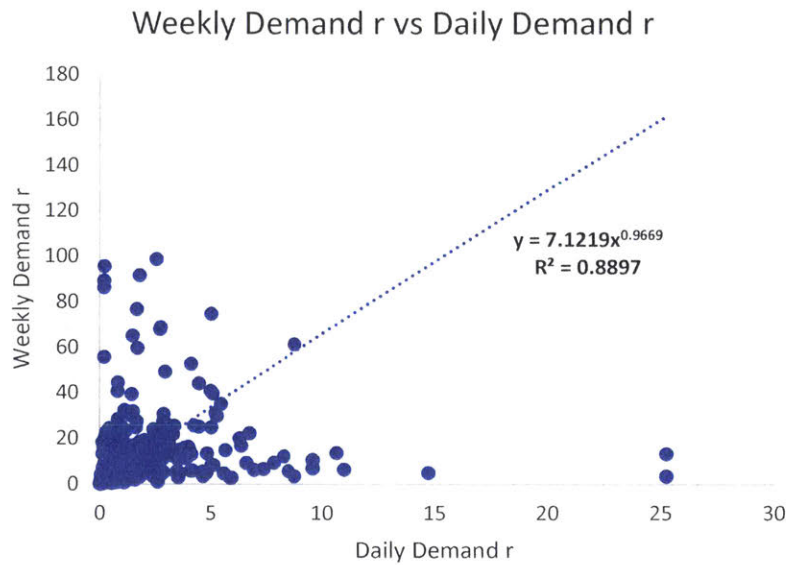
Figure 16: Scatter Plot of Daily and Weekly 'r' parameter obtained from parts with Negative Binomially Distributed Demands

The scatter plot for the 'p' parameter is presented in Figure 17 below. The trendline fitted has an equation $p_{weekly} = 1.1.3 * p_{daily}^{1.00}$ which can be approximated to $p_{weekly} \sim p_{daily}$. This also agrees with the theoretical results.

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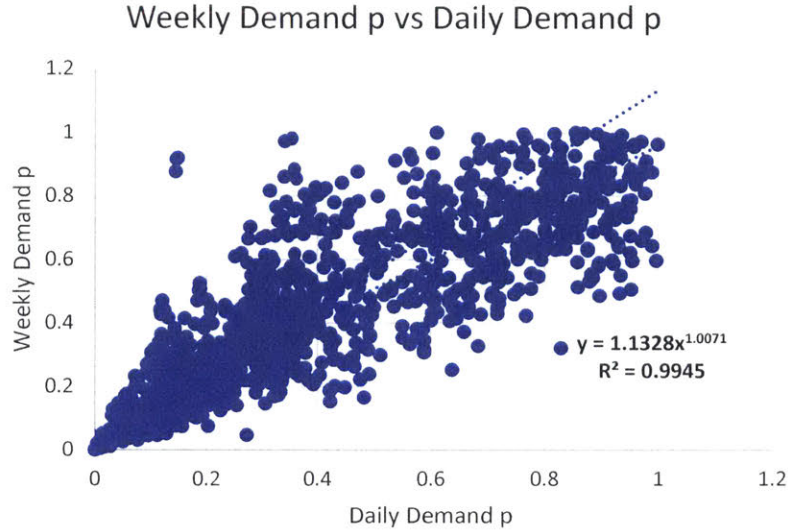
Figure 17: Scatter Plot of Daily and Weekly 'p' parameter obtained from parts with Negative Binomially Distributed Demands

If the daily demand for a part 'P_i' is Negative Binomially distributed with parameters 'r_{P_i}' and 'p_{P_i}', then the Theoretical Service Level for this part bin, 'TSL_{P_i}', with current re-order point 'ROP_{P_i}' and replenishment lead time 'LT_{P_i}' is estimated using the expression below in MATLAB.

$$TSL_{P_i} = nbincdf\left(ROP_{P_i}, r_{P_i} * LT_{P_i}, p_{P_i}\right) \tag{32}$$

where nbincdf(X, R, P) returns the negative binomial cumulative distribution

function with parameters R and P at the values in X

If the daily demand for P_i is Binomially distributed with parameters 'n_{P_i}' and 'p_{P_i}', the Theoretical Service Level is computed using

$$TSL_{P_i} = binocdf\left(ROP_{P_i}, n_{P_i} * LT_{P_i}, p_{P_i}\right) \tag{33}$$

where binocdf(X, N, P) returns the binomial cumulative distribution

function with parameters N and P at the values in X

Similarly, if the daily demand for P_i is Poisson distributed with parameter 'λ_{P_i}', the Theoretical Service Level is computed using

$$TSL_{P_i} = poisscdf\left(ROP_{P_i}, \lambda_{P_i} * LT_{P_i}\right) \tag{34}$$

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where $poisscdf(X, \lambda)$ computes the Poisson cumulative

distribution function with parameter λ at the values in X.

3.1.6.4 Setting Re-order Points for Desired Service Levels

Finally, for any part P_i Re-order Point, ROP, to achieve Desired Service Level DSL can be computed using Equation 27 from earlier:

$$ROP_{P_i} = F_Y^{-1}(DSL)$$

In MATLAB, the implementation of the above formula is as shown below.

If demand of P_i is Negative Binomially distirbuted, then

$$ROP_{P_i} = nbininv\left(DSL, r_{P_i} * LT_{P_i}, p_{P_i}\right) \tag{35}$$

where $nbininv(Y, R, P)$ returns the inverse of the negative binomial cdf with

parameters R and P.

If demand of P_i is Binomially distirbuted, then

$$ROP_{P_i} = binoinv\left(DSL, n_{P_i} * LT_{P_i}, p_{P_i}\right) \tag{36}$$

where $binoinv(Y, N, P)$ returns the inverse of the binomial cdf with

parameters N and P

If demand of P_i is Poisson distirbuted, then

$$ROP_{P_i} = poissinv\left(DSL, \lambda_{P_i} * LT_{P_i}\right) \tag{37}$$

where $poissinv(P, \lambda)$ returns the inverse of the Poisson cdf

with parameter λ

Utilizing Equation 32-34, the Theoretical Service Level (TSL) for Current Re-order Points and Re-order Points for Desired Service Levels of 98% were computed for all the commonly short parts. This 98% is not an optimal but simply chosen to serve as a reference. The results are presented in Table 10 below. Additionally, the table lists the Distribution of Daily Demands, Replenishment Types and Lead Times for each listed part.

Short Part No.	No. of Shortage Instances	Current Max Level	Current ROP	TSL (%)	ROP for 98% SL	Daily Demand Distribution	Replenishment Type	LT (Days)
E17296280	12	80	40	92	76	Negative Binomial	EWM REPL MIN/MAX	2
E17327190	12		10	94	28	Negative Binomial	Free Stock DFT	2
E15001083	12		3	72	7	Negative Binomial	Kanban	5
E17348360	11		10	93	32	Negative Binomial	Free Stock DFT	2
E17355650	8		5	97	8	Negative Binomial	Free Stock DFT	2
E17090150	8	150	50	99	41	Negative Binomial	EWM REPL MIN/MAX	2
E17783100	7	20	10	100	6	Negative Binomial	EWM REPL MIN/MAX	2
E17270580	7	75	25	60	127	Negative Binomial	Kanban	5
E47000042	7			NA	NA	NA	VMI	2
E17476310	7	20	8	99	8	Negative Binomial	EWM REPL MIN/MAX	2
E15009900	7	NA	NA	NA	25	Negative Binomial	Primed SMKT/MOD	84
E11485090	6	45	20	86	36	Negative Binomial	EWM REPL MIN/MAX	2
E17759370	6		0	4	16	Negative Binomial	Kanban	5
4210300	6		100		6	Negative Binomial	VMI	7
E17116700	6	NA	NA	NA	27	Negative Binomial	Primed SMKT/MOD	35

Table 10: List of Top 15 Commonly Short Parts along with respective Theoretical Service Levels, Observed Service Levels, Re-order Points for 98% SL

Information for VMI parts are unavailable as movements of these parts were not captured in the MB51 Report and hence fitting distributions and estimating parameters are not possible. Further for parts of Primed SMKT/ MOD Replenishment Type, TSL is also unavailable as these parts do not have bins with re-order points. They are strictly MRP driven. Nonetheless, a re-order point to achieve desired service level can be computed as the demand distributions are known for such parts.

A detailed discussion on addressing the shortage problem of parts, given the information presented in Table 10, is presented in *Section 4.1 Eliminating Shortages of Commonly Short Parts.*

For same list of parts, Table 11 below lists the Re-order points for TSLs between 95% and 99.9%.

Short Part No.	ROP 95%	ROP 96%	ROP 97%	ROP 98%	ROP 99%	ROP 99.9%
E17296280	52	58	65	76	94	159
E17327190	13	17	21	28	42	95
E15001083	6	6	6	7	7	10
E17348360	15	19	24	32	46	102
E17355650	4	5	6	8	12	27
E17090150	32	34	37	41	48	72
E17783100	5	5	6	6	7	9
E17270580	96	103	113	127	152	233
E47000042						
E17476310	6	7	7	8	9	12
E15009900	23	23	24	25	26	30
E11485090	29	30	33	36	41	58
E17759370	13	14	15	16	18	25
4210300	3	4	5	6	8	17

Table 11: Re-order Points for Service Levels Between 95% and 99.9% for Top 15 Frequently Short Parts

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3.2 Addressing CO27 Shortages

Based on the data collection results, 30% of the shortages are caused by CO27 parts. These are bulky parts that are only stocked in the Warehouse. When a Shop Order containing such parts is released by the Picker, a request for these parts is automatically sent to the Warehouse. The required parts are then transferred over to the Supermarket within a day & a half on average as seen in Figure 6. Hence, Shop Orders with such parts will inevitably be picked to short given that the parts are not stocked in the Supermarket to begin with. The aim of this section is to alleviate the occurrences of such shortages.

3.2.1 Implementation of FIFO Pick Policy

Presently, Pickers choose a Shop order to Pick, from a stack of Shop Orders placed in the Supermarket. The stack contains Shop Orders sorted in decreasing urgency from top to bottom and Pickers are supposed to Pick Shop Orders on top of the pile first. However, this is not strictly followed. Also, the positions of Shop Orders in the pile are constantly adjusted by the Production Leads. Hence, there is no fixed sequence for Picking. Lack of a pre-determined pick sequence results in having the request for CO27 parts sent, only when the Shop Order containing such parts, is released by a picker. If information on which shop order will be picked on which day is known in advance, the scheduled delivery of these parts can be planned for such that they arrive on the pick date of the Shop Order.

The implementation of a priority policy for processing Shop Orders can allow for such scheduled deliveries. Once such policy is First-In First-Out (FIFO) which dictates that the items in a queue be processed in the order of their arrival into the queue. For the case of the Supermarket, the translates to Picking Shop Orders in the order that they were placed the in the stack. As per the current operational strategy followed by Varian, Supermarket Shop Orders need to be printed and placed in the stack, 5 days before their respective Need Dates.

$$D_{print} = D_{need} - 5 \tag{38}$$

$$where,$$

$$D_{print} = Date\ on\ which\ Shop\ Order\ is\ Printed$$
$$D_{need} = Date\ on\ which\ Completed\ Subassembly\ is\ Needed$$

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The Need Date is the date on which the built sub-assembly is required on the production floor. Hence, within 5 days- parts for a Shop Order need to be picked, the sub-assemblies need to be built from these parts and the completed sub-assembly needs to be tested. With the addition of a FIFO policy, the Pickers will be picking Shop Order that are required the earliest.

With this policy in place, the pick date (D_{pick}) of a Shop Order can be estimated if the number of Shop Orders ahead in the queue (N) and the average daily pick rate of Shop Orders (λ) in the Supermarket, are known. The number of Shop orders ahead in the queue can be defied as the Backlog. At present, the average daily pick rate is around 26 Shop Orders per day. Equation 39 below presents the relationship between these variables.

$$D_{pick} = D_{print} + \frac{N}{\lambda} \tag{39}$$

where,

$PF = Expected\ Pick\ Date$

$D_{print} = Date\ on\ which\ Shop\ Order\ is\ Printed$

$N = Backlog$

$\lambda = Average\ Daily\ Pick\ Rate\ for\ Shop\ Orders$

Provided there is no Backlog, Equation 38 above can be combined with Equation 39 to obtain Equation 40 below.

$$D_{pick} = D_{print} = D_{need} - 5 \tag{40}$$

The zero Backlog reflects a situation where Shop Orders are picked on the same day that they are printed. This can be achieved by increasing the picking capacity in the Supermarket.

Regardless of whether backlog exists, the transfer of CO27 parts for a Shop Order can be scheduled by knowing its estimated pick date as computed using Equation 39. With this information, the request for parts can be sent, some 'T' days, before the Pick Date. From historical data on CO27 transfer times, a statistically significant value of T can be chosen to ensure that the parts will be delivered some SL% of the time, within T days. The process of identifying this T which achieves a delivery percentage of SL is the same as that covered for sizing part bins in Section 3.1.6.4 Setting Re-order Points for Desired Service Levels

The flowchart in Figure 18 below describes the logic sequence to release a request for CO27 parts.

```
                         ┌─────────────────┐
                         │  Shop Order Pile │◄──────────────┐
                         └─────────────────┘                │
                                  │                         │
                                  ▼                         │
                    ┌──────────────────────────┐            │
                    │                    N_i   │            │
                    │  D_pick,i = D_print,i + ──│            │
                    │                     λ    │            │
                    └──────────────────────────┘            │
                                  │                         │
                                  ▼                         │
  ┌───────────────┐  True      ╱─────────╲   False         │
  │ Request CO27  │◄───────────   D_pick,i == T   ──────────┘
  │    Parts      │            ╲─────────╱
  └───────────────┘
```
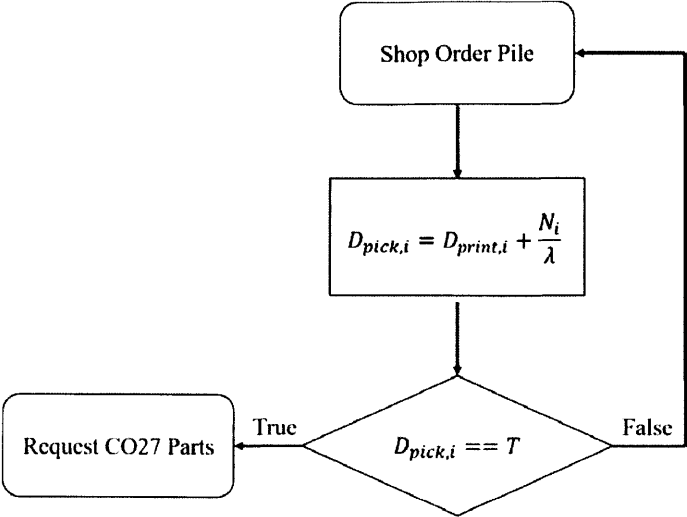
Figure 18: Flowchart Depicting Logic of Requesting CO27 Parts in Advance

3.2.2 Effect of FIFO Picking on Part Demand

As recommended above, the implementation of a FIFO policy would allow for the scheduled delivery of CO27 parts required for a Shop Order, on the date that the Shop Order is picked. Following the implementation, the daily demand of parts picked in the Supermarket is bound to change. Depending on the change, the re-order points of bins in the Supermarket might need to be increased to achieve the same service levels as recommended in *Section 3.1.6.4 Setting Re-order Points for Desired Service Levels*. The aim of this sub-section highlights the author's efforts to evaluate this change as well as the impact FIFO picking will have on inventory levels in the Supermarket.

To determine daily part demand for Shop Orders alone, a different approach from the one covered in *Section 3.1.6 Part Demand & Distribution Fitting*, was utilized. The demand computed in the previous section is the total daily demand for each part. It includes demand for Shop Orders, Sales Orders, Tool Orders and Part Breakage Request Orders. It is difficult to filter out, accurately, just the Shop Order transactions in the MB51 Report. The steps required to generate just the Shop Order Part demands are highlighted in the points below.

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1. First, the daily Shop Order Pick Demand of different Supermarket Sub-assemblies as observed Since January 2017 was computed with information on pick dates of these sub-assemblies provided. An explanation of how this was done is presented in the next Section.

2. Next, for the part of interest, a list of sub-assemblies that require this part along with the quantity required for each is gathered. With the above information, the daily Shop Order demand for the part can be calculated using the formula in Equation 41.

$$\begin{pmatrix} d_{p,1} \\ d_{p,2} \\ \vdots \\ d_{p,N} \end{pmatrix} = \sum_{k=1}^{n} \begin{pmatrix} D_{k,1} \\ D_{k,2} \\ \vdots \\ D_{k,N} \end{pmatrix} * q_{p,D_k} \tag{41}$$

where,

$$\begin{pmatrix} d_{p,1} \\ d_{p,2} \\ \vdots \\ d_{p,N} \end{pmatrix} = Column\ vector\ of\ Daily\ SO\ Demand\ of\ Part\ p\ over\ N\ days$$

$$n = Number\ of\ Subassemblies\ Fed\ by\ Part\ p$$

$$\begin{pmatrix} D_{k,1} \\ D_{k,2} \\ \vdots \\ D_{k,N} \end{pmatrix} = Column\ Vector\ of\ Daily\ Demand\ of\ Subassembly\ k\ over N\ days$$

$$q_{p,D_k} = Qunatity\ of\ Part\ p\ required\ in\ Subassembly\ k$$

To obtain the expected daily part demand with FIFO picking, the Pick Date of the subassembly in changed to the date corresponding to its Need Date minus 5 days. This reflects the situation where there is no backlog and Shop Orders are picked on the same day that they are printed. This assumption is necessary as the quantity of backlog is unknown. In the future, if this quantity is determined, the Pick Date formula in the MATLAB script can be changed from that described in Equation 40 to Equation 39. Following this, the daily FIFO sub-assembly demand is generated. This demand is then substituted in Equation 41 to estimate the daily FIFO part demands.

3.2.2.1 Generating Shop Order Demand Before and After FIFO Picking

Varian currently maintains a spreadsheet called 'STD Labor Hours', which records information of Shop Orders that have been picked, built and delivered to the production floor. These Shop Orders are considered "Completed". A screenshot of this spreadsheet is shown in Figure 19. Each row in the document is an entry for a Shop Order with unique Shop Order Number listed under the "SO" column. The other columns of interest in this document are the "Part#", "SO", "Qty" and "Need Date" columns. The "Part#" column lists the unique assembly number for the sub-assembly requested in the Shop Order. The "Qty" column records the number of such sub-assemblies required for the Shop Order while the "Need Date" specifies the delivery date of the completed sub-assembly.

Order Type	Part#	Description	SO	Qty	Need Date	Complete Date	Build Standard	Actual Hours	On Time To Need
GS	E11143600		1181540	8	06-01-17	03-01-17	0.5	1	TRUE
238762	E11575480		1181589	1	06-01-17	06-01-17	0	12.5	TRUE
231579	E11326120		1181802	1	06-01-17	04-01-17	4.5	6	TRUE
231579	E11134890		1181803	1	06-01-17	28-12-16	4	4.5	TRUE
TRANSFER	E11049530		1182311	4	06-01-17	01-01-17	1	4.5	TRUE
TRANSFER	E11136680		1182312	2	06-01-17	30-12-16	1	2	TRUE
TRANSFER	E11371790		1182314	1	06-01-17	04-01-17	14.5	13.5	TRUE
TRANSFER	E11399250		1182315	1	06-01-17	05-01-17	1.5	2.5	TRUE
TRANSFER	E11414160		1182316	2	06-01-17	03-01-17	5	10.5	TRUE
TRANSFER	E11550420		1182318	1	06-01-17	04-01-17	13	9.5	TRUE
TRANSFER	E11600090		1182360	1	06-01-17	06-01-17	12.5	2	TRUE
TRANSFER	E11616510		1182361	1	06-01-17	05-01-17	0	2	TRUE
TRANSFER	E11485050		1182384	1	06-01-17	04-01-17	4	4	TRUE
TRANSFER	E11313420		1182385	50	06-01-17	05-01-17	0.5	5.75	TRUE
231581	E11295760		1182457	1	06-01-17	03-01-17	1.5	1.5	TRUE

Figure 19: Screenshot of STD Labor Hours Spreadsheet Maintained by Varian

While the actual pick date for these Shop Orders are not recorded in the same spreadsheet, this data was obtained from EWM and combined into the STD Labor Hours spreadsheet. Given the pick dates, the shop order quantities and the assembly numbers, the daily demand of each subassembly can be derived. A MATLAB script, 'SO_Demand.m', was written to read this document and generate a table in the format as shown in Table 12 below. At the time of analysis, the spreadsheet contained instances of 398 unique subassembly orders over the period of 1st Jan 2017 – 22nd June 2017.

	Day1	Day 2	:	Day 172
Assyn 1	3	2	:	1
Assyn 2	7	0	:	2
:			:	
:			:	
Assyn 398	0	7	:	4

Table 12:Format of Daily Assembly Demand as Outputted by MATLAB Script 'SO_Demand'

A similar table for the expected FIFO daily demand was generated by changing the pick dates to the dates corresponding to 5 days before the respective Need Dates. The daily demand plots before and after FIFO picking for Assembly E11641090 is presented in Figure 20.
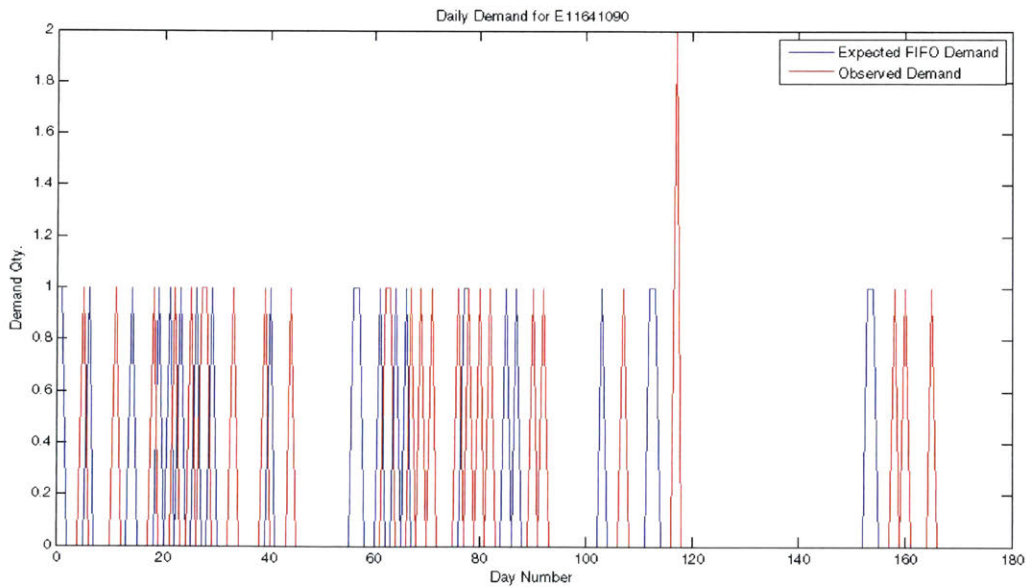
Figure 20:Plots of Observed Daily Demand and Expected Daily FIFO Demand for Sub-assembly E11641090

3.2.2.2 Generating Part Demand Before and After FIFO Picking

Following the generation of daily sub-assembly demands, the daily part demand for Shop Orders alone, is calculated using the formula in Equation 41. MATLAB script

'*SO_PartDemand.m*' reads a spreadsheet which lists the different sub-assembly numbers that the part of interest feeds, along with the quantities required per sub-assembly. It then computes the daily demand for that part using daily sub-assembly demand information and the information from the spreadsheet mentioned above. Figure 21 below is a plot of the observed daily demand and the FIFO daily demand for Part E17476310.
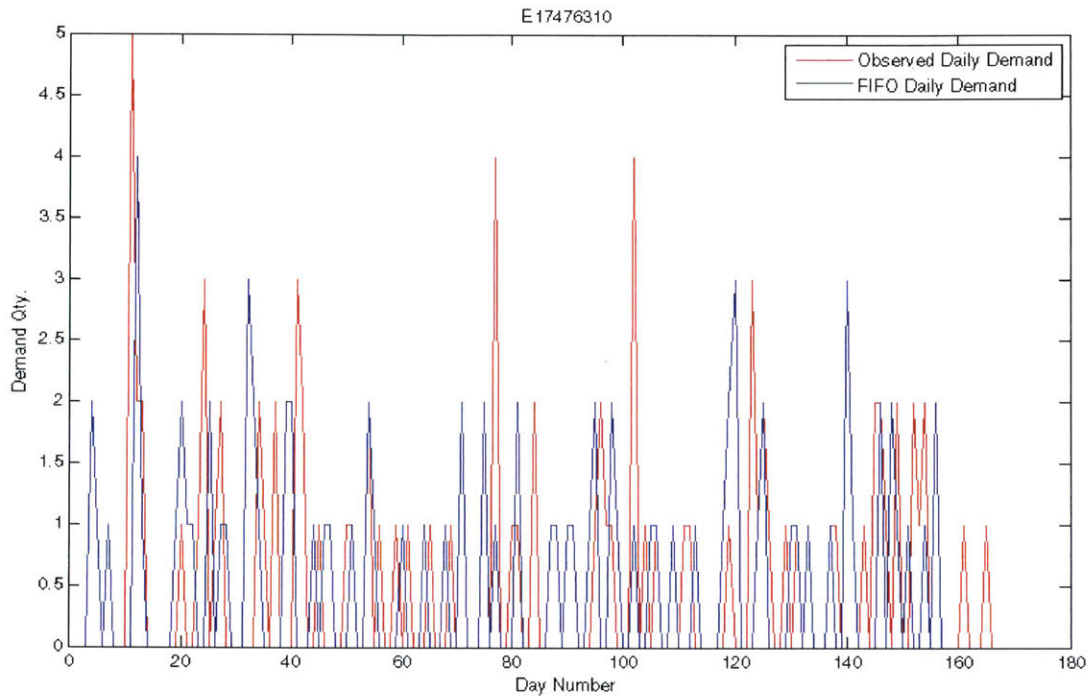
Figure 21: Observed Daily Demand and Expected FIFO Daily Demand for Part E17476310

It is interesting to note that while the mean daily demand is the same in both cases, the standard deviation of daily demand is usually lower or the same when FIFO picking occurs. Table 13 below lists the mean and standard deviation for two daily demands of a few parts listed in the first column. It also lists the best fit distribution along with corresponding distribution parameters.

	Observed Demand		FIFO Demand		
	Mean Daily Demand	Std. Dev. Daily Demand	Mean Daily Demand	Std. Dev. Daily Demand	% Inc. in Std. Dev.
E17296280	2.03	3.65	2.03	3.24	-11.23
E15001083	0.03	0.18	0.03	0.18	0.00
E17090150	1.78	3.24	1.78	3.00	-7.37
E17270580	0.25	0.55	0.25	0.62	12.48
E17476310	0.50	0.89	0.50	0.79	-10.95

Table 13:Mean & Standard Deviation for Observed and FIFO Daily Demands for Parts E17479310 and E17296280

With lower standard deviations, we can expect the Re-order Points to be lower as well. This implies that the overall inventory level can be reduced with FIFO picking. The conclusion of this section is clear: The implementation of FIFO picking in the Supermarket can eliminate 21% of shortages caused by CO27 part shortages and has the potential to lower inventory levels in the Supermarket. *Section 4.2 Impact of FIFO Pick Policy on Supermarket Bin Levels* explores the extent by which inventory can be lowered with FIFO picking.

3.3 Alternative Inventory Management Strategy- Single Stock Location

The Supermarket at present is a subsection of the production floor at Varian, that is responsible for the delivery of sub-assemblies to the MOD Build sites on the same production floor. These sub-assemblies are assembled on work benches within the Supermarket, by trained Assemblers. The parts required to build sub-assemblies are picked from material bins (except for CO27 Parts) within the Supermarket, by Pickers. Of the 5,480 different part types stored in the Supermarket, 54.1% of them are also stocked in the Warehouse.

The MIT Team explored the concept of having the Warehouse as the single stock location for all parts thereby eliminating the need for the Supermarket to store piece parts. In such a system, Shop Order will now be picked in the Warehouse and delivered to Assemblers in the Supermarket. This idea of a Single Stock Location is by no means original. It has been suggested by a previous MIT Team as well as by Manufacturing Engineers at Varian. However, the feasibility of this system has never been evaluated. In their work, Xu & Zhang evaluate issues surrounding this move such as required trucking capacity, storage space in the Warehouse and part replacement requests. [2] Their work concludes the move as a feasible one, with the added benefits of eliminating shortages and decreasing labor costs.

Complementary to the above change, the author examines the idea of storing bins of completed subassemblies in the Supermarket to satisfy daily Shop Order demand. In such as system, the On-time Delivery performance of the Supermarket can be definitively set by Varian as the Service Level of the sub-assembly bins will equal the On-time Delivery percentage. A pull based replenishment system is proposed to replenish these bins as and when an assembly is consumed. The request will drive material for the sub-assembly from the Warehouse to the Assembler in the Supermarket. The aim of this chapter is to discuss this system and evaluate tradeoffs between cost and the benefits of such as system.

3.3.1 Ineffectiveness of Current Gold Square System

This proposed concept is an extension of the Gold Square Bins that are currently employed by in Varian. However, at present, the Gold Square Bin are not strictly replenished and are often empty. Hence, they do no consistently achieve any service level. This sub-section discusses

causes for its poor performance and explains why the Gold Square Bins would work under the newly proposed system.

Hypothesis for the ineffectiveness of the current Gold Square system are listed below.

1. The lack of incentive to keep the bins replenished. Given the absence of assigned priority/ pick sequence for Shop Orders, a new Shop Order can be added to the top of the Pile at any point, thereby giving it the highest priority. When this is feasible, there is no incentive for Production Managers to add Gold Square Replenishment Shop Orders to the Pile. When there is a need for a Gold Square Sub-assembly, a Shop Order for this assembly can be added to the top of the pile to expedite its production. The labor hours that would have gone into replenishing Gold Square Bins can instead be used to reduce the Backlog.

2. The bins are not correctly sized to prevent stockouts.

3. In the present prioritization scheme, Shop Orders for Production have greater priority than for Gold Square Bins. Hence, the lead time for replenishment of a Gold Square Sub-assembly is variable

In the proposed system, all sub-assembly requirements – for Production, for Sales, for Customer Orders, will all be satisfied by the Extended Gold Square Bins. Hence, there will only be one type of Shop Order- to replenish a bin. The priority will thus be equal among all Shop Orders. A Replenishment Shop Order will be printed as soon as a sub-assembly is consumed. With a FIFO pick system in place, Shop Orders printed earlier, will be picked ahead of others printed afterwards.

3.3.2 Sizing Sub-Assembly Bins

The methodology for sizing sub-assembly bins is no different from sizing bin for parts. The bins are sized such that sub-assembly demand is satisfied a certain percentage of the time. This percentage is the Service Level. This factor needs to be set by Varian. For the sub-assembly bins a pull based replenishment system is proposed such that a replenishment request is sent as soon as an assembly is withdrawn from its bin. At present, the lead time of replenishment for a Gold Square Sub-assembly is on average 7 days. However, this is due to the fact that Gold Square Shop Orders have lower priority and hence spend a longer time in the Shop Order Pile. Five days for every sub-assembly, is a reasonable lead time given that at present, Shop Orders for Tools are currently printed 5 days before the completed sub-assembly is required.

At present, Gold Squares bins are sized using the formula in Equation 42. The Bin Size, Q, is simply the sum of the weekly average demand (μ_{weekly}) and the weekly standard deviation (σ_{weekly}) . The equation is not formulated to achieve any set service level.

$$Q_{GS} = \mu_{weekly} + \mu_{sigma} \tag{42}$$

To correctly size bins for sub-assemblies, the same methodology as presented in *Section 3.1.6 Part Demand & Distribution Fitting* was followed. The daily FIFO sub-assembly distributions as computed in *Section 3.2.2 Effect of FIFO Picking on Part Demand* were utilized. The Desired Service Level (DSL) was set to 90% for each bin. The choice of 90% for DSL, it not based on any optimization but rather arbitrary. The results for 90% will serve as a comparative measure for Management to eventually decide what the DSL should be.

Bin Sizes for the 398 sub-assemblies for which demand was observed over 1st Jan 2017- 22nd June 2017, were computed. The results for some of these sub-assemblies which are currently Gold Square sub-assemblies is found is Table 14: List of Ten Gold Square Sub-Assemnlies with Current Bin Size and Bin Size Required for 90% SL below. For the assembly listed in the first column, the 'Current Bin Size' column lists the bin size currently set by Varian for the assemblies. The third column is the bin size value computed for the assembly if an SL of 90% is required in the current system. The last column lists the bins size values computed to achieve a service level of 90% in the new system. It is important to remember that the replenishment time in the present system is around 7 days while the replenishment time used to compute the bin sizes for the new system is 5 days.

Assy. No.	Current Bin Size	Bin Size for 90% SL in Current System	Bin Size for 90% SL in Proposed System
E11387310	6	13	10
E11409240	10	12	10
E11143600	15	26	20
E11594660	9	16	12
E11486370	3	3	2
E11295760	2	4	3
E11349770	2	3	2
E11594670	5	7	5
E11327270	4	10	7
E11632390	4	5	4

Table 14: List of Ten Gold Square Sub-Assemnlies with Current Bin Size and Bin Size Required for 90% SL

It is interesting to observe that the bin sizes currently set, all achieve a service level below 90%. Further, the bin sizes to achieve 90% service levels in the new system are comparable to the bin sizes currently set.

The implications of the results including the finished goods holding cost and the cycle time benefits of the proposed system are evaluated in *Section 4.4 Evaluation of Sub-Assembly Storage System.*

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Chapter 4

Discussion of Results

The aim of this chapter is to interpret the results of the solutions techniques covered in Chapter 3. The first section addresses the causes of shortages for the commonly short parts in the Supermarket. Recommendations to eliminate majority of the shortages are then discussed. The second section delves deeper into the implementation of FIFO policy in the Supermarket. It covers the advantages in terms of further reducing shortages while lowering inventory levels in the Supermarket. The last section surveys the bin sizes of the completed assembly storage proposal and evaluates the tradeoffs of stocking finished goods.

4.1 Eliminating Shortages of Commonly Short Parts

The goal of this section is to examine the causes of shortages of commonly short parts and to highlight changes recommended to eliminate majority of the shortages.

4.1.1 Discussion of Results for Continuously Reviewed Parts

The parts analyzed in this sub-section are those whose quantities are continuously monitored. These parts are of Replenishment Types- EWM REPL, Kanban and Primed SMKT/MOD. For EWM REPL and Kanban types, replenishment requests are automatically sent to either the Warehouse or Supplier, when the bin level drops to the set re-order point. For Primed SMKT/MOD parts, MRP drives material into these bins. The results of demand distribution fitting and Theoretical Service Level estimations are analyzed to uncover reasons behind shortages for these parts. Of the 253 unique part type shortages observed, around 191 of these belong to the category of present discussion. Figure 22 below is a frequency plot of these 191 part types when grouped into bins representing the number of instances of shortage for the part. For example, the first data bar suggests that 2 different part types experienced 12 instances of shortages each.
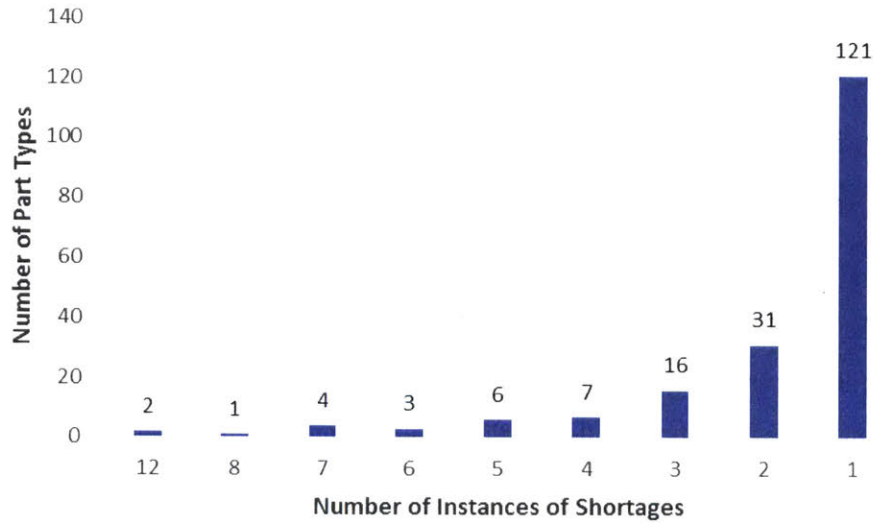
Figure 22: Frequency plot of continuously reviewed parts when grouped into bins of shortage occurrences

As evident in the figure above, 121 part types only experienced a single instance of shortage. The average Theoretical Service Level among these parts is 96%. Given this service level and the duration over which the data collection, observing 1 short for each of these types is statistically reasonable. The figure also suggests that fixing the shortage problem for 23 parts types (those encompassed in first 6 bars), eliminates over 70% of all the shortages.

Table 15 below lists the top 8 most frequently short parts among these 191. The last column lists the required re-order points to achieve 98% service levels based on demands experienced. This number may or may not be an optimal. It is chosen at this point simply as a reference to guide the discussion. Service levels below this mark are treated as low and above as high service levels. The implications of choosing 98% on the impact of shortages is presented in *4.3.1 Performance Outcome of Implementing Recommendations*.

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Short Part Number	Number of Shortage Instances	Replenishment Type	Current Max Level	Current ROP	Daily Demand Distribution	Theoretical Service Level (%)	ROP for 98% DSL
E17296280	12	EWM REPL MIN/MAX	80	40	negative binomial	92%	76
E15001083	12	Kanban		3	negative binomial	72%	7
E17090150	8	EWM REPL MIN/MAX	150	50	negative binomial	99%	41
E17783100	7	EWM REPL MIN/MAX	20	10	negative binomial	100%	6
E17270580	7	Kanban		80	negative binomial	92%	127
E17476310	7	EWM REPL MIN/MAX	20	8	negative binomial	99%	8
E15009900	7	Primed SMKT/MOD	3	1	negative binomial	NA	25
E11485090	6	EWM REPL MIN/MAX	45	20	negative binomial	86%	36

Table 15: Top 8 Most Frequent Short Parts that are Under Continuous Review

4.1.1.1 Detailed Investigation of Shortage Causes

At first glance of Table 15, it is interesting to note that among the top eight of these commonly short part types, the Theoretical Service Levels are both high and low. It should be noted that the TSL for parts of Replenishment Type Primed SMKT/MOD are unavailable as these parts do not have bins with re-order points. Quantities of these parts are driven by MRP.

To obtain clarity on the results, each part listed above was analyzed. This involved looking at the instances of demand that led to depletion of the bins and identifying the cause for depletion in each case. An interesting trend surfaced- For the parts with low (<98%) TSLs, shortages were a result of incorrectly sized re-order points that failed to satisfy demand over replenishment periods. However, for parts with high (>98%) TSLs, shortages were almost always caused because of depletion of stock in the Warehouse. The next few paragraphs highlight these causes of shorts for each of the above listed parts.

E17296280:

Consider the combined demand, supply, bin level & shortage plot (Figure 23 below) for Part E17296080 as generated using the *PartDemand_Daily.m* MATLAB script.

Figure 23:Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts Plot for Part E17296280

Every single demand peak that led to the depletion of the bin, was a demand from Sales. This is deduced by tracking the movement of the parts using the MMBE transaction code on SAP. The same pattern in material movements is observed for other peaks in the demand.

The analysis sheds a couple of insights. Firstly, the fact that Sales is consuming parts from Supermarket Bins suggests that the Warehouse ran out of stock for these parts. This suggests that Sales demand increased from forecasted value. Secondly, the re-order point for this part only achieves a Theoretical Service Level of 92% for the demand encountered. Instances of shorts can be reduced by increasing the re-order point to achieve higher service levels. But if stocks are empty in the Warehouse, higher service levels will have no impact. Hence, Sales demand needs to be addressed.

E15001083:

Consider the combined demand, supply, bin level & shortage plot (Figure 24 below) for Part E15001083 as generated using the PartDemand_Daily MATLAB script.

Figure 24:Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts Plot for Part E15001083

The re-order point for this part is 3 units while the replenishment lead time is 5 days. The TSL is 72%. This is reflected in the figure above where the bin level hits zero almost certainly after it drops to 1 unit. Increasing the re-order point to 7 units will achieve a service level of 98%. It is interesting to note that the re-order point for the part was 8, between Day 40 and Day 80. During this period, the bin level did not drop to zero. The re-order point was since changed to 3 units.

E17090150:

Consider the combined demand, supply, bin level & shortage plot (Figure 25 below) for Part E17090150 as generated using the PartDemand_Daily MATLAB script.
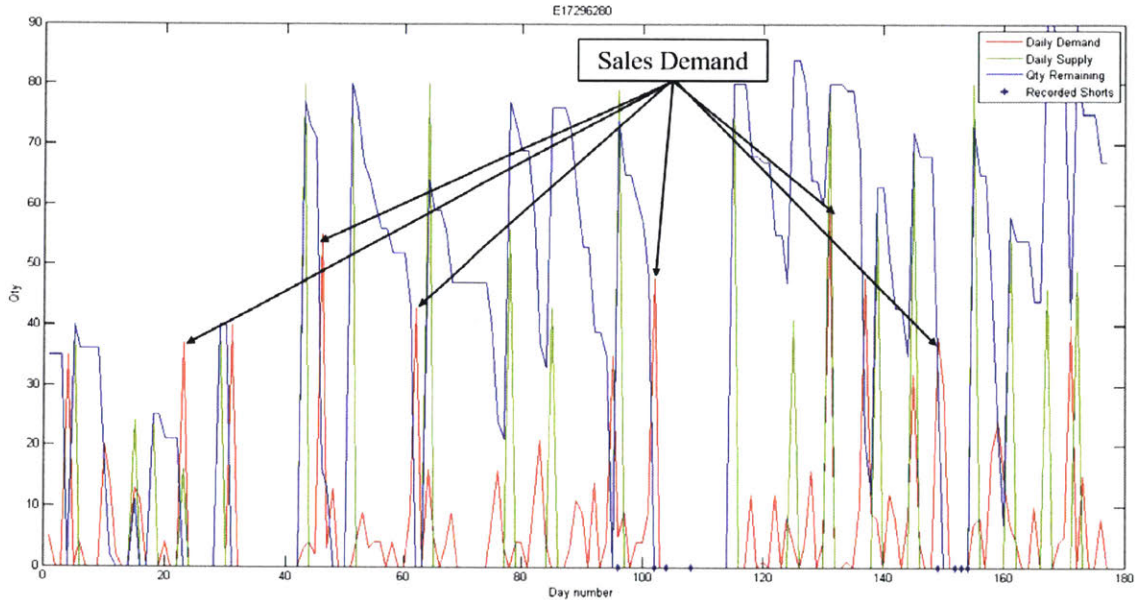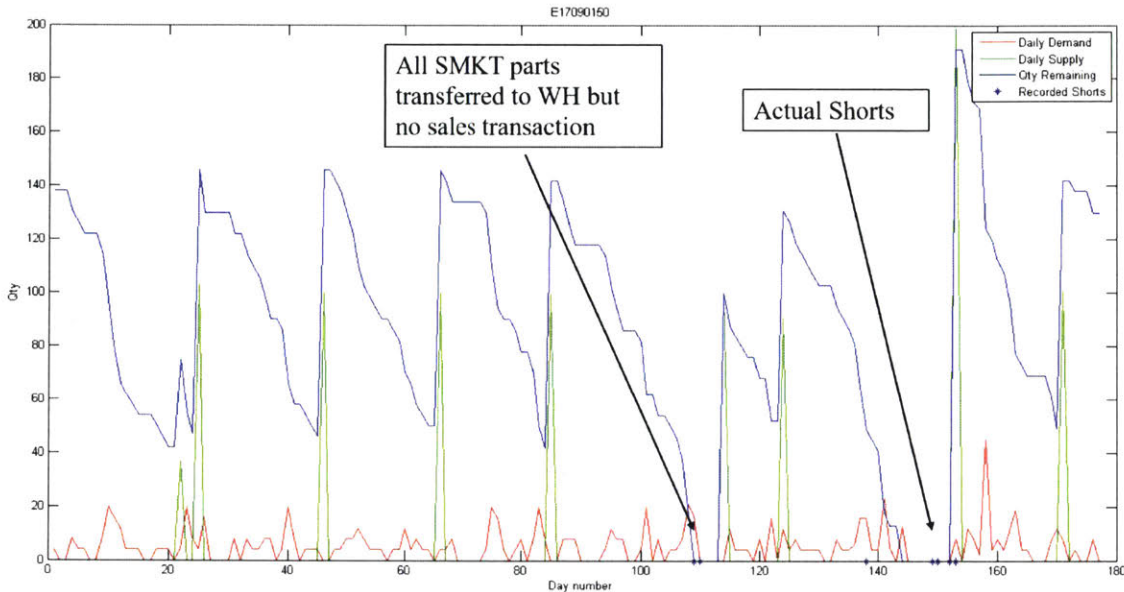

Figure 25:Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts Plot for Part E17090150

The current re-order point for Part E17090150 has a TSL of 99%. All the instances of recorded shortages were observed during two windows. The first where all the parts in the Supermarket were transferred to the Warehouse on what might have been a cancelled Sales Transaction and the second, when the Warehouse ran out of stock.

To prevent recurring shortages of this part, the inventory in the Warehouse needs to be managed better. A recommendation for introducing a re-order point for such bins in the Warehouse is proposed in *Section 4.1.4 Introduction of Re-order Point Policy for Frequently Short Parts in the Warehouse.*

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E17783100:

Consider the combined demand, supply, bin level & shortage plot (Figure 26 below) for Part E17783100 as generated using the PartDemand_Daily MATLAB script.

Figure 26:Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts Plot for Part E17783100

Part E17783100 has a TSL of 100%. Again, shortages were only observed when Warehouse had no remaining stock of the part to transfer over to the Supermarket.

E17270580:

Consider the combined demand, supply, bin level & shortage plot (Figure 27 below) for Part E17270580 as generated using the PartDemand_Daily MATLAB script.
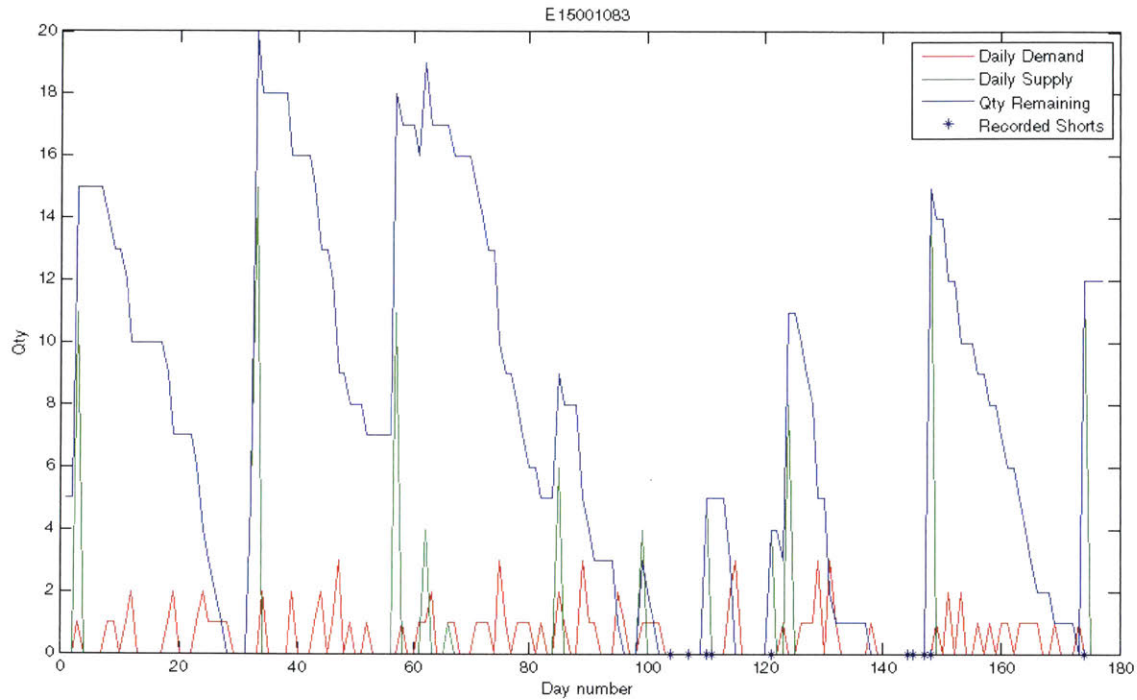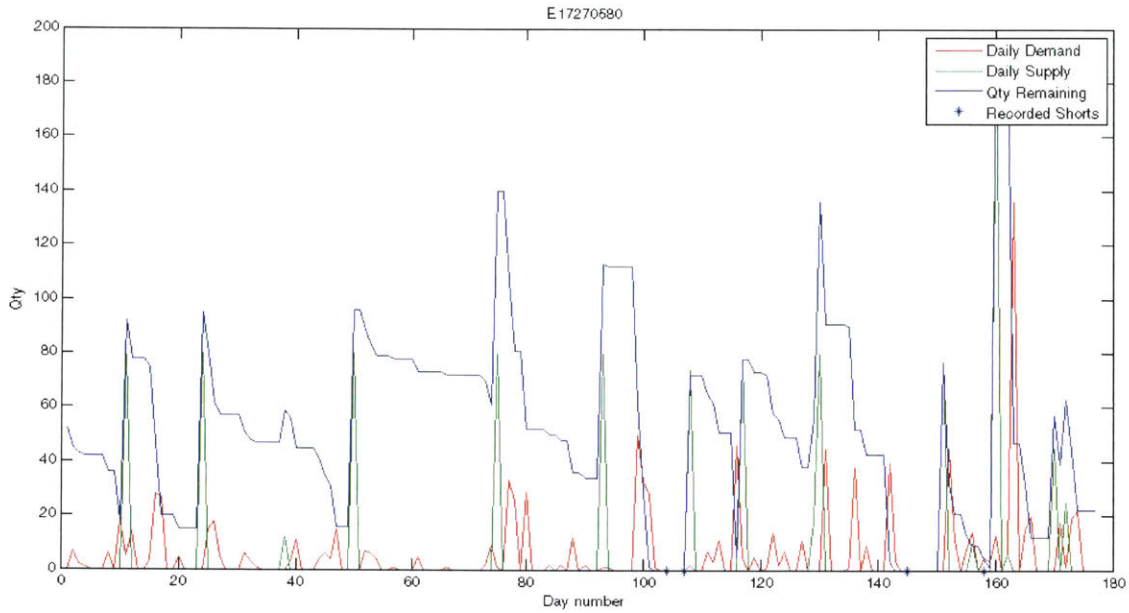
Figure 27: Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts
Plot for Part E17270580

Part E17290580 is another Kanban part with a poor TSL of 60%. Increasing re-order to 127 units from 25units will increase the Service Level of this part type to 98%.

E15009900:

Consider the combined demand, supply, bin level & shortage plot (Figure 28 below) for Part E15009900 as generated using the PartDemand_Daily MATLAB script.
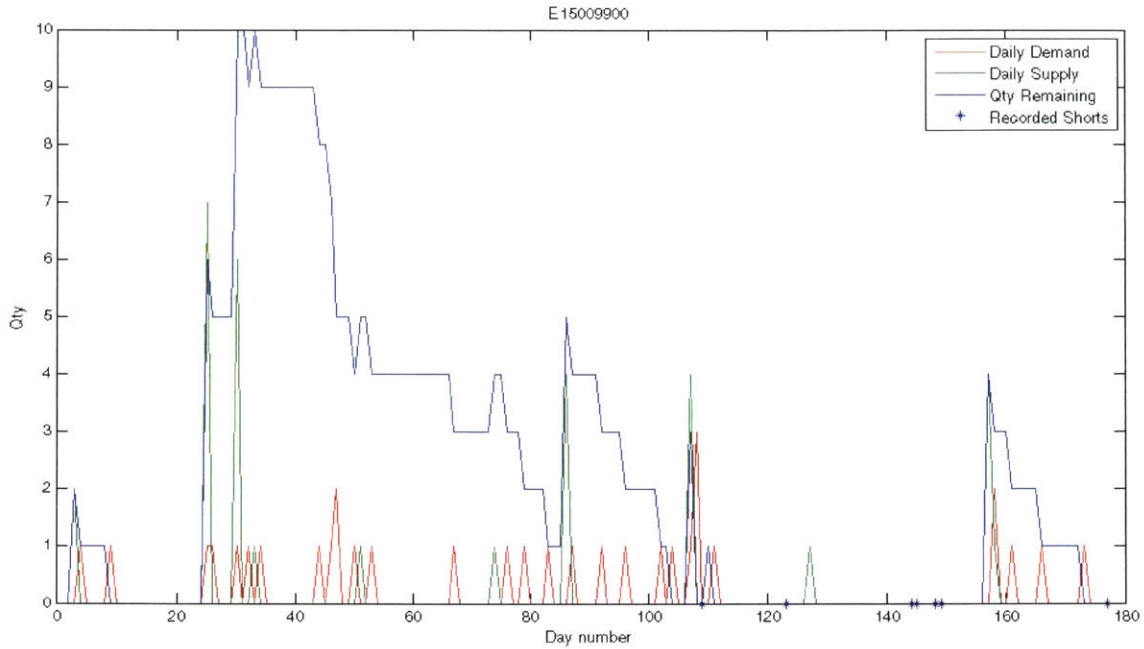
Figure 28: Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts
Plot for Part E15009900

Part E15009900 is an MRP driven part in the Supermarket. Hence, it does not have any
associated Max Level or Re-order Point. The replenishment lead time is 84 days for this part.
The consequence of this bin being is dire as evident by shortages encountered over the
prolonged replenishment period. Converting such bins from MRP replenishment to a Kanban
based replenishment with re-order point equal to 25 units will achieve a 98% service level.

E11485090:

Lastly, consider the combined demand, supply, bin level & shortage plot (Figure 29 below) for
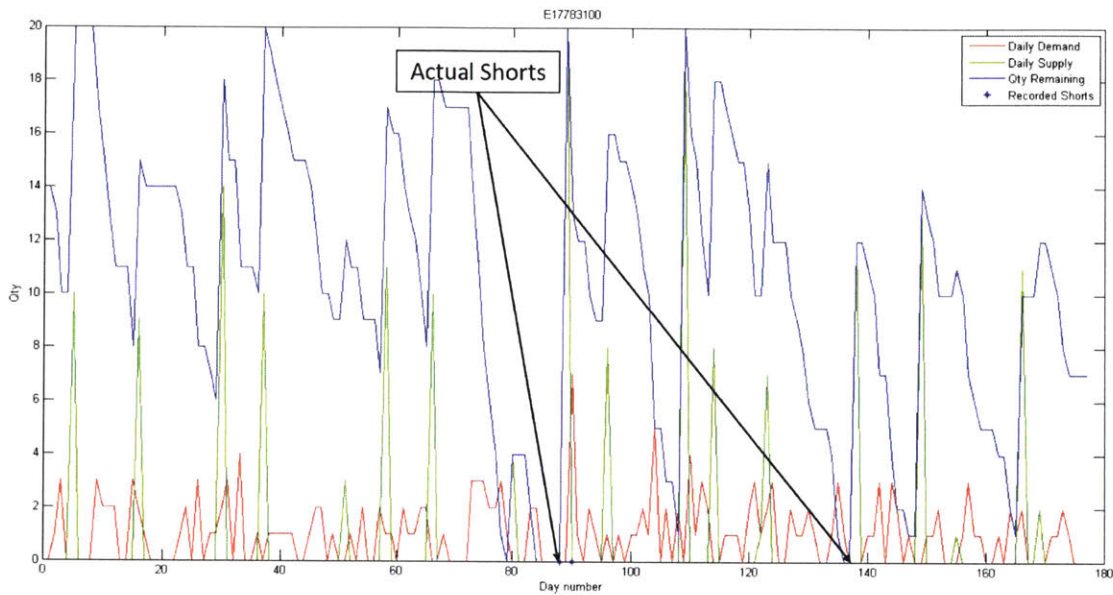Part E11485090 as generated using the PartDemand_Daily MATLAB script.
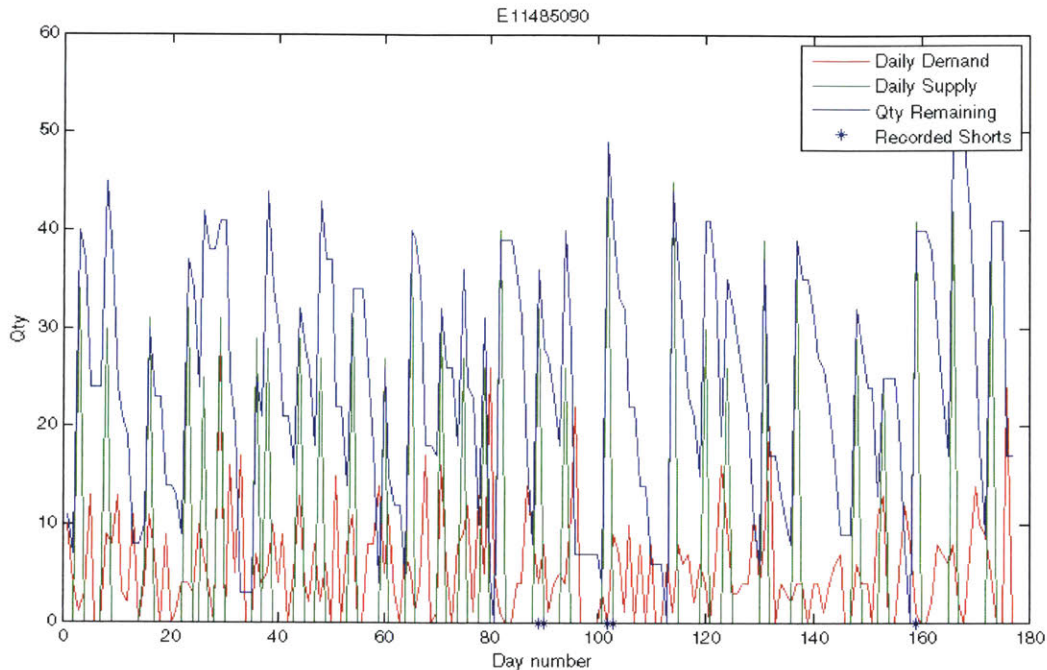
Figure 29: Combined Daily Demand, Daily Supply, Daily Bin Level and Recorded Shorts Plot for Part E11485090

The re-order point for part E11485090 currently has a TSL of 86%. It is replenished from the Warehouse and the instances of shortages were all due to insufficient stock over the replenishment period.

4.1.1.2 Results of Detailed Investigation

The results of the analysis are summarized below:

1. For the parts with low (<98%) TSLs and significant number of shortages, the shortages were a result of incorrectly sized re-order points that failed to satisfy demand over replenishment periods.

2. For parts with high (>98%) TSLs and significant number of shortages, the shortages were almost always caused because of depletion of stock in the Warehouse

3. Overall there are 36 part types in the category for which the current re-order point achieves a service level below 98% for which more than 1 instance of shortage was recorded. Correcting the re-order points will significantly eliminate instances of shortages in the Supermarket.

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4.1.1.3 Recommendations to Eliminate Majority of Shortages

1. For parts mentioned in Points 1 &3 in Section 4.1.1.2, increase bin level to achieve service level of 98%. The cost and performance implication of this quantity is discussed in *Section 4.3 Expected Outcomes from Implementation of Bin Recommendations and FIFO* Policy

2. For Primed SMKT/MOD parts, abolish MRP driven policy and instate Kanban policy for replenishment with Bin size to achieve 98% service levels

3. For the parts mentioned in Point 3 in Section 4.1.1.2, introduction of Re-order Point Policy is recommended for stock in Warehouse. Detailed discussion on this presented in *Chapter 4.1.4 Introduction of Re-order Point Policy for Frequently Short Parts in the Warehouse*

4.1.2 Discussion of Results for Parts Stored in Free Stock Bins

The parts that are discussed in the section are those whose quantities are manually inspected at Varian. These include parts of MinMax and VMI MinMax replenishment types. For both these replenishment types, the on-hand balances of the parts are not recorded in EWM or SAP. While the MinMax bins are replenished with stock from the Warehouse, the VMI bins are replenished directly by the Supplier. For the MinMax parts, it is the collective responsibility among the Pickers to manually request replenishment for the bins whose levels have dropped to 'half' the bin capacity. However, there is no time dedicated for the review of these bins. The review is meant to take place as the Picker picks from the bins. On the other hand, the VMI part bins are reviewed once a week, on Tuesdays, by an on-site representative of External Vendor. Each VMI bin has specified re-order point and re-order quantity as highlighted in *Section 3.1.1 Present Replenishment Strategies & Bin Sizing Techniques*. Out of the 253 different part types that were observed short, 62 belong to the category of present discussion. Among these sixty-two, 27 are of MinMax and 35 are VMI Minmax Replenishment Types respectively. Subsection 4.1.2.1 addresses the MinMax shortages and 4.1.2.2 does the same for VMI.

4.1.2.1 Investigation of MinMax Shortages

Figure 22 below is a frequency plot of the 27 MinMax part types when grouped into bins representing the number of instances of shortage for the part. For example, the first data bar suggests that 1 part types experienced 12 instances of shortages each.
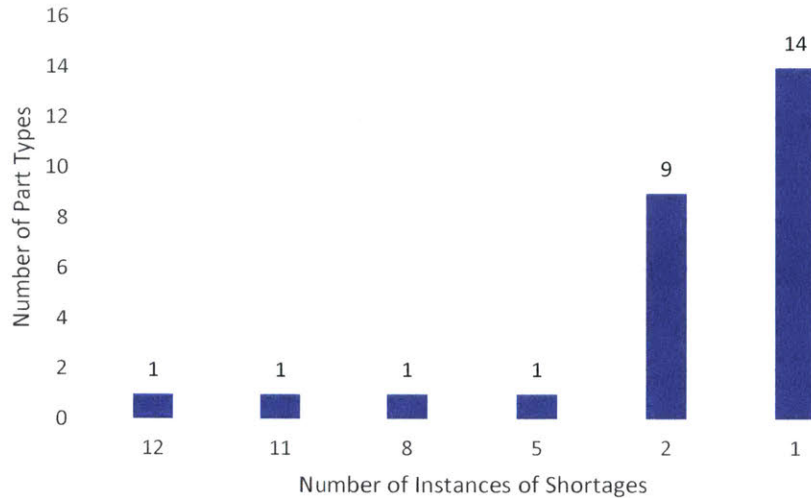
Figure 30: Frequency Plot of MinMax Parts when Grouped into Bins of Shortage Occurrences

The above figure suggests that addressing shortages caused by a few parts, will significantly reduce the shortages of this category. It is interesting to note that the average Theoretical Service Levels among the top 13 most frequently short parts (encompassed in first 5 bars of Figure 30) is 97%. Table 16 below lists these top 13 most frequently short parts along with the present Wand (Re-order) quantities and Theoretical Service Levels for the present re-order points.

Short Part Number	Number of Shortage Instances	Current ROP	Daily Demand Distribution	Theoretical Service Level (%)
E17327190	12	10	negative binomial	94%
E17348360	11	10	negative binomial	93%
E17355650	8	5	negative binomial	97%
E17319790	5	60	negative binomial	97%
P12803502	2	50	negative binomial	99%
E34000726	2	20	negative binomial	94%
2549275	2	50	negative binomial	97%
E17438730	2	30	negative binomial	98%

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E40001297	2	75	negative binomial	98%
E45000692	2	30	negative binomial	97%
E17350540	2	15	negative binomial	99%
E17045252	2	300	negative binomial	98%

Table 16: List of Top 13 most Frequently Short MinMax Parts along with respective Shortage Instance Count, Current Re-order Points, Daily Demand Distribution and Theoretical Service Levels

Given the significant number of shortages despite high Theoretical Service Levels, shortages could be caused due to two foreseeable reasons:

1. Actuals shortage of the part
2. Delayed request for replenishment

To determine the dominant cause, the stock quantity of the parts in the Warehouse was compiled for the dates of each recorded shortage. This information was obtained using the MB5B Transaction on SAP which outputs the stock quantity for a part on a given day and in given storage location. An interesting observation is that none of these parts have demand from Sales. This was concluded based on the lack of observation of the 643 MvT Transaction for these parts. Table 17 and Table 18 below list the stock quantities, in the Warehouse, for parts E17327190 and E17348360 respectively, on the dates of recorded shortages for each part.

Date of Recorded Short	Stock Qty. in Warehouse
18-Apr-17	22
19-Apr-17	22
29-May-17	30
30-May-17	30
24-May-17	0
25-May-17	0
26-May-17	0
09-Jun-17	1
10-Jun-17	1
11-Jun-17	1
12-Jun-17	0

13-Jun-17	0

Table 17: Stock Quantity of E17327190 in the Warehouse on Dates of Recorded Shorts

Date of Recorded Short	Stock Qty. in Warehouse
18-Apr-17	5
04-May-17	27
24-May-17	4
25-May-17	4
27-May-17	4
29-May-17	29
30-May-17	25
26-May-17	4
11-Jun-17	0
12-Jun-17	57
13-Jun-17	57

Table 18: Stock Quantity of E17348360 in the Warehouse on Dates of Recorded Shorts

As observed in the case of these two parts as well as the others, over half of the shortages in the Supermarket occur despite stock being available in the Warehouse. Given that the TSLs are already high, it can be concluded that delays in the request for replenishment is significant. The preset policy of having Pickers 'wand' these bins as they pick Shop Orders, is ineffective. While the Pickers are responsible for 'wanding' these bins, the fault does not lie with them, but rather in the Policy itself for the following reasons:

1. The current policy requires a bin to be 'wanded' when half full. This notion of 'half' is extremely subjective and hence what seems like half to one might not be for another.

2. The performance metric for a Picker is the number of kits picked per day. Hence, there is no incentive for a Picker to spend the extra effort and time (both of which worsen his/her performance metric) to put in replenishment requests for these bins.

The above two shortcomings can be addressed by Varian by:

1. Highlighting the Re-order quantities on the bins

2. Either hiring an additional person to review bin levels periodically or allocating time for a Picker to review bin levels outside of the Picking process.

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3. An alternative to Point 2 would bereplacing the physical bins with Weight Tracking Bin systems that automatically send replenishment requests to the Warehouse when the measured weight drops below the weight of the re-order point parts.

If a weekly review policy is implemented, it is important to modify the lead time of punishment of these parts to the sum of the review period and transfer period. Following this modification, the new re-order points can be calculated as before.

While improper bin review is a significant cause of shortage among the MinMax parts, the instances of stockouts in the Warehouse need to be addressed as well. Section 4.1.4 proposes the introduction of a Re-order Point Policy for stock in Warehouse, to complement current MRP system. A detailed discussion on this is presented in 4.1.4 Introduction of Re-order Point Policy for Frequently Short Parts in the Warehouse.

4.1.2.2 Investigation of VMI Shortages

As pointed out in Section 3.1.6 Part Demand & Distribution Fitting, the distribution of VMI parts was unobtainable given that the re-supply & pick transactions are not recorded in Varian's systems. Thus, the evaluation of Theoretical Service Levels for these parts is not possible. Nonetheless, recommendations to reduce instances of VMI shortages can be suggested based on the understanding of current replenishment strategy. At present, the re-order points for VMI bins is set equal to the product of the supplier lead time of the part, LT, and the mean daily demand, μ_{daily}, as obtained from the Sales & Forecasting Department. The expression for re-order point is presented below.

$$ROP_{VMI} = LT * \mu_{daily} \tag{43}$$

where ,

$LT = Replenishement\ Lead\ Time\ in\ days$

$\mu_{daily} = Average\ Daily\ Demand$

Looking past the lack of consideration for demand variability, the formula is erroneous as it fails to account for the mean demand over the review period. At present the value of lead time (LT) that is used is equal to the number of days between sending a replenishment order and receiving new stock. However, the review of inventory levels is done only once a week. Since parts are consumed 7 days a week, there is a good chance that a bin level might drop below the

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re-order point, a day or two after it is reviewed. In such situations, the remaining quantity in the bin needs to satisfy demand until the next review date and then till replenishment stocks arrive. Hence, a correction to the formula to improve service levels is to add the review period to the lead time of the part. The corrected, but still incomplete formula, is presented below.

$$ROP_{VMI} = (r + LT) * \mu_{daily} \tag{44}$$

$$where,$$

$$r = Review\ Period = 7\ days$$

$$LT = Replenishement\ Lead\ Time\ in\ days$$

$$\mu_{daily} = Average\ Daily\ Demand$$

The formula is incomplete as it still fails to account for variability in demand. Nonetheless the performance of the bins with re-order points calculated with the formula above will certainly improve. In addition, Varian should consider enforcing a cost penalty on the supplier when shortages are encountered.

4.1.3 FlexSim Simulation of Bin Performance Before and After Recommendations

To guide the discussion, a service level of 98% is selected as the Desired Service Levels for bins in the Supermarket. The re-order points needed to achieve this, for the most frequently short parts, are listed in Table 15. The effectiveness of the proposed bin sizes was validated through numerical simulation. FlexSim, an event simulation software package, was unitized for this purpose. [16] The setup in FlexSim is as shown in Figure 31 below. The object 'E17296280 Bin' is a Queue Object in the software serves as buffer under normal circumstances. For this simulation, it is treated as a Supermarket Bin. The object 'Picker' is a Processor Object in the software. The appearance of the Processor was changed to that of a Human Operator, to enhance the visual accuracy of the simulation. The object 'SMKT Kit' is an instance of a Sink Object.
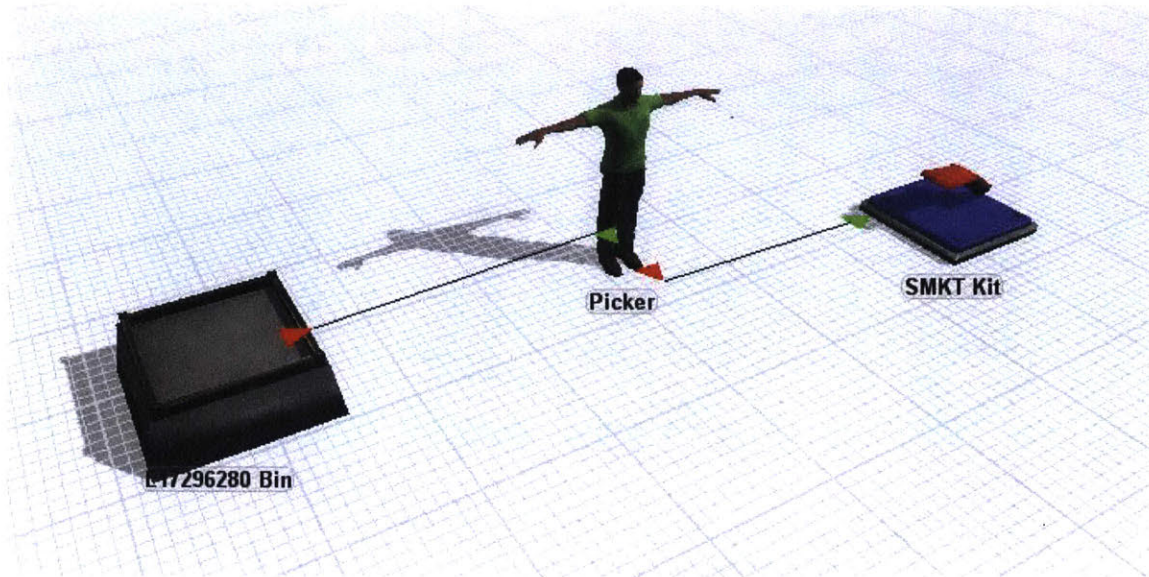
Figure 31: FlexSim Setup Environment

The Queue Object is setup such that on resetting the simulation, its contents are initialized to the specified Max Level of the bin for the part being simulated. In each iteration of the simulation, the code for this object checks whether the current bin level has dropped to its assigned Re-order Point. If so, replenishment quantity equal to the difference between the Max Level and Re-order Point is created in the Queue Object after a delay equal to the corresponding replenishment time of the part. Hence, the Queue Object is self-replenishing based on its code which eliminates the necessity for a Source Object.

The Processor Object (human figure for representation purposes) serves as a source of demand for the parts stocked in the Queue Object. The key parameter for this object is the Process Time. To model the simulation as close to reality as possible, the Process Time parameter needs to be set as a Statistical Distribution corresponding to the distribution of the part as obtained in Section *3.1.6.4 Setting Re-order Points for Desired Service Levels*. Most of the parts including the top 15 most frequently short parts, have negative binomial demand distributions. Unfortunately, FlexSim does not provide the option of setting the Process Time distribution to a negative binomial one, as seen in Figure 32 below.
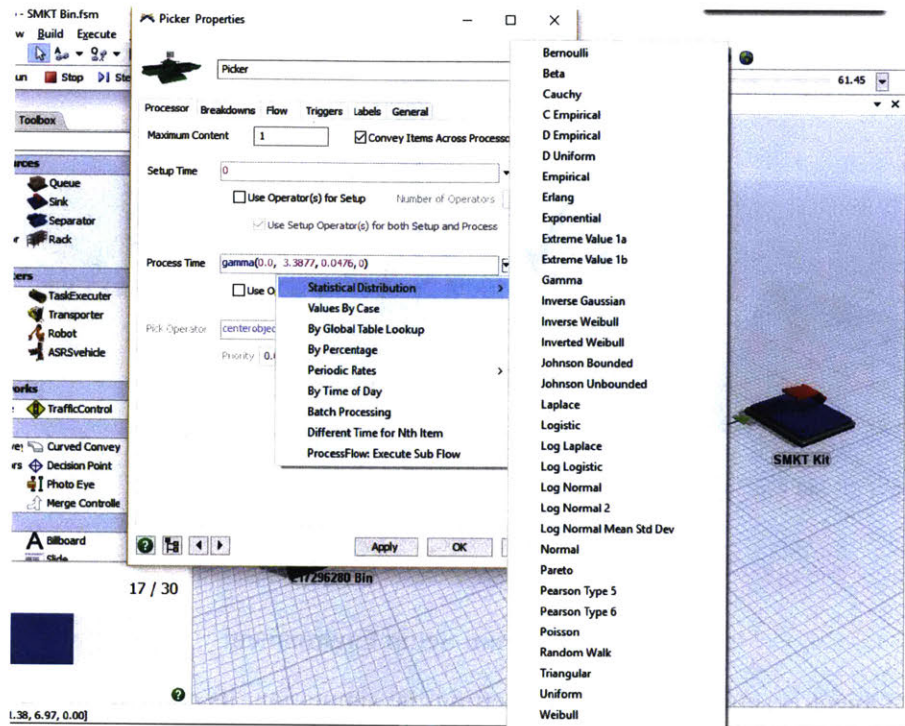
Figure 32: Available Choice of Selections of Statistical Distribution for Process Time Parameter in FlexSim

On recommendation from Professor Gershwin, running the simulation with a continuous analog of the discrete Negative Binomial distribution was explored. From literature survey, the gamma distribution was identified as the best continuous analog for the Negative Binomial distribution. [17] This was empirically verified by fitting a Gamma distribution to part demands and comparing plots of the PDFs of the newly fitted Gamma distribution and the PDF of the negative binomial distribution of the same part. As seen in Figure 33 below, the plot in red is the PDF of the part demand fitted with a Negative Binomial distribution. The PDF in green, is that of the same part demand fitted with a Gamma distribution. As evident the Gamma PDF plot closely follows that for the Negative Binomial distribution. This trend was observed for all the other parts for which these plots were generated. Hence, the choice of the continuous Gamma distribution as a repayment for the discrete Negative Binomial distribution is justified. The plot in yellow, is the PDF of the part demand fitted with a Poisson distribution and serves as a visual reminder of the importance of choosing the right distribution for the simulation.
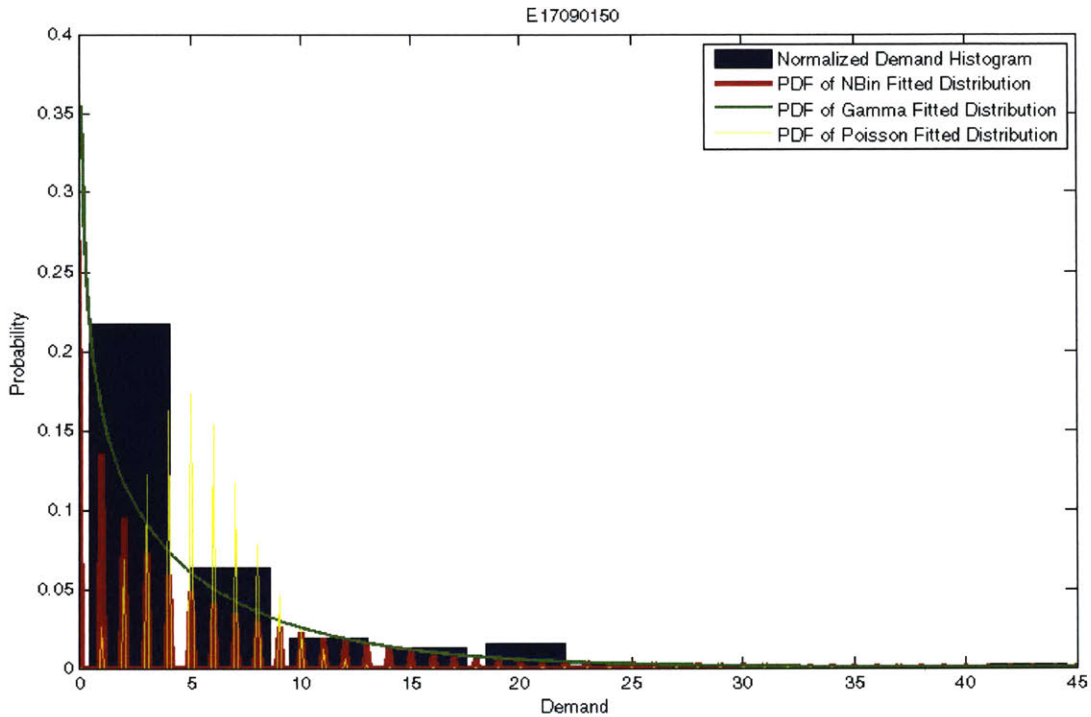
Figure 33: PDF Plots of Daily Demand for Part E17090150 when fitted with Negative Binomial, Gamma and Poisson Distributions

Lastly, the parameters of the Gamma distribution as obtained from the fitdist function in MATLAB, are appropriately adjusted before inputted into the Process Time function. This adjustment is required as the distribution is fit to the demand data which provides information on the number of parts processed in one time unit (Day). However, the Process Time parameter models the time (in Days) between the processing of two different parts.

The accuracy of the simulation setup was first tested by running the simulation with the Max Level & Re-order Point of the Queue Object, set to the current values for the part. A graph of the average content over time was plotted and the results were compared to the bin level graph for the same part as observed since January 2017. Figure 34 & Figure 35 below are the observed and simulated bin level plots for Part E11485090 which currently has a Theoretical Service Level of 86%. The Max and Min Levels for this part bin are 45 and 20 respectively. The replenishment lead time, provided stock is available in the Warehouse is 2 days.
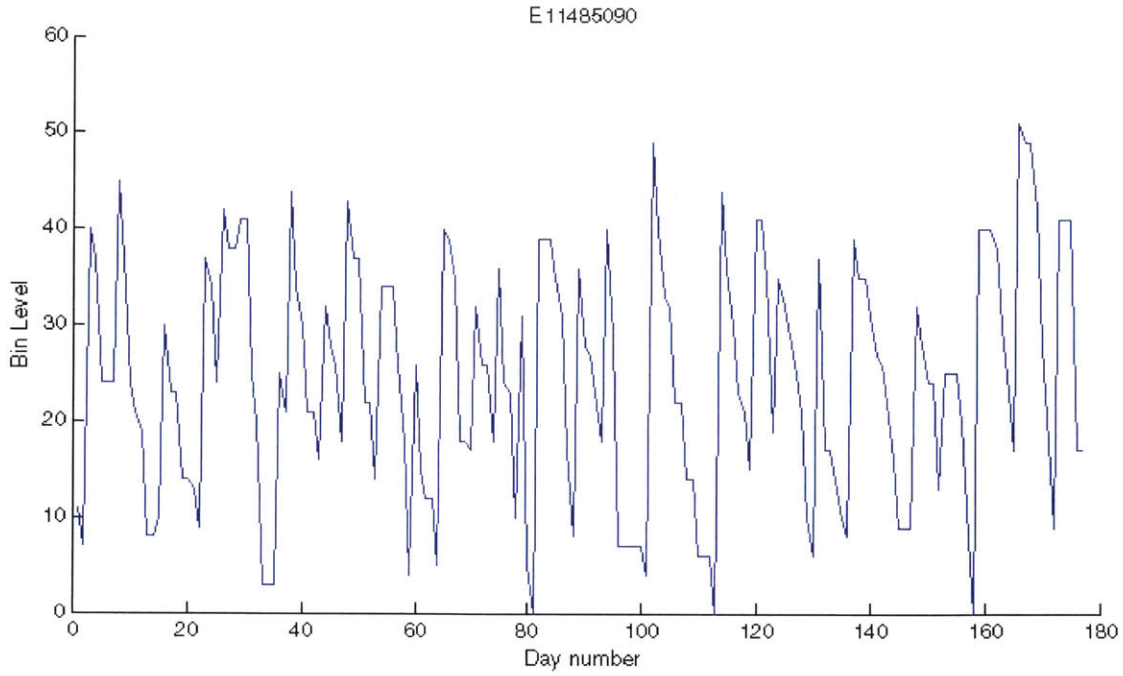
Figure 34: Observed Bin Level for Part E11485090
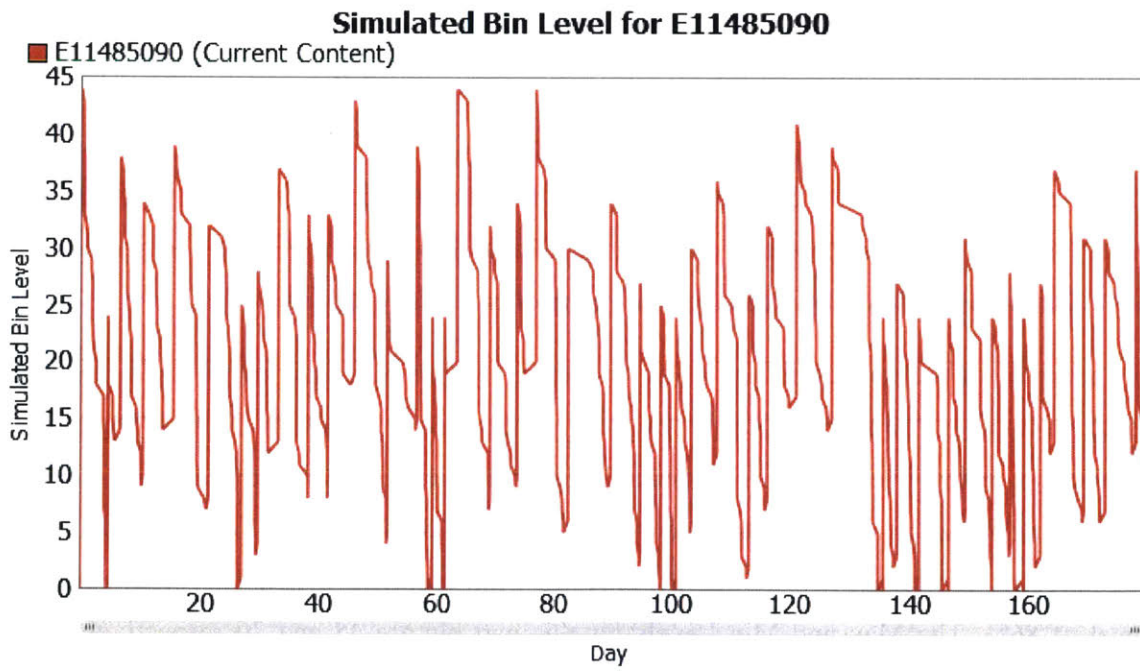
Figure 35: Simulated Bin Level for Part E11485090

As evident, the simulation closely resembles the observed results. The minor variations are attributed to the following reasons:

1. In reality, replenishment lead time is a random variable that follows a certain distribution. The re-supply might appear earlier than 2 days or later. However, in the simulation, the replenishment lead time is a constant (2 days) due to lack of data required to model the replenishment process

2. Observed demand is discrete while simulated demand is continuous

Overall, the positive results of the simulation reinforce the accuracy of the fitted distribution and parameters of the distribution. Following this, the Min Level was set to 36 which is the estimated value to achieve a Theoretical Service Level of 98%. The Max Level is set to 61 to achieve the same difference between the two levels, before and after. The simulation was run again without adjusting the Processor settings. The result of the simulation after the update to the levels is presented in Figure 36 below.
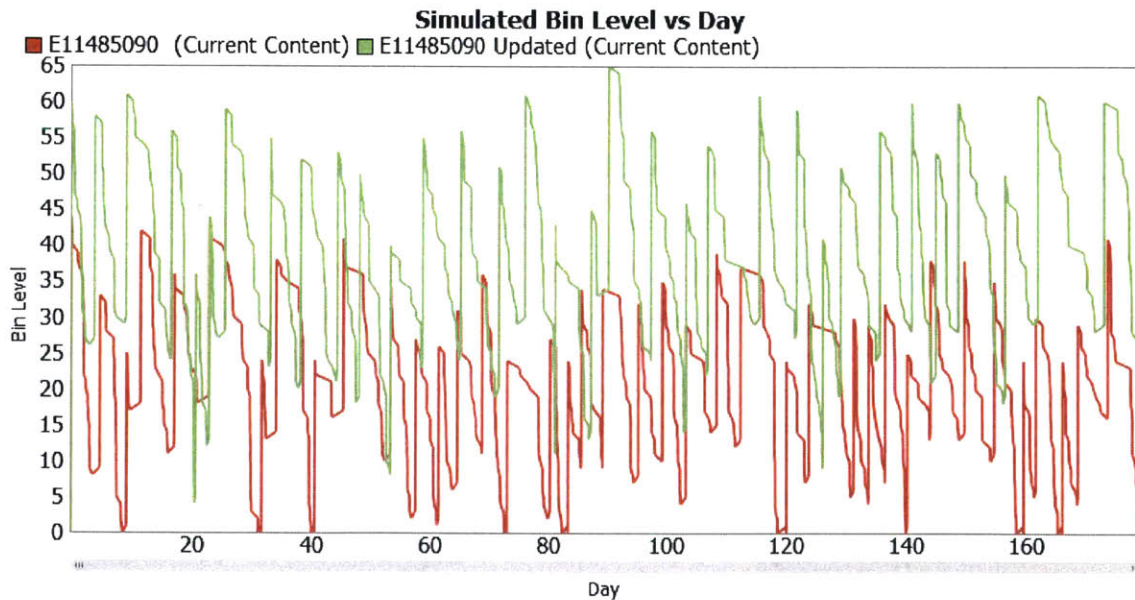
Figure 36: Simulated Bin Level for Part E11485090 Before and After Bin Size Update

As evident, the performance of the updated bin is as expected and achieves the Service Level desired. This validates the techniques employed to determine the Theoretical Service Levels as well as to determine bin sizes/re-order points correctly. This concludes the efforts to size bins to achieve target service levels. The impact of the recommendations advised in this section is explored in Section 4.2 Impact of FIFO Pick Policy on Supermarket Bin Levels.

4.1.4 Introduction of Re-order Point Policy for Frequently Short Parts in the Warehouse

As encountered in the investigation of frequently short parts, depletion of stocks in the Warehouse, led to shortage over prolonged number of days. This was the case for parts of Replenishment Types EWM REPL and Free Stock DFT (MinMax) with current re-order points set to achieve high service levels. These instances reflect the shortcomings of the current MRP system.

Parts are driven to the Warehouse from Suppliers to satisfy both Production Demand as well as Sales Demand. To determine the demand quantity for Production, the system relies on the Production Schedule. This document, as maintained by Varian is a list of both confirmed and forecasted customer orders and respective delivery dates in the upcoming months. With this information, Tool laydown dates are assigned. The Production Demand for parts comes from knowing the Tools required and their laydown dates. For confirmed orders, the exact BOM of the Tool is known and hence the MRP system drives the exact quantities required. For unconfirmed orders, a 'Standard Configuration BOM' is referenced by MRP. This BOM is for the core tool along with the most likely selections and options that a customer is expected to order. The Sales demand which is forecasted, is provided by the AGS Team. The Production Schedule is updated once a week and loaded into the MRP system at the same time. The Sales demands are updated only once a month. When the demand for a part is within its lead time, the MRP system will drive the required quantity to the Warehouse from the Supplier.

There are two critical problems with the current system. The first problem as hypothesized by the author is the lack of responsiveness of the current MRP system to react to changing demand forecasts (from Sales and Production). This is especially likely for Sales Demands. Given that their demands are updated only once a month, the new requirements for a part might not be able to be fulfilled by the Supplier within the lead time for the part. The second and most worrisome problem is the disregard of demand variability when driving quantities to the Warehouse. While the exact quantities are known for confirmed orders only, the other demands are all based on a forecast. Driving the exact forecasted quantities without accounting for variation in demand is bound to lead to poor service levels.

It is the recommendation of the author to move away from MRP replenishment and instead adopt a re-order point based replenishment system for these parts. The re-order points are

calculated such that demand (factoring variability) can be satisfied for a high percentage of the time. This system can first be tested for a few parts- namely the ones that have experienced significant shortages due to Warehouse stockouts. Table 19 below is a list of such parts along with calculated Re-order Points for their bins in the Warehouse (see last column). The re-order points were calculated in the same way as for bins in the Supermarket. The demand for these parts in the Warehouse was extracted just as described in *Section 3.1.6.1 Demand Data Collection* but with an MB51 Report generated for the Warehouse stock location. Also, Supplier Lead Times, which are significantly longer than the average 2-day Warehouse-Supermarket Transfer Times, were used in the estimation.

Part No.	Replenishment Type	Sup. LT (days)	SMKT Shortage Count	SMKT TSL	WH ROP for 98% SL
E17327190	Free Stock DFT	60	12	94%	213
E17296280	EWM REPL MIN/MAX	5	12	92%	494
E17348360	Free Stock DFT	60	11	93%	204
E17090150	EWM REPL MIN/MAX	45	8	99%	776
E17355650	Free Stock DFT	35	8	97%	37
E17783100	EWM REPL MIN/MAX	5	7	100%	43
E17476310	EWM REPL MIN/MAX	35	7	99%	137
E11485090	EWM REPL MIN/MAX	5	6	86%	169

Table 19: List of Parts that have Experienced Significant Number of Shortages Due to Stockouts in the Warehouse

4.2 Impact of FIFO Pick Policy on Supermarket Bin Levels

As introduced in *Section 3.2 Addressing CO27 Shortages*, the implementation of a FIFO policy for picking Shop Orders would allow for CO27 parts in a Shop Order to arrive in the Supermarket on the day as the Shop Order is picked. Such a system has the potential to eliminate 21% of all shortages observed. The aim of this section is to determine whether switching to FIFO picking would have any strain on the material requirements in the supermarket. In *Section 3.2.2.2 Generating Part Demand Before and After FIFO Picking*, lower or equal standard deviations for daily part demands was observed for most of the parts that were analyzed. This suggests that inventory levels could be lowered in the Supermarket. Again, it should be noted that only 5 parts were analyzed dude to time constraints.

Demand distributions can be estimated as before for the observed demand and FIFO demands. Both the demands in this case are the demand for parts for Supermarket Shop Orders only. The demand used to size re-order points for bins in *Section 3.1.6.4 Setting Re-order Points for Desired Service Levels*, includes demand from Supermarket Shop Orders, Sales Orders, Tool Orders and Part Breakage Request Orders. Nonetheless, since Shop Order demand is the bulk of the total demand, estimating reductions in inventory levels based on shop order demand only is a good indicator of total inventory reduction that can be expected.

For the parts listed in Table 13 in *Section 3.2.2.2 Generating Part Demand Before and After FIFO Picking*, distributions were fit to the observed and FIFO demands respectively using the same technique as covered in *Section 3.1.6.2 Fitting Distributions to Daily Demand Data*. Table 20 below summarizes the findings of the distribution fitting exercise.

	Observed Demand			FIFO Demand		
Part No.	Demand Distribution	Parameter 1	Parameter 2	Demand Distribution	Parameter 1	Parameter 2
E17296280	negative binomial	0.161	0.073	negative binomial	0.196	0.088
E15001083	binomial	1.000	0.035	binomial	1.000	0.035
E17090150	negative binomial	0.161	0.083	negative binomial	0.183	0.093
E17270580	negative binomial	1.076	0.809	negative binomial	0.323	0.559
E17476310	negative binomial	0.795	0.615	negative binomial	1.688	0.773

Table 20: Results of Distribution Fitting for Observed and FIFO Demands

The re-order points in each case was then estimated using Equation 27. Table 21 below presents the re-order points computed for Shop Order demands based on observed demand and FIFO demand respectively. For both observed and FIFO demands, the ROPs are estimated such that a service level of 98% is achieved. This 98% is once again a reference.

Part No.	Observed ROP	FIFO ROP	% Decrease in ROP
E17296280	28	26	7
E15001083	1	1	0
E17090150	25	23	8
E17270580	4	5	-25
E17476310	5	4	20

Table 21: Re-order Points for Parts based on Observed and FIFO Shop Order Demands

As evident, the ROPs for the parts mostly either decreases or stays the same. However, give the sample size of the parts analyzed, it is naïve to generalize these results for all the parts stocked in the Supermarket. Nonetheless, based on the results above, FIFO has the potential to lower inventory levels in the Supermarket.

4.3   Expected   Outcomes   from   Implementation   of   Bin Recommendations and FIFO Policy

At present the On-time Delivery of the Supermarket is around 60%. Of the 40% of kits that were late, over 75% of them incurred a shortage during the pick process. When a Supermarket sub-assembly is late to the production floor, it might lead to rework. In a quarter, Varian spends roughly $157,000 in rework hours due to material shortages. However not all this rework cost is attributed to delays out of the supermarket. An unknown proportion of the cost is due to shortages of piece parts (termed Z-pick Parts) that are delivered directly to the production floor from the Supplier/Warehouse. Thus the $157,000 is incurred because of late sub-assembly delivery from the Supermarket and late delivery of Z-pick Parts. The late delivery of sub-assemblies has been linked to delays in completing kits that have been picked to a short. Hence, alleviating the shortage problem will directly reduce the number of supermarket sub-assemblies fail to meet Need Dates.

The aim of this section is to first evaluate the performance outcome of the picking process following the implementations recommendations covered in Section 4.1 Eliminating Shortages of Commonly Short Parts and the FIFO Pick Policy as presented in *Section 3.2 Addressing CO27 Shortages*. Following this, it aims to quantify the increase in inventory cost resulting from the implementation of the same recommendations.

4.3.1 Performance Outcome of Implementing Recommendations

Implementing the recommended changes will significantly reduce the instances of picked-to-short kits. To illustrate this, the probabilities of picking a kit to a short in the present system and in the new system are evaluated. This probability is estimated from the product of the effective service levels of the part. The effective service level (SL_{eff}) is as defined in Section 3.1.4 Discussion on Service Level.

The kit of focus, for assembly E11641090, is one of the most frequently picked-to-short kits as observed over the data collection period. This sub-assembly kit was picked to a short nearly 63% of the times is was picked. The BOM for this kit has 133 parts. Out of these, 14 were parts for which shortages were observed over the data collection period. For the remaining 109 parts, an effective service level of 100% is assumed.

To compute the effective service levels of the parts after the implementation of the recommendations, equation 37 is used.

$$SL_{eff} = \frac{T - LT}{T} * 100 + \frac{LT}{T} * SL \tag{45}$$
$$where,$$

$SL_{eff} = Effective\ Service\ Level$

$T = Time\ between\ Orders$

$LT = Replenishment\ Lead\ Time$

$SL = Service\ Level\ of\ Re - order\ Point$

Given that the difference between the new max levels and the re-order points for the bins is the same as before, the time between orders (T) is not expected to change. However, these values are not constant across parts. The T values are determined by observing the supply plots generated from '*SearchPart_Daily.m*' MATLAB script discussed in *Section 3.1.6.1 Demand Data Collection*. For MinMax VMI parts, since the same data is unavailable, a T value of 30 days is assumed based on the knowledge that the supplier targets 12 replenishments per part

each year. Table 22 below lists the 14-different short part parts present in the kit's BOM. The second column lists the total number of instances of recorded shortage of this part, over the data collection period. The third and fourth column list the values of T and LT respectively for these parts. The effective service level for the parts post implementation of recommendations is found in the last column.

Short Part No.	Instances of Shortages	T (days)	LT (days)	SL_eff Post Recommendations
E17327190	12	10	2	99.60%
E17348360	11	7	2	99.43%
E11485090	6	7	2	99.43%
4210300	6	30	7	99.53%
E17329780	5	10	2	99.60%
E17319790	5	12	2	99.67%
E17335140	3	5	2	99.20%
3330407	3	30	2	99.87%
3330404	2	30	2	99.87%
E16298451	2	9	5	98.89%
E17320950	2	13	2	99.69%
1231200403	1	30	2	99.87%
E48000009	1	30	2	99.87%
E78000048	1	30	2	99.87%

Table 22: Effective Service Levels of Parts from the Profiler BOM following the Implementation of Recommendations

The expected overall service level for the E11641090 Shop Order following the implementations of the recommendations is 94.5%. This implies that the picked-to-short probability post the implementation of the recommendations is an expected 5.5%. **This equates to a 91% reduction in the occurrences of picked-to-short kits.**

Table 23 below highlights the expected picked-to-short percentages for associated values of Re-order Point Service Level.

ROP Service Level	95	96	97	98	99
Picked-to-Short Percentage	13.22%	10.71%	8.13%	5.49%	2.78%

Table 23: Picked-to-Short Percentages for Kits for Corresponding ROP Service Levels

4.3.2 Cost Associated with Recommendations

The aim of this sub-section is to highlight steps needed to evaluate the costs of the recommendations proposed. One of the recommendation as discussed in *Section 4.1.1.3 Recommendations to Eliminate Majority of Shortages* is to increase the re-order points for 36 part types such that a service level of 98% is achieved for these. It is also recommended to abolish the MRP driven replenishment for Primed SMKT/MOD parts and instead have these parts replenished via the Kanban system. Other recommendations include the introduction of re-order points for certain parts in the Warehouse along with the implementation of weekly stock review of MinMax parts in the Supermarket.

The 98% service level as brought up earlier is a figure chosen to drive the discussion. Nonetheless the results of this evaluation will provide insights on the appropriateness of this figure.

Of these 36 part types, 28 are of EWM REPL and 8 of Kanban Replenishment Types respectively. There is no cost associated with increasing the inventory of EWM REPL parts in the Supermarket as this would only involve storing more parts here than at the Warehouse. Space in the Supermarket is not as issue as confirmed with the Material Manager. Hence, the real costs are derived from the increase of Bin Sizes for existing Kanban parts as well as the newly proposed Kanban parts (currently MRP driven Primed SMKT/MOD parts).

For a Kanban parts, the overall increase in inventory cost can be estimated by taking the product of the per unit cost and the difference in average bin level before and after the change. Last year's team showed that he average bin level is equal the size one bin. [10]

For previously Primed SMKT/MOD parts, the increase in cost is equal to cost of the average inventory level of the bins in the new Kanban system. This is because with an MRP driven system, the exact quantity of parts required are driven. The average buffer level in the new system would equate to the parts in excess of MRP requirements.

For the MinMax parts, it is recommended to have a dedicated review period, once a week, to check the inventory levels of the bin. Hence, extra labor hour for about 2 hours is required once a week. This amounts to $200 per week for monitoring MinMax inventory.

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Lastly for the implementation of a re-order point policy of certain parts in the Warehouse, the increase in inventory cost will be equal to the cost of the increase in average inventory level for these parts in the Warehouse. While the average value in the new system will need to be obtained from simulation, a conservative estimate is to consider the cost of re-order point parts.

Table 24 lists the total one-time inventory investment required to implement the recommendations at Service Levels listed in the first column. Apart from this cost, a quarterly expense of $2,600 is required for monitoring MinMax bins.

	Kanban	Primed	BL80 ROP	Total
SL 99	$ 48,891.00	$28,079.92	$ 241,059.95	$ 318,030.87
SL 98	$ 34,529.00	$26,235.14	$ 197,921.60	$ 258,685.74
SL 97	$ 26,086.00	$25,284.96	$ 172,155.66	$ 223,526.62
SL 96	$ 20,254.00	$24,072.18	$ 153,963.81	$ 198,289.99
SL95	$ 15,919.00	$23,764.02	$ 144,205.27	$ 183,888.29

Table 24: Estimates of Inventory Investment Required for Implementation of Recommendations

4.4 Evaluation of Sub-Assembly Storage System

The biggest outcome of the new system will be excellent on-time delivery of sub-assemblies from the Supermarket. When sub-assemblies are stored in the Supermarket, On-time delivery percentage of Supermarket Subassemblies is equal to the Service Level. The observed on-time delivery of the Supermarket since December 2016 is plotted in the figure below. On average, over the data collection period, the On-time Delivery of the Supermarket was 62%.
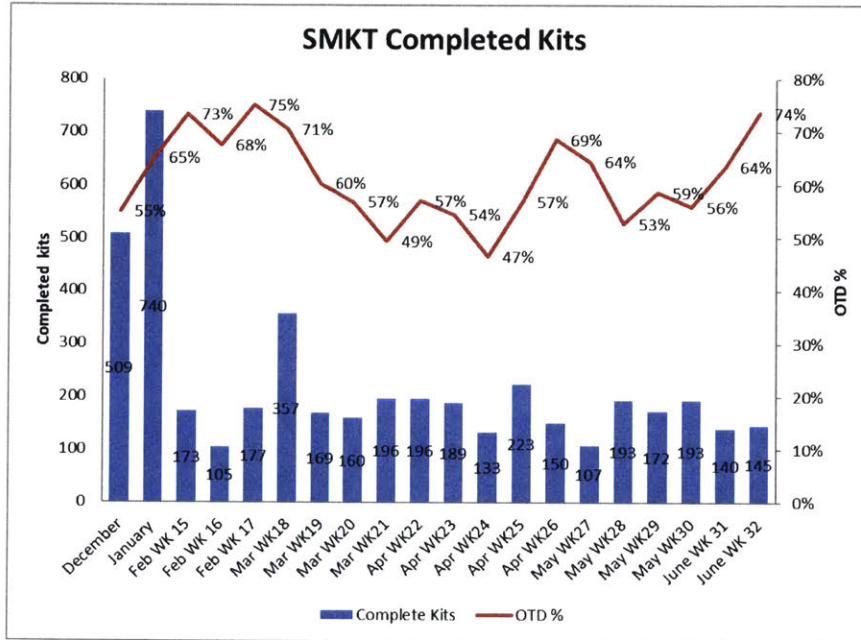
Figure 37: On-time Delivery Tracking for Supermarket Sub-assemblies

In the proposed system, a sub-assembly will be withdrawn from its bin on the exact date it is needed. When the service level is 90%, the sub-assembly will be picked on its need date, 90% of the time. Therefore for 90% of the time, the on-time delivery of the Supermarket will be 100%. For the remaining 10% of the time, the quantity of importance is the duration of the shortage. From a FlexSim simulation of the system for Sub-assembly E11387310, the average duration of a sub-assembly shortage was 2.5 days.

The capital cost to set up the system, apart from material costs, is the labor cost required to build the assemblies to stock the bins up to their calculated levels, for the first time. Labor is required to pick parts for the sub-assemblies and for building them. For each sub-assembly, the Standard Build Time is available. The average pick time for a Shop Order is 40mins per Shop Order. With this information and knowing the bin sizes required, the total labor costs can be

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estimated. If the estimated bin size for an assembly is zero, then one unit of the assembly is stored.

To stock bins to achieve a service level of 90%, a one-time investment of $8,827,357 is required. This amount excludes the investment in material costs required for the sub-assemblies. The payback duration is 21 years for this investment. In fact, the system does work out financially any of the service levels as presented in Table 25 below. The expected yearly savings is the saving from reduced rework hours. At present, Varian spends nearly $628,000 a year on rework due to late delivery of material for Tools. However, not 100% of the late materials are from Supermarket Sub-assemblies. Assuming that 90% of the cost is due to late Supermarket delivery, the yearly rework cost due to Supermarket late delivery is $565,200. Given that the Supermarket currently has an On-time Delivery percentage of roughly 60%, we can assume that the $565,200 rework cost is for a SL of 60%. Assuming a linear decrease in rework costs with increasing service level percentages, the amount of rework cost savings per year can be estimated for each service level.

	SL 60	SL 70	SL 80	SL 90	SL 99.9
Pick Hours (hr)	288	309	357	505	1576
Assembly Hours (hr)	44318	44413	44586	87769	218140
Total Labor Hours (hr)	44606	44723	44944	88274	219716
Total Setup Cost ($)	$ 4,460,640	$ 4,472,273	$ 4,494,373	$ 8,827,357	$ 21,971,625
Expected Yearly Savings ($)	$ -	$ 162,000	$ 324,000	$ 486,000	$ 648,000
Payback Duration (yrs)	-	32	16	21	39

Table 25: Setup Cost and Estimated Payback Periods for Proposed Sub-Assembly Storage System

An alternative system that would work out better financially, is the storage of 'Picked-to-Complete' kits in the Supermarket. For such a system, the replenishment lead time is equal to the average time taken for a Shop Order to be received in the Warehouse and subsequently picked & trucked over the Supermarket. Xu and Zhang, in their work conclude that this process on average requires 2 hours if no shortages are present. [2], [1] The overall cycle time for a Supermarket Sub-assembly would significantly reduce as Assemblers would no longer need to

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wait for Shop Orders to be picked and delivered to the Supermarket. Using a conservative replenishment time of one day, stocking quantities of picked-to-complete kits were computed.

The setup cost (ignoring material costs) would equal the labor cost associated with the Pick Hours for the total number of kits in this system. The Picking Costs for each service level is presented below.

	SL 60	SL 70	SL 80	SL 90	SL 99.9
Pick Hours (hr)	265	265	265	277	1845
Total Labor Cost	$ 26,533	$ 26,533	$ 26,533	$ 27,667	$ 184,533

Table 26: Estimated Labor Costs for Set-up of Picked-to-Complete Kit Bins

If the capacity to assemble sub-assemblies is sufficient, the service level for the Picked-to-Complete Kit Bins is equal to the On-time Delivery Percentage. Hence, along with the added benefit of reduced cycle time, Varian can set its on-time delivery percentage by storing appropriate quantities of picked-to-complete kits for its sub-assemblies.

This idea has plenty of room for optimization. It may not be essential to have separately sized picked-to-complete bins for all 398 sub-assemblies. Many of the sub-assemblies that are built, are variations of a few kinds. By clustering sub-assemblies with similar BOMs, it is possible to store 'Common Starter Kits' that are stocked to assemble all possible sub-assemblies within a cluster. This will reduce the number of picked-to-complete kits stocked in the Supermarket. While this concept need to be explored in greater detail, a clustering algorithm was developed by the author to identify the different clusters and the sub-assemblies within each cluster. This is presented in Appendix C.

Nonetheless, the methods used to size sub-assembly bins can be utilized by Varian to correctly size their present Gold Square Bins.

4.5 Scaling of Observed Demand for Future Quarters

The distinction between Observed Daily Demand and MRP Demand is elucidated in *Section 3.1.6 Part Demand & Distribution Fitting*. In instances of computing re-order points and bin sizes, the distribution of observed demand and corresponding parameters were utilized. However, the demand at Varian changes from quarter to quarter. Hence, it is desirable to know beforehand what the re-order points should be for the upcoming quarter. A suggested approach is to identify a scaling relationship between the MRP Demand from a previous quarter and the

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MRP Demand for an upcoming quarter. The idea is to obtain the Expected Observed Demand for the upcoming quarter by scaling the observed demand in the previous quarter by the same scaling factor derived from comparing the MRP Demands. Then, distributions can be fit to this Expected Observed Demands to size bins for the upcoming quarter. This strategy intuitively makes sense given that Varian builds the same proportion of tools each quarter. Nonetheless, the existence of such a relationship will first need to be verified. Given time constraints, this idea was not further explored. However, it could be explored as potential topic for future work.

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Chapter 5

Conclusions and Recommendations for Varian

The aim of this chapter is to summarize the work done determine the causes of shortages and also to highlight the recommendations proposed to alleviate the occurrences of shortages.

5.1 Conclusions

Overall, the investigation into occurrences of part shortages in the Supermarket yielded many insightful results. The importance of data collection cannot be overstressed. The gathering of Shortage Data over the initial few months allowed the Team to diagnose the causes of shortages in the Supermarket. Without this firsthand information, none of the work that followed would have been accomplished. It was ascertained that, nearly 60% of the time a part was short in the Supermarket, it was available in the Warehouse. In 6% of the cases, the part was held up at Inspection or at Quality. Around 14% of the shortages were caused by inventory managed by the External Vendor. The remaining 20% of shortages were due to stockouts at Varian. Of this 20%, some of the short parts are stored in the Supermarket alone while others have primary stock locations in the Warehouse.

The exact quantification of the financial impact of the part shortage problem was not possible. While Varian spends $157,000 per quarter on additional rework due to material shortage on the production floor, it is unclear what fraction of this amount is attributed to late delivery of Supermarket Sub-assemblies. This is because the rework logbook currently does not record data of the material/sub-assembly that cause rework hours.

The importance of demand distributions and service levels was discussed in the context of reducing shortages. The Theoretical Service Level (TSL) was defined as the expected service level of the bin when the bin level drops to its re-order point. A method to evaluate the overall effective service levels for inventory bins was proposed as seen in Equation 17. An unbiased method to determine re-order points/stock quantities was introduced that relied on the distribution of daily demand pooled over the replenishment period.

The detailed investigation into the causes of short parts was performed. Frequently short parts were grouped based on their current Replenishment Types. The analysis paved the way for the following conclusions:

- For parts of EWM REPL type, an interesting trend was observed. Shortages of parts with high TSLs (>98%) were predominantly caused by stockouts in the Warehouse. On the contrary shortages of parts with low TSLs (<98%) resulted from incorrectly set re-order points. This was confirmed from comparisons of the FlexSim simulations of the bins levels for the TSL and for a higher TSL (98%).
- For Kanban parts, shortages were almost always due to bins currently sized to achieve poor service levels.
- Parts of Primed SMKT/MOD type have significantly longer lead times (average of 48 days) and are strictly MRP driven. Analysis showed that MRP system is slow to react to demand changes of these parts.
- For Free Stock DFT (MinMax) types, the combination of untimely reviews of inventory bins and stockouts in the Warehouse led to multiple shortages.
- Material transaction of VMI parts are not recorded on the Varian system and so specific reasons for shortages were not deductible. Nonetheless, the present formulae for re-order points as used by the vendor fails to account for the one a week review period.

The implementation of a FIFO policy for processing Shop Orders is proposed. This policy would allow for the delivery of CO27 parts to the Supermarket, to be scheduled in advance such that the parts required would arrive on the same day that the Shop Order is picked. The impact of this policy on inventory levels was evaluated. For most of the parts, the analysis suggests that the re-order points can be lowered to achieve the same service level as earlier. However, given the small sample of parts analyzed, future work is required to confirm this result.

Lastly, the concept of only storing completed sub-assemblies in the Supermarket was explored with a pull based replenishment of the consumed sub-assemblies. By sizing bins of these sub-assemblies to meet specific service levels, the on-time delivery of sub-assemblies from the Supermarket would always equal the service level. Such a system would have the added benefit of reducing nearly 5 days of cycle time that comes from picking, assembling and testing sub-assemblies before leaving the Supermarket. However, this concept proved to be financially

unviable. An alternative strategy was suggested but not explored in great depth given time constraints of this project. This involved storing picked-to-complete kits in the Supermarket as opposed to completed sub-assemblies. Since the replenishment time for picking is shorter, fewer picked kits would be required to achieve the on-time delivery performance. However, the cycle time reduction does not include the time required to build and test sub-assemblies. This concept has potential and requires future work. Nonetheless, the techniques used to size bins for sub-assemblies can be utilized to size present Gold Square bins.

Recommendations were made based on the conclusion summarized in the section to reduce the occurrences of picked-to-short kits. These are highlighted in the next section.

5.3 Recommendations to Lower Shortages

Several recommendations are suggested based on the conclusions discussed above. Note, while 98% is suggested as a value of Theoretical Service Levels, it may not be optimal as discussed in Section 5.4. However, from observations of shortages, 98% seems like a good value as majority of parts with TSLs above this percentage were seldom short unless Warehouse stockouts were experienced.

1. For short parts of Replenishment Types EWM REPL and Kanban with low (<98%) TSLs, increase re-order points to values suggested to achieve TSLs of 98%.

2. For short parts of Replenishment Type Primed SMKT/MOD, switch to a 2-bin Kanban based system with bin sizes that achieve 98% TSLs as shown in Table 10.

3. For MinMax parts, dedicate time each week to review inventory levels. Include the length of the review period in the formulation of re-order points. Alternately, consider the usage of weight tracking bins that automatically re-order parts when weight drops below respective thresholds.

4. For short parts of Replenishment Type EWM REPL with MinMax with significant instances of Warehouse stockouts, introduce re-order points for bins in the Warehouse. Methods to calculate these values as well as the calculated values for some frequently short parts are presented in *Section 4.1.4 Introduction of Re-order Point Policy for Frequently Short Parts in the Warehouse*. It is also recommended to update this re-order point on a monthly basis as the Sales forecast is updated.

5. For VMI inventory, record transactions on EWM/SAP to allow for demand characterization and subsequent evaluation of current re-order points. In the meanwhile,

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suggest vendor to change formula of re-order point to cover demand over the review period, as presented in *Section 4.1.2.2 Investigation of VMI Shortages*. Also, consider penalizing the vendor when VMI shortages are observed.

6. Implement FIFO policy for processing Shop Orders to prevent CO27 shortages.

5.4 Benefits of Recommendations

An analysis was performed to gauge the improvement of the system after the implementation of the recommendations discussed in the precious section. Specifically, the probability of picking a Profiler (E11641090) kit to a short was evaluated. In the current system, the probability of the Profiler kit picked-to-short is roughly 62% of the time over the period of data collection. It is possible for this number to be even higher given that data was not collected on a regular basis. If the recommendations listed above are implemented, the picked-to-short percentage of the same kit is estimated to be 5.5%. This is indicative of a 91% reduction in the instances of picked-to-short profiler kits. Given that this kit is one of the most frequently picked-to-short kits, the results can be conservatively generalized to all the kits. The expected picked-to-short percentages for different values of TSLs are summarized in the table below.

TSL %	95	96	97	98	99
Expected Picked-to-Short Percentage	13.22%	10.71%	8.13%	5.49%	2.78%

The recommendation for a choice of TSL cannot be made at this point given the unquantified financial impact of shortages. Without this information, it is not possible to compare the rework cost savings from increasing TSLs with the investment required to increase TSLs. Once the financial impact is ascertained, costs listed in *Section 4.3.2 Cost Associated with Recommendations,* can be used to compute expected payback periods of the investments. By comparing the payback periods, an optimal value of TSL can be selected.

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Appendix

A. Material Movement Block Diagram

C. MATLAB CODES

i. PartDemand.m

```
clear all
filename='SMKT_Matmov_2017';
[~,~,rawdata]=xlsread(filename,1);
containum=cellfun(@isnumeric,rawda
ta);
rawdata(containum)=cellfun(@num2st
r,rawdata(containum),'UniformOutpu
t',false);
for i=1:4
    rawdata(i,:)=[];
end
rawp=rawdata(:,1);
rawd=rawdata(:,5);
locr=[];
urawd=unique(rawd);
urawd(length(urawd))=[];
urawweek=weeknum(datenum(urawd));
```

ii. ExportDemand_Daily.m

```
plist=unique(rawp);
plist(1)=[];
plist(length(plist))=[];
output=[];
length(plist)
l=[];
D=[];
S=[];
datum=736696;
for j=1:length(plist)
    if strcmp(plist(j),'NaN')
        l=[l,j];
    end
        if
strcmp(plist(j),'Material')
            l=[l,j];
        end
end
plist(l)=[];
for p=1:length(plist)
    x=plist(p)
for i=1:length(rawp)
    if strcmp(rawp(i),x)
        loc1=i+1;
    end
end
loc2=0;
tloc=loc1;
while loc2==0
    if strcmp(rawp(tloc),'NaN')
        loc2=tloc-1;
    else
        tloc=tloc+1;
```

```
    end
end
cdata=rawdata([loc1:loc2],:);
cqty=str2num(char(cdata(:,6)));
j=[];
tdata=[];
qdata=[];
for i=1:length(cqty)
    if cqty(i)<0 %item consumed
        tdata= [tdata;cdata(i,:)];
    else
        qdata=[qdata;cdata(i,:)];
%supply
    end
end
Dp=zeros(max(datenum(urawd))-
datum+1,1);
Sp=zeros(max(datenum(urawd))-
datum+1,1);
%--------------------
%Computing Demand
%tdata= Stkloc MVT NAN NAN Date
Qty
%              1    2   3   4   5    6
if length(tdata)>0
[sortl,
sortloc]=sort(datenum(tdata(:,5)))
;
sdata=tdata(sortloc,:);
date=sdata(:,5);
week=datenum(date)-datum+1;
qty=str2num(char(sdata(:,6)));
uweek=unique(week);
[weekcount]=hist(week,uweek);
Tp=zeros(length(uweek),1);
wsum=0;
for i=1:length(uweek)
tdata=sdata([wsum+1:weekcount(i)+w
sum],:);
  tqty=str2num(char(tdata(:,6)))*-
1;
    Tp(i)=sum(tqty);
    wsum=wsum+weekcount(i);
end
for i=1:length(uweek)
Dp(uweek(i))=Tp(i);
end
end
dp_length=length(Dp);
%----------------------
% Computing Supply
if length(qdata)>0
[sortl,
sortloc]=sort(datenum(qdata(:,5)))
;
sdata=qdata(sortloc,:);
date=sdata(:,5);
week=datenum(date)-datum+1;
qty=str2num(char(sdata(:,6)));
```

```matlab
uweek=unique(week);
[weekcount]=hist(week,uweek);
Tp=zeros(length(uweek),1);
wsum=0;
for i=1:length(uweek)
tdata=sdata([wsum+1:weekcount(i)+w
sum],:);
tqty=str2num(char(tdata(:,6)));
    Tp(i)=sum(tqty);
    wsum=wsum+weekcount(i);
end
for i=1:length(uweek)
Sp(uweek(i))=Tp(i);
end
end
Mean_Demand=mean(Dp);
Std_Demand=std(Dp);
Mean_Supply=mean(Sp);
Std_Supply=std(Sp);
output(p,1)=Mean_Demand;
output(p,2)=Std_Demand;
output(p,3)=Mean_Supply;
output(p,4)=Std_Supply;
D(p,:)=Dp';
S(p,:)=Sp';
end
xlswrite('ExportedDemandDaily',
output,1);
xlswrite('ExportedDemandDaily',pli
st,'plist');
xlswrite('ExportedDemandDaily',D,'
Weekly_Demand');
xlswrite('ExportedDemandDaily',S,'
Weekly Supply');
```

iii. SearchPart_Daily

```matlab
%Change x to desired part number
and q0 to qty on 2nd Jan 2017.
x='E17296280';
q0=40;

close all;
datum=736696;
for i=1:length(rawp)
    if strcmp(rawp(i),x)
        loc1=i+1;
    end
end
loc2=0;
tloc=loc1;
while loc2==0
    if strcmp(rawp(tloc),'NaN')
        loc2=tloc-1;
    else
        tloc=tloc+1;
    end
end
```

```matlab
cdata=rawdata([loc1:loc2],:);
cqty=str2num(char(cdata(:,6)));
j=[];
tdata=[];
qdata=[];
for i=1:length(cqty)
    if cqty(i)<0 %item consumed
        tdata= [tdata;cdata(i,:)];
    else
        qdata=[qdata;cdata(i,:)];
%supply
    end
end
%-------------------------------
%Computing Demand
%tdata= Stkloc MVT NAN NAN Date
Qty
[sortl,
sortloc]=sort(datenum(tdata(:,5)))
;
sdata=tdata(sortloc,:);
date=sdata(:,5);
week=datenum(date)-datum;
%week=weeknum(datenum(date));
weekno=weeknum(week);
qty=str2num(char(sdata(:,6)));
uweek=unique(week);
[weekcount]=hist(week,uweek);
Tp=zeros(length(uweek),1);
wsum=0;
for i=1:length(uweek)
tdata=sdata([wsum+1:weekcount(i)+w
sum],:);
tqty=str2num(char(tdata(:,6)))*-1;
    Tp(i)=sum(tqty);
    wsum=wsum+weekcount(i);
end
Dp=zeros(max(datenum(urawd))-
datum+1,1);
for i=1:length(uweek)
Dp(uweek(i))=Tp(i);
end
%--------------
% Computing Supply
[sortl,
sortloc]=sort(datenum(qdata(:,5)))
;
sdata=qdata(sortloc,:);
date=sdata(:,5);
week=datenum(date)-datum;
qty=str2num(char(sdata(:,6)));
uweek=unique(week);
[weekcount]=hist(week,uweek);
Tp=zeros(length(uweek),1);
wsum=0;
for i=1:length(uweek)
tdata=sdata([wsum+1:weekcount(i)+w
sum],:);
```

```
tqty=str2num(char(tdata(:,6)));
        Tp(i)=sum(tqty);
    wsum=wsum+weekcount(i);
end
Sp=zeros(max(datenum(urawd))-
datum+1,1);
for i=1:length(uweek)
Sp(uweek(i))=Tp(i);
end
qeod=[];
qeod(1)=q0-Dp(1)+Sp(1);
for i=2:length(Dp)
    qeod(i)=qeod(i-1)+Sp(i)-Dp(i);
end
%-----------------------------
%Plotting Results
figure(1);
subplot(2,2,1);
plot(Dp,'r');
xlabel('Day number');
ylabel('Demand'); title(x);
subplot(2,2,2);
%hold on;
plot(Sp,'g');
xlabel('Day number');
ylabel('Supply'); title(x);
subplot(2,2,3);
hist(Dp);
title('Demand Histogram');
xlabel('Demand Bins');
ylabel('Frequency');
subplot(2,2,4);
hist(Sp);
title('Supply
Histogram');xlabel('Supply Bins');
ylabel('Frequency');
Mean_Demand=mean(Dp)
Std_Demand=std(Dp)
Mean_Supply=mean(Sp)
Std_Supply=std(Sp)
figure(2);
plot(Dp,'r');
xlabel('Day number'); ylabel('Bin
Level'); title(x); %Qty
hold on;
plot(Sp,'g');
xlabel('Week number');
ylabel('Supply'); title(x);
plot(qeod,'b');
plot(shorts,zeros(1,length(shorts)
),'*','MarkerFaceColor','red');
legend('Daily Demand','Daily
Supply','Qty Remaining','Recorded
Shorts');
```

iv. getshorts.m

```
function [shorts]= getshorts(x)
filename='SMKT Short Data
Compiled';
sheetnames={'2.2-2.10 & 2.21-
3.3','~3.8-3.31','4.5-5.5','5.15-
5.30','6.1'};
% range GL,Actual ranges in
spreadsheet
range=[7,13;8,11;9,12;9,12;9,12];
shorts=[];
for i =1:length(sheetnames)
    i;
[~,~,rawdata]=xlsread(filename,cha
r(sheetnames(i)));
containum=cellfun(@isnumeric,rawda
ta);
rawdata(containum)=cellfun(@num2st
r,rawdata(containum),'UniformOutpu
t',false);
rawdata(1,:)=[];
dates=rawdata(:,1);
gl=rawdata(:,range(i,1));
ac=rawdata(:,range(i,2));
locgl=[];
locac=[];
for j=1:length(gl)
    if strcmp(x,gl(j))
        locgl=[locgl,j];
    end
end
for j=1:length(ac)
    if strcmp(x,ac(j))
        locac=[locac,j];
    end
end
tshorts=[];
tshorts= [tshorts,dates(locgl)'];
tshorts=[tshorts, dates(locac)'];
shorts=[shorts, tshorts];
end
```

v. MRPDemand.m

```
clear all;
%filename='E17296280_Feb_1st';
filename='E17296280 SUPPLY
CONSUMPTION Feb';
%filename='E17296280 SUPPLY
CONSUMPTION Today';
[~,~,rawdata]=xlsread(filename,1);
containum=cellfun(@isnumeric,rawda
ta);
rawdata(containum)=cellfun(@num2st
r,rawdata(containum),'UniformOutpu
t',false);
datum=736696;
```

```matlab
rawdata(1,:)=[];
rawdata(length(rawdata(:,1)),:)=[]
;
data(:,1)=rawdata(:,6); %qty
data(:,3)=rawdata(:,10); %demand
type
data(:,2)=rawdata(:,15); %date
tooldata=[];
otherdata=[];
%Segregating Manufacturing Demand
from other Demand
for i=1:length(data(:,1))
    if strcmp(data(i,3),'Tool')
        tooldata=[tooldata;
data(i,[1:2])];
    else
        otherdata=[tooldata;
data(i,[1:2])];
    end
end
rdate=tooldata(:,2);
rdemand=str2num(char(tooldata(:,1)
));
%week=weeknum(datenum(rdate));
week=datenum(rdate)-datum;
%actually days
uweek=unique(week);
[weekcount]=hist(week,uweek);
%Aggregating demand on same
week/day
Tp=zeros(length(uweek),1);
wsum=0;
for i=1:length(uweek)

tdata=tooldata([wsum+1:weekcount(i
)+wsum],:);

tqty=str2num(char(tdata(:,1)));

    Tp(i)=sum(tqty);
    wsum=wsum+weekcount(i);
end
Dp=zeros(max(week)-min(week)+1,1);
for i=1:length(uweek)
Dp(uweek(i))=Tp(i);
end
Mean=mean(Dp([min(week):length(Dp)
]))
Std=std(Dp([min(week):length(Dp)])
)
figure();
subplot(2,1,1);
plot(Dp); xlabel('Day of Year');
ylabel('MRP Demand'); title('MRP
Daily Demand Feb 1st - June
30th');
subplot(2,1,2);
hist(Dp);
title('MRP Demand Histogram');
```

```matlab
xlabel('Demand Bin'); ylabel
('Frequency');
```

vi. CharacterizeDemand.m

```matlab
%clear all;
filename='ExportedDemandDaily';
sheetname='Daily_Demand';
z=[];
data=[];
[data]=xlsread(filename,sheetname)
;
data(:,1)=[];
distname=[];
params=zeros(length(data),2);
paramname={'',''};
for(i=1:length(data))
    Dp=data(i,:);

[D,PD]=allfitdist(Dp,'NLogL','DISC
RETE');
distname=[distname;cellstr(D(1).Di
stName)];
    params(i,:)=D(1).Params;

paramname(i,:)=D(1).ParamNames;
end
filename2='NLogL Weekly Demand';
xlswrite(filename2,distname,'Distn
ame');
xlswrite(filename2,params,'Params'
);
xlswrite(filename2,paramname,'Para
m Name');
```

vii. ExportBinSize.m

```matlab
%Run CharacterizeDemand First
%size bins
%Desired Service level
sl=0.999;
[~,~,plist]=
xlsread('ExportedDemandDaily','pli
st');
containum=cellfun(@isnumeric,plist
);
plist(containum)=cellfun(@num2str,
plist(containum),'UniformOutput',f
alse);
[~,~,shortdata]=xlsread('Part
Shortages Analysis','Short
Parts');
containum=cellfun(@isnumeric,short
data);
shortdata(containum)=cellfun(@num2
str,shortdata(containum),'UniformO
utput',false);
```

```matlab
csl=[];
binsize=[];
shortdata(1,:)=[];
shortplist=shortdata(:,1)
shortmin=shortdata(:,10); %set to
10 if qmin specified in column J
for i=1:length(shortmin)
    if strcmp(shortmin(i),'')
        shortmin{i}='2';
    end
    if strcmp(shortmin(i),'ActiveX
VT_ERROR: ')
        shortmin{i}='2';
    end
end
shortmin=str2num(char(shortmin));
%min qty
lt= shortdata(:,23); % set to 23
if lt is specified in column W
for i=1:length(lt)
    if strcmp(lt(i),'ActiveX
VT_ERROR: ')
        lt{i}='2';
    end
end
lt=str2num(char(lt)); % LT of
parts
for i =1:length(shortplist)
    i
    tsl=0;
     x=shortplist(i);
    loc=find(strcmp(plist,x))
    if(loc>0)
    tdname=distname(loc);
    dat=data(loc,:);
    dat(1)=[];

    if strcmp(tdname,'negative
binomial')
tsl=nbincdf(shortmin(i),params(loc
,1)*lt(i),params(loc,2));

dsl=nbininv(sl,params(loc,1)*lt(i)
,params(loc,2));
    end
    if strcmp(tdname,'poisson')

tsl=poisscdf(shortmin(i),params(lo
c,1)*lt(i));

dsl=poissinv(sl,params(loc,1)*lt(i
));
    end
    if strcmp(tdname,'binomial')

tsl=binocdf(shortmin(i),params(loc
,1)*lt(i),params(loc,2));
```

```matlab
dsl=binoinv(sl,params(loc,1)*lt(i)
,params(loc,2));
    end
    end
    csl=[csl;tsl];
    binsize=[binsize;dsl];
end
```

viii. SO_Demand.m

```matlab
clear;
filename='STD_Labor_Hours.xlsx';
[a,b,rawdata]=
xlsread(filename,'Final2'); %for
STD_labor_hours
containum=cellfun(@isnumeric,
rawdata);
rawdata(containum)=cellfun(@num2st
r,rawdata(containum),'UniformOutpu
t',false);
rawdata(1,:)=[];
assyn=rawdata(:,2);
l=length(assyn);
assyd=rawdata(:,3);
so=rawdata(:,4);
%assyqty=str2double(rawdata(:,5));
datum=736696;
assyqty=rawdata(:,5);
ndate=rawdata(:,6);
%pdate=rawdata(:,7); %Existing
Pick Dates
pdate=cellstr(datestr(datenum(ndat
e)-5)); % FIFO picking
pday=num2cell(weekday(pdate));
pweek=num2cell(weeknum(pdate));
%if interested in finding weekly
demand
pweek=num2cell(datenum(pdate)-
datum+1) %if interested in finding
daily demand
header={'Assy No.', 'Description',
'SO', 'Qty','Need Date','Pick
Date','Pick Day','Pick Week'};
data=[assyn,assyd,so,assyqty,ndate
,pdate,pday,pweek];
[sortl
sortloc]=sort(datenum(pdate));
%sorted data set
sortdata=data(sortloc,:);
sassyn=sortdata(:,1);
sassyd=sortdata(:,2);
sso=sortdata(:,3);
sassyqty=sortdata(:,4);
sndate=sortdata(:,5);
spdate=sortdata(:,6);
spday=sortdata(:,7);
spweek=sortdata(:,8);
```

```
week=cell2mat(spweek);
qty=str2num(char(sassyqty));
uweek=unique(week); %list of
unique week numbers
uassyn=unique(sassyn);
%counting number of shop orders
during each week
[weekcount]=hist(week,uweek);
c=1;
Ta=zeros(length(uweek),length(uass
yn));
wsum=0;
for i=1:length(uweek)
tdata=sortdata([wsum+1:weekcount(i
)+wsum],:);
     for j=1:length(uassyn)
        if
ismember(uassyn(j),tdata(:,1))

tqty=str2num(char(tdata(:,4)));
        for
k=1:length(tdata(:,1))
            if
strcmp(uassyn(j),tdata(k,1))

Ta(i,j)=Ta(i,j)+tqty(k);
            end
          end
         end
     end
 wsum=wsum+weekcount(i);
end
Da=zeros(max(uweek),length(uassyn)
);
for i=1:length(uassyn) %fill up 1
column at a time
    temp=zeros(max(uweek),1);
%temporary array to append to Da
    tp=Ta(:,i); %extract 1 column
of Ta at a time for each asembly
    for j=1:length(uweek)
        temp(uweek(j))=tp(j);
```

```
        end
    Da(:,i)=temp;
end
```

ix. So_PartDemand

```
filename='E17296280';
%filename='E17476310';
[~,a]=xlsread(filename,'sheet1','A
:A');
a(1)=[];
[q]=xlsread(filename,'sheet1','E:E
');
Dp=zeros(max(uweek),1);
for i=1:length(a)
    if ismember(a(i),uassyn)

[~,loc]=ismember(a(i),uassyn);
        Dp=Dp+Da(:,loc)*q(i);
    end
end
figure();
subplot(2,1,1);
plot(Dp);
title(filename);
xlabel('Day no');
ylabel('Demand Qty.');
subplot(2,1,2);
hist(Dp,sqrt(length(Dp)));
ylabel('Frequency');
xlabel('Demand Bin');


Mean=mean(Dp)
Std=std(Dp)
```

C. Clustering Algorithm

The aim of this section is to present a method of clustering sub-assemblies based on the similitude of the line items in their corresponding Shop Orders. The k-means clustering function in MATLAB is utilized. A spreadsheet is first created where each sheet contains the BOM of a sub-assembly in the format as exported from SAP. The sheet names are renamed to the corresponding Sub-Assembly Numbers to which the contents of the sheet belong. A MATLAB script 'ClusterVariations.m' was written to read through this document and first

create a vector containing a list of unique part numbers from the part number listed in all the sheets of the spreadsheet. Next, the script generates a matrix in the format listed below. The entries in the table are binary values: 1 if the part in the column header is present in the BOM of assembly in the row header; 0 else. Alternatively, the algorithm can be changed such that the entries in the cells are the quantity of parts required in respective sub-assemblies.

Assy. No.	P_1	P_2	P_3	:	P_n
A_1	0	0	1	:	1
A_2	1	0	1	:	0
:	:	:	:	:	:
A_m	0	0	1	:	0

The script the clusters the different sub-assemblies into 'k' number of clusters using the *kmeans* function in MATLAB. The value of k is user defined. An inference on k is usually made through visualizing scatter plots of the dependent variable (A_i *in this case*). However, given that there are n dimensions (corresponding to number of unique part types), it is not possible to directly visualize this 2D space. A t-Distirbuted Stochastic Neighbor Embedding (t-SNE) technique can be utilized for dimensionality reduction of the n-dimension data to 2-dimension data. [19] Once reduced, the position of each sub-assembly number, relative to one another, can be plotted in 2D space. Another approach is to examine the within-cluster sums of point-to-centroid distances. This information is returned by the *kmeans* function in MATLAB. The goal in this case would be to minimize this distance while not increasing k such that the number of sub-assemblies per cluster drastically reduces.

At Varian, variation of sub-assemblies with the same general purpose exist that differ in their build depending on the customer requirements. Nine different sub-assemblies that are variations of one another were analyzed using the techniques discussed above. For these, four different clusters were identified. The table below presents the sub-assembly numbers for these as well as the cluster number and number of lines items in the sub-assembly's BOM.

Assy. No.	Cluster No.	No. of Line Items
E11641095	[4]	145
E11342861	[1]	101
E11349360	[2]	116
E11356640	[3]	107

E11641080	[4]	143
E11641090	[4]	141
E11357960	[3]	110
E11550420	[2]	119
E11579880	[4]	120

This method can be further expanded to cluster all 398 sub-assemblies mention in *Section 4.4 Evaluation of Sub-Assembly Storage System*. The MATLAB script is provided below.

ClusterVariations.m

```
clear;
filename='ClusterVariations';
sheet=cellstr(['E11641095';'E11342
861';'E11349360';'E11356640';'E116
41080';'E11641090';'E11357960';'E1
1550420';'E11579880']);
sheet1='E11641095';
sheet2='E11342861';
sheet3='E11349360';
sheet4='E11356640';
sheet5='E11641080';
sheet6='E11641090';
sheet7='E11357960';
sheet8='E11550420';
sheet9='E11579880';
xlRange='A2:I146';
l=9; %number of assemblies
[A1 B1]=xlsread(filename,sheet1);
[A2 B2]=xlsread(filename,sheet2);
[A3 B3]=xlsread(filename,sheet3);
[A4 B4]=xlsread(filename,sheet4);
[A5 B5]=xlsread(filename,sheet5);
[A6 B6]=xlsread(filename,sheet6);
[A7 B7]=xlsread(filename,sheet7);
[A8 B8]=xlsread(filename,sheet8);
[A9 B9]=xlsread(filename,sheet9);
%compiling parts
p1=B1(:,2);
p2=B2(:,2);
p3=B3(:,2);
p4=B4(:,2);
p5=B5(:,2);
p6=B6(:,2);
p7=B7(:,2);
p8=B8(:,2);
p9=B9(:,2);
p1(1)=[];
p2(1)=[];
p3(1)=[];
p4(1)=[];
p5(1)=[];
p6(1)=[];
p7(1)=[];
p8(1)=[];
p9(1)=[];
p2=unique(p2);
p2(1)=[];
%compiling descriptions
d1=B1(:,3);
d2=B2(:,3);
d3=B3(:,3);
d4=B4(:,3);
d5=B5(:,3);
d6=B6(:,3);
d1(1)=[];
d2(1)=[];
d3(1)=[];
d4(1)=[];
d5(1)=[];
d6(1)=[];
plist=unique([p1;p2;p3;p4;p5;p6;p7
;p8;p9]');
n=length(plist);
mat=zeros(l,n);
p=zeros(n,l); % compiled parts
pl=[length(p1),
length(p2),length(p3),length(p4),l
ength(p5),length(p6),length(p7),le
ngth(p8), length(p9)]; %lengths of
part arrays
%filling up mat from p1
for i =1:n
    mat(1,i)=ismember(plist(i),p1);
    mat(2,i)=ismember(plist(i),p2);
    mat(3,i)=ismember(plist(i),p3);
    mat(4,i)=ismember(plist(i),p4);
    mat(5,i)=ismember(plist(i),p5);
    mat(6,i)=ismember(plist(i),p6);
    mat(7,i)=ismember(plist(i),p7);
    mat(8,i)=ismember(plist(i),p8);
    mat(9,i)=ismember(plist(i),p9);
end
% clustering
rng default
k=4;
[idx,C,D]=kmeans(mat,k);
```