Production Ramp-up of a Hardware Startup: Developing Inventory Management Strategies and Establishing a Framework for Vendor Selection

By

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Bachelor of Engineering in Industrial Engineering & Management,
B.M.S College of Engineering, 2015

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

Master of Engineering in Advanced Manufacturing & Design

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Abstract

It is imperative for hardware startups to have a clear plan of action while scaling-up production. Manufacturing and operations related activities should be accorded the same importance as design and engineering. New Valence Robotics Corporation (NVBOTS), a high-technology automated 3D printing manufacturing startup was experiencing high growth. The demand for their 3D printers was rising and they were looking to expand into new markets. In order to ramp up production and meet growing needs of the market, it was an absolute necessity to restructure their production planning and inventory management strategies.

Inventory is the life-blood of every organization and mandates efficient management, especially for startups which have significant cash constraints. Most big organizations have sophisticated ERP systems and dedicated inventory personnel that help in efficient inventory management. This thesis aims to assist startups that lack the above mentioned luxuries. The purpose of this thesis is to help NVBOTS: (1) to efficiently manage inventory by classifying them into groups with similar characteristics, (2) to determine *how much* and *when* to order each type of SKU so as to minimize capital requirements, (3) to accurately keep track of on-hand, incoming and outgoing inventory, (4) to provide a framework for vendor selection.

Some of the inventory classification methods considered include ABC analysis, Price vs Lead Time trends, by part type and by vendor. After inventory was classified, Economic Order quantity, Economic Production Quantity, QR and Base Stock models were applied to each of the categories. The results from these models were analysed and then appropriate ordering strategies were decided for each of the categories. The thesis also suggests some common practices for physical inventory control including inventory room layout, 5S methods and cycle counting. In addition to this, the vendor matrix method of rating vendors provides a methodology to qualify vendors, based on certain criteria.

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Definition of Key Terms

Ordering Cost: Fixed cost incurred every time an order for parts is placed with a supplier. These costs are independent of the order size and include telephone, order checking, labour and transport.

Holding Cost: It is the cost associated with storing parts in the warehouse. This includes the cost of capital to acquire that inventory, storage costs, insurance cost, obsolescence cost. Holding cost per unit is usually expressed as a percent of the unit price of that part.

Base Stock: Usually there is maximum limit to which the consumed inventory is replenished to. This level is referred to as the base stock level.

Safety Stock: It is also referred to as buffer stock. It is the extra inventory that is required to mitigate the risk of stockouts due to uncertain supply and demand scenarios.

Service Level: It is probability of having inventory on hand so as to ensure that the demand of the customer is satisfied immediately or the probability that all demand is satisfied.

Review Period: It is the time between two successive evaluations of inventory status to determine whether to reorder or not, if yes then quantity is also decided. Review period is decided by the firm.

Lead Time: It is the time between when the order is placed with the supplier and when it is received at the warehouse. It is expressed in either days or weeks usually.

Reorder Point: The order for replenishing inventory is placed with the supplier when the stock levels for that SKU falls to a particular limit. This limit is called the reorder point and is expressed in number of parts. It serves as a trigger for placing an order.

Fill Rate: It is the percent of demand that is satisfied. Also known as customer service ratio.

Pipeline Inventory: Inventory in transit (transportation network and the distribution system) including the flow through intermediate stocking points. The flow time through the pipeline has a major effect on the amount of inventory required in the pipeline.

Cycle Stock: It is the portion of inventory that the company cycles through to satisfy regular sales orders. It is part of on-hand inventory and eventually cycle stock inventory refreshes itself, or turns over, as new items replace older ones.

Cycle Length: It is a term used in the Economic Production Model. It refers to the total time for processing a given lot size of each part type that is made on the same machine.

Stock Keeping Unit (SKU): It refers to the different part types each with a unique part number that helps in easy identification and storage.

Shortage Cost: Cost of disrupting production activities which include idle machine and worker times, and cost of lost sales resulting in dissatisfied customers.

Abbreviations Used

NVBOTS – New Valence Robotics Corporations

AM – Additive Manufacturing

FDM – Fused Deposition Modeling

FFF – Fused Filament Fabrication

SOP's – Standard Operating Procedures

SKU – Stock Keeping Unit

EOQ – Economic Order Quantity

EPQ – Economic Production Quantity

ROP – Reorder Point

MRP – Material Resource Planning

JIT – Just in Time

ERP – Enterprise Resource Planning

PO – Purchase Order

RFQ – Request for Quotation

BOM – Bill of Materials

AD – Adhesives

PP – Printed Parts

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Chapter 1
Introduction

This thesis describes a project aimed at assisting a growing hardware startup in structuring their raw-material inventory management strategies and vendor selection methods. The project involved a thorough evaluation of existing inventory management and control practices and its applicability to a startup like New Valence Robotics Corporation (NVBOTS), which was transitioning into a big company.

This project along with the work of Jain [1] and van Grootel [2], was a collaborative effort of three Massachusetts Institute of Technology (MIT) students to help NVBOTS scale-up their manufacturing and operations, each focusing on a specific area of the overall problem.

This chapter provides an overview of hardware startups and introduces NVBOTS. It also outlines the research motivation, problem statement, purpose and structure of the thesis.

1.1. High-Technology Manufacturing Startups

1.1.1 Overview of Startups

Startups are crucial for a country's economy and for creation of jobs. In fact, net job growth in the US economy occurs only through startups [3]. The importance of startups for an economy cannot be stressed enough, but relatively little academic literature exists on the topic of manufacturing strategies for startups.

Unlike big companies, startups have constraints on capital and other resources. They rely highly on "human capital" to make up for the lack of sophisticated systems. In most startups, there is little organizational hierarchy in the company, leading to flat organizational structures. Given that the environments of startups change rapidly, flat organizational structures work well for startups since they allow the startups to respond to changes quickly with little inertia [4]. Flat structures allow for better communication compared to traditional hierarchical structures, leading to increased agility and flexibility in the company. This is one of the main strengths of startups.

Working at a startup inherently involves careful risk management [5]. These risks may take multiple forms, at the same or different times, including financial risks, technology risks, market risks, et cetera. A crucial part of this risk management is tied up with 'firefighting', which refers to tackling unanticipated problems and developments in a rational and calm way [5]. In such cases, prioritization of important tasks and time management become major drivers of success. This culture of constant firefighting is characteristic to startups.

1.1.2 Hardware Startups

An important distinction needs to be made between two broad categories of startups and the nuances of each type – software and hardware startups. Hardware startups refer to those startups that produce physical products such as consumer goods and high-technology products, whereas software startups produce products that are some variations of software or services based on software. More often than not, products of high-technology hardware startups involve significant mechanical components and electronics that are sometimes interfaced with software as well. Unlike software startups, hardware startups need to address areas of production and logistics including manufacturing, packaging, shipping, and customs [6]. All these lead to higher capital requirements for hardware startups.

For hardware products such as consumer electronics, moving from concept to mass production may take as long as six to nine months after the associated technologies have been proven [7]. For more complex hardware products, such as automobiles and aircrafts, this timeline may even take years instead of months. Multiple reasons may contribute to this longer timeline [7]. Firstly, learning about the nuances of the hardware product requires several iterations.

Secondly, a hardware product involves custom components, procuring these components may take significant amounts of time. Thirdly, different stages of the product development process cannot be parallelized, such engineering validation, user testing, and subsequent design modifications.

Hardware startups usually have low volumes of production during the initial periods. This prohibits them from having a significant impact on the supply chain. Due to high capital requirements and limited inward cash flows, it is very important for hardware startups to plan well and utilize their resources in the most efficient manner. They rely highly on the potential of their technology and try to make inroads into main stream markets by leveraging their “innovative technology”.

1.1.3 Production Ramp-up: Meaning, Significance and Challenges

Production ramp-up refers to the time period between the development cycle of a company’s product and the company’s full capacity production [8]. In other words, for a hardware startup, production ramp-up refers to the process of rapid growth of production once the startup has validated its business model for repeated revenue generation. If external entities such as venture capital (VC) firms have invested in a startup, this production ramp-up and the associated scale-up of the company becomes crucial because of added pressure by investors for returns on their investments. This phase of production ramp-up is marked by many risks and challenges, including threat from competitors, legal risks, and market risks, on top of internal challenges such as having inefficient practices which become too costly as the company grows.

One of the major risks associated with growth and production ramp-up in startups is the availability of sufficient funds [5]. These funding requirements depend significantly on whether the startup predominantly deals with software or hardware. Usually VC firms shy away from manufacturing and hardware startups due to their significant up-front capital requirements and long timelines for returns on investments [9]. Consequently, from a risk point of view, VC firms might prefer to invest in software startups where the up-front costs are lower than those for hardware, with relatively quicker returns on investments. Even if a hardware startup manages to secure proper funding, there is always the challenge of sustaining those funds till the company starts generating revenue [5]. Consequently, a combination of risks associated with funding poses significant challenges to growth and production ramp-up for hardware startups.

In startups, the lack of formal organizational structures provides them with operational agility and flexibility, which allows companies to pivot and capture the highest value opportunities. However, as a startup enters its growth phase, this lack of structure and protocol in the company can hinder further growth [10]. Although an unstructured approach allows a startup to remain adaptable during its incubation period, the growth phase requires some structure for accountability of results to scale the business to bigger markets and customers. Adding this structure and discipline to a startup may cause disruptions and may pose an issue for the scale-up and growth of the company.

During growth phase, a product might go through design and manufacturing modifications in preparation to cater to bigger markets. This would require working closely with the suppliers and vendors for its custom component requirements. Since startups produce in small batches, it is a challenge to have efficient control on the supply chain. This may lead to sourcing issues and hence hardware startups must be ready with alternatives. All of these issues make the ramp-up stage very crucial. It could "make or break" a startup and therefore careful planning is of utmost importance.

1.2 Company Background

1.2.1 Overview of NVBOTS

New Valence Robotics Corporation (NVBOTS) is a Boston based manufacturing startup founded in March 2013 by four former MIT students. NVBOTS is the world's first and only manufacturer of automated 3D printers which function with no human intervention whatsoever. The mission of NVBOTS is to build a globally distributed network of intelligent automated additive manufacturing equipment [11]. NVBOTS' 3D printers are connected to a cloud-based interface through which users can send print jobs that queue up and are processed in the system. Once a print job has been released and completed, the printed part is automatically removed from the print bed using a patented removal mechanism and the printer is ready for the next print job. The NVBOTS Logo is as shown below in Figure 1-1.

Figure 1-1: NVBOTS Logo [12]

Since its inception, NVBOTS has been committed to delivering on three fronts, “education, innovation and commercialization”. Their flagship product the NVPro, which is based on Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF) technology, caters to the education sector which is currently their primary market. NVPro has enabled students to visualize their learnings and empowered them with a tool that helps them create “extraordinary things” [12]. With respect to commercialization, NVLABS, the R&D division at NVBOTS is developing an ultra-high speed, multi-metal 3D printing solution which essentially is an “automated factory in a box” capable of building multiple metals in the same build [13].

As the first end-to-end provider of automated 3D printing solution, NVBOTS offers its NVPro customers with a seamless interfacing platform – NVCloud, through which print jobs can be monitored and approved from any device, at any time, from anywhere. Customers also have full access to the NVLibrary which is a comprehensive digital database of curricula, lesson plans and ready-to-print parts, especially for the education sector. The NVCare offers free training and support for all users, for the first 12 months. To add to this, NVBOTS also supplies qualified and calibrated filaments in a hassle-free manner to the customers [14]. This makes NVBOTS a popular choice in this market. Figure 1-2 below shows the range of products and services offered by NVBOTS.

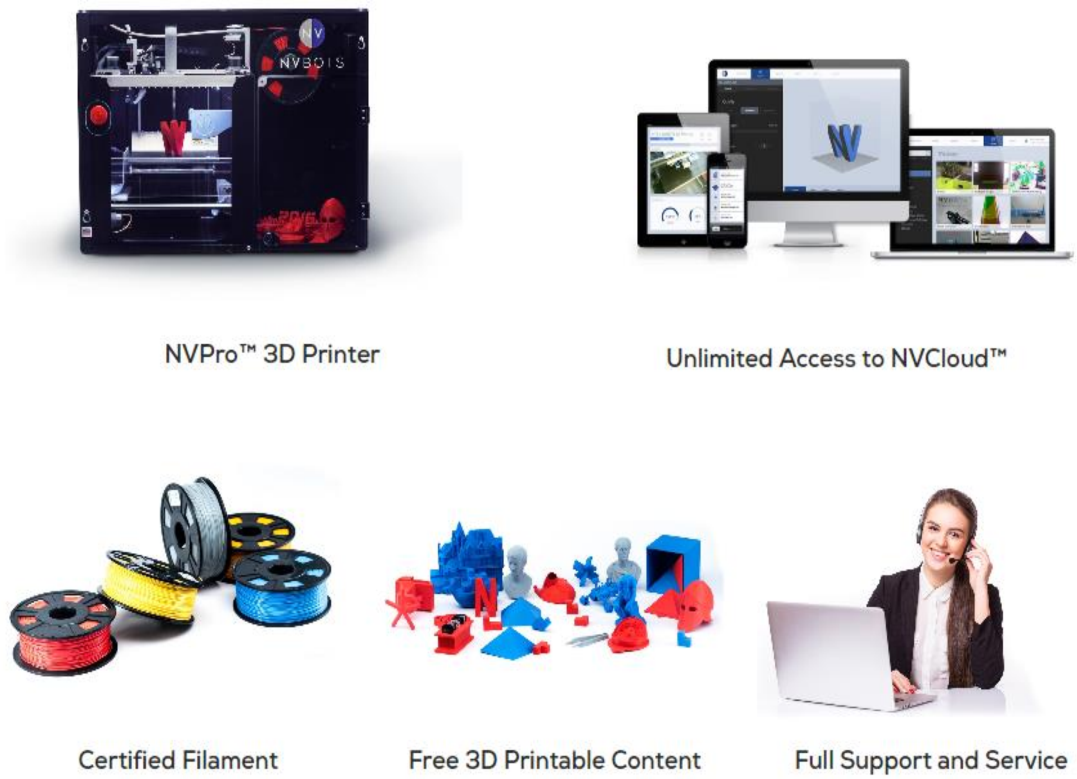

Figure 1-2: Services offered by NVBOTS [15]

1.2.2 NVBOTS Facility

NVBOTS currently has 18 full time employees divided across engineering, software development, production, operations and sales. The production floor is about 1200 square-foot in size with space divided for assembling and quality control. The workbenches are organized for specific sub-assemblies and the workers move from one workbench to another to complete the assembly of the printer. All the raw-material stock keeping units (SKUs) are stored in the inventory room until a work order is issued for making new printers. After the work order is issued, the workers kit the required material into a box before bringing them onto the production floor for assembly. The inventory room also houses a Coordinate Measuring Machine (CMM) which is used to check for dimensional accuracy of a few components and the gantry. NVLABS is where the R&D activities for improving metal 3D printing technology is carried out. A schematic of the plant layout is shown in Figure 1-3.

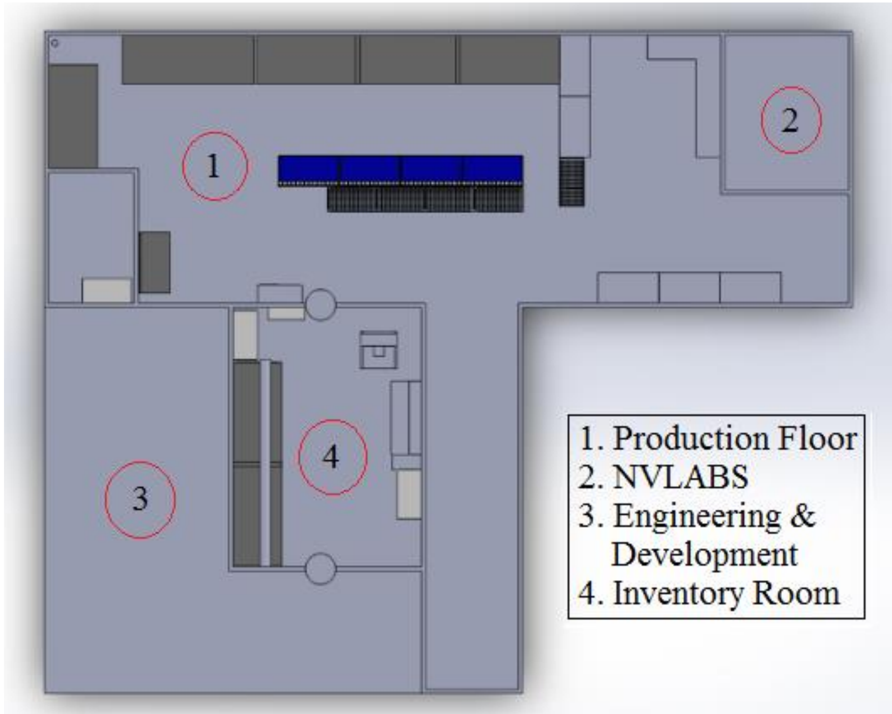

Figure 1-3: NVBOTS Facility Layout

1.2.3 Products: NVPro and NVCloud

The first NVPro 3D printer to be released into the market was REV E version in 2014. With constant technological advancement, engineering development and study of the existing printers, many design improvement iterations were made to the current REV H version.

The NVPro 3D printer shown in Figure 1-4, is a Fused Filament Fabrication (FFF) printer which has a built volume up to 570 inch cube and has a layer resolution equal to 100 microns. The material extruded through the nozzle is PLA (polylactic acid) which is laid out layer-by-layer at a maximum print speed of 180mm/s [15]. Since the printer has the automated part removal feature and a camera that allows real-time viewing, the need for an external operator is completely eliminated. Users can interface with the printer using NVCloud platform. The dashboard, as shown in Figure 1-5 and Figure 1-6, provides a live feed of the current print, indicates temperatures of the nozzle and the printbed, provides ability to queue and manage multiple prints, indicates the amount of filament left and also allows access to the NVLibrary of printable parts [16].

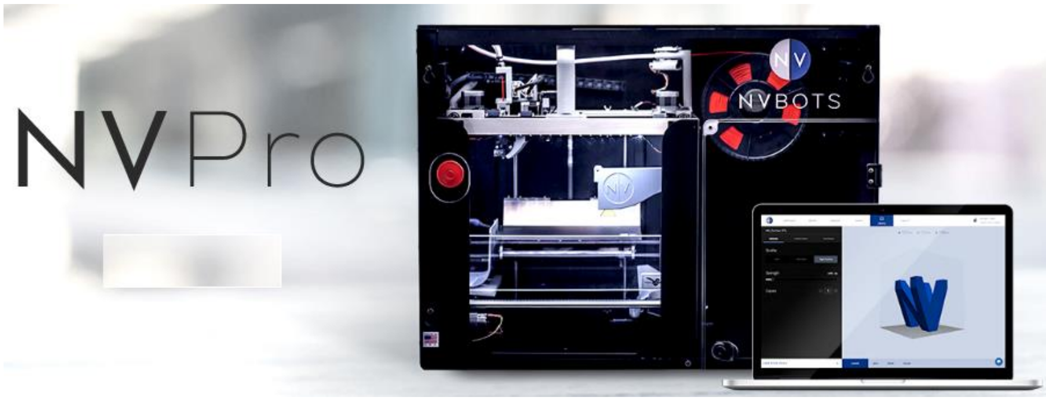

Figure 1-4: NVPro Printer [15]

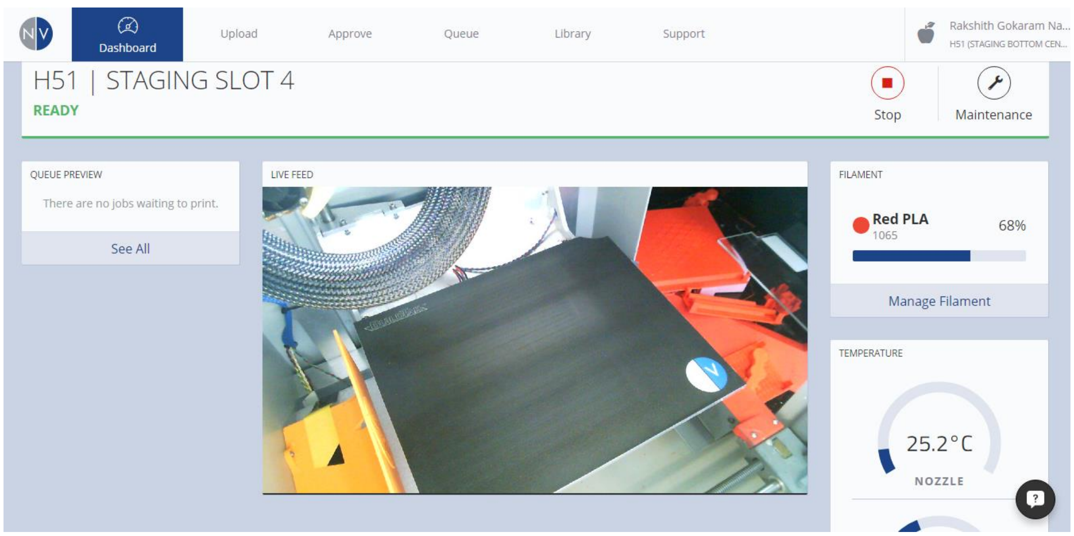

Figure 1-5: NVCloud Dashboard and Live Feed [16]

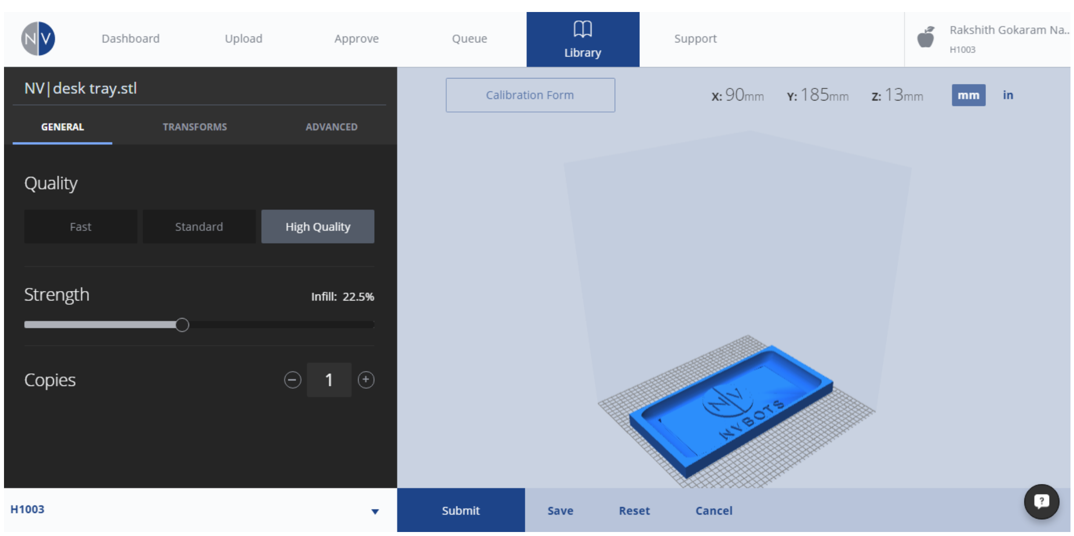

Figure 1-6: Print Preview Feature [16]

1.3 Research Motivation

NVBOTS is currently in a high growth phase, with planned production of its printers increasing from approximately 20 printers a year to 25 printers a month. Successfully catering to this order of magnitude increase in production would mandate significant changes in the company's operations. Additionally, this increase in production would be accompanied by NVBOTS' transition to a bigger production facility 18-24 months hence, and the development of NVBOTS' proprietary metal printer technology.

Thus far, the company's production, inventory management and overall operations were carried out in a 'good enough' approach based on past experiences of employees as opposed to being based on rigorous theory. Since refinement of engineering design of the printers had been the major focus of NVBOTS so far, streamlining the company's production had not taken top priority. Work was organized on google spreadsheets and often carried out on ad-hoc basis with undocumented procedures. Often this led to issues such as poor product quality, inventory stockouts, et cetera.

While this approach offers significant agility to NVBOTS to respond to drastic changes in the product and the market, ramping up the production of printers to cater to higher demands would require a much more systematic approach for production and overall operations. To realise this goal of smooth production ramp-up at NVBOTS, the M.Eng team (Master of Engineering in Advanced Manufacturing and Design program) from Massachusetts Institute of Technology (MIT) comprising of the author, Jain [1] and van Grootel [2], worked from February to August of 2016, on specific areas of manufacturing and operations.

1.3.1 Problem Statement

The overall problem at NVBOTS was the lack of structure in its manufacturing and operations related activities, which could potentially hinder them from scaling-up. The three projects done by the M.Eng students at NVBOTS can be bifurcated into two major problem areas namely, manufacturing systems and inventory management.

Problem Area 1: Manufacturing Systems

- There was little structure as to when printers should be made, and how many should be made. Decisions on new builds were made ad hoc. Batch sizes of 3, 6 or 12 printers were made sometimes as a result of, or sometimes in reaction to demand. A clearer policy should be developed in order to create more structure on the production floor. It is not strictly required to consistently build in the same batch size, nor is it required to build either in anticipation or in reaction to a sale, but the policy should be sensible and very clear.
- The capacity was unknown. This caused problems as it made it difficult to plan expansion timeline, to project the feasibility of sales, or develop a recruiting plan for hiring new assemblers.
- Long lead time to deliver a 3D printer to a customer. The lead time was set at around six weeks in order to ensure that the production team had sufficient time to finish the builds. However, six weeks is a long time, and with competition growing fiercer the lead time may become an important competitive advantage. NVBOTS should attempt to reduce this lead time.

Problem Area 2: Inventory Management

- Lack of a proper framework for data collection. NVBOTS doesn't have any data with regards to past sales, nature of demand, unit price variation of parts, supplier lead times, volume discount information, ordering cost, et cetera. Without this essential database, decisions are bound to be made on an ad-hoc basis. Lack of this database hinders NVBOTS from analysing trends in demand, identifying risky vendors who are always late on delivery, and from purchasing the right material, at the right price, at the right time and in the right quantity.
- Inefficient tracking of incoming and outgoing raw-material inventory. As noticed by the M.Eng team, NVBOTS faced frequent raw-material stockouts which resulted in expensive delays in production. The main cause for these stockouts was due to lack of knowledge of the exact stock levels of the various SKUs, caused by infrequent updating of the MRP system. In addition to this, multiple storage locations, inefficient logging of inventory sheets by persons handling inventory, and lack of good housekeeping practices led to more confusion within the inventory room. A structured policy detailing the procedure for inventory control would help enforce discipline.

- Lack of a methodical approach for ordering parts from suppliers and for scheduling printed parts production in-house. The two key decisions with respect to inventory management are “how much to order?” and “when to order?”. Currently, these decisions were being made on an ad-hoc basis resulting in a lot of inventory for a few SKUs and very little for others. NVBOTS being a startup was prone to capital constraints, hence it was vital to optimize the inventory on hand to ensure that the amount of locked-up inventory is minimum. At the same time to ensure that they do not compromise on their ability to make printers when needed.

  NVBOTS made certain components required to make 3D printers by printing them in-house. This process lacked methodology. The number of production printers for making the parts needed to be determined and the lot size in which these printed parts had to be made was to be estimated.
- Lack of an established vendor selection criteria. Being a startup, NVBOTS initially considered any supplier that was willing to supply the specified part irrespective of the cost, lead times and quality. Considering that they were scaling up, it was essential for NVBOTS to evaluate vendors to understand their capabilities. For this, NVBOTS needed to establish criteria on which to select vendors, and how to score each vendor against that criteria. This would be useful while scaling up, as it provides them a metric against which to compare vendors. Exploring dual sourcing and long-term contract options will become easier with a proper vendor evaluation methodology. Though vendor development and selection is not of immediate concern, the value that it brings has to be acknowledged.

1.3.2 Overview of Sub-Projects

The manufacturing systems project was dealt by both Jain [1] and van Grootel [2]. Each of them developed a specific set of simulations, with two primary goals. The first goal was to investigate different manufacturing strategies and policies, and to develop an understanding of the different trade-offs that exist for each policy if they were to be implemented at NVBOTS. The second goal was to provide ballpark estimates for performance of each policy under different scenarios, and to recommend a policy for NVBOTS. The manufacturing strategies outlined by van Grootel [2] include Build-to-Order and Push systems, and Jain’s [1] thesis dealt with Constant-Work-in-Process (CONWIP) and Push-Pull boundary systems.

The author of this thesis worked to solve the inventory management problem at NVBOTS. The project involved a thorough evaluation of existing inventory models and their suitability to NVBOTS. The primary aim was to setup a framework so as to ensure efficient data collection. The inventory was then classified into certain categories so as to mandate efficient management. Based on available data and reasonable assumptions, an ordering strategy for each of the categories was determined so as to ensure minimum capital requirements. In addition to this, an efficient inventory tracking system, room layout, cycle counting and lost inventory reconciliation policies were proposed. A vital addition to this project has been the inclusion of vendor selection methodology to assist NVBOTS to properly qualify and compare future vendors.

1.4 Thesis Overview

As previously stated, the overall problem statement was to assist NVBOTS to ramp-up their production in a hassle-free manner. This thesis specifically focuses on the problems associated with raw-material inventory management and tracking. The purpose of this thesis is to help NVBOTS: (1) to efficiently manage inventory by classifying them into groups with similar characteristics, (2) to determine *how much* and *when* to order each type of SKU so as to minimize capital requirements, (3) to accurately keep track of on-hand, incoming and outgoing inventory, (4) to provide a framework for vendor selection.

1.4.1 Thesis Structure

- **Chapter 1** covered startups and the problems they face during ramp-up stage, NVBOTS' company background, overall problem statement and the purpose of this thesis.
- **Chapter 2** presents an overview of additive manufacturing, its types, its market potential and its common application.
- **Chapter 3** presents the initial research and findings of the M.Eng team at NVBOTS, which helped honing in on specific problem areas.
- **Chapter 4** presents an overview to inventory classification methods, the purpose of classification and how raw-material inventory was classified at NVBOTS.

- ❖ **Chapter 5** presents an introduction to inventory management and commonly used inventory models.
- ❖ **Chapter 6** presents the data collection methodology, application of inventory models at NVBOTS, analysis and validation of the models, and final recommendations.
- ❖ **Chapter 7** presents physical inventory control practices, reconciliation of lost inventory, 5S and housekeeping methods, efficient inventory tracking methods and storing, and recommendations.
- ❖ **Chapter 8** presents the need for vendor selection, vendor evaluation matrix, its application, results and summary.
- ❖ **Chapter 9** presents a summary of the work done by the M.Eng team, provides roadmap for future work at NVBOTS and key takeaways.

It is also important to take note that the first three chapters were written by the author in collaboration with Jain [1] and van Grootel [2], and included here verbatim.

Chapter 2

Overview of Additive Manufacturing

2.1 Additive Manufacturing: Overview and Characteristics

NVBOTS is in the Additive Manufacturing industry, and it is beneficial at this point to explain what Additive Manufacturing means. It is also important to understand the business opportunity and market growth for AM, and how this growth could impact NVBOTS.

Additive Manufacturing (AM) is a collection of manufacturing processes wherein parts are built up layer by layer. AM differs from conventional manufacturing processes that typically involve material removal (such as cutting, milling, grinding), material formation (such as casting, injection molding), or deformation of an existing shape (such as bending). Instead, a part built by AM is built up as consecutive layers.

Some advantages of AM include:

- **AM is flexible**. Many different types of parts can be made in succession, with very little or no setup time between them. Little tooling and little changeover costs are required. The exception to this may be a cost associated with switching materials, which often involves something as minor as mounting a different spool onto the machine.
- **AM can make almost all geometries**, including those which are impossible to make via conventional methods. This opens up new design possibilities such as making parts much lighter by making them hollow. Figure 2-1 shows one such application.
- **There is little material waste.** Beyond reducing the weight of the final part, AM has a significant benefit over subtractive processes such as milling or cutting – it results in lesser

material waste. Only the material that is required is put down, with the exception of supports which make up a small proportion of the total material use [17].

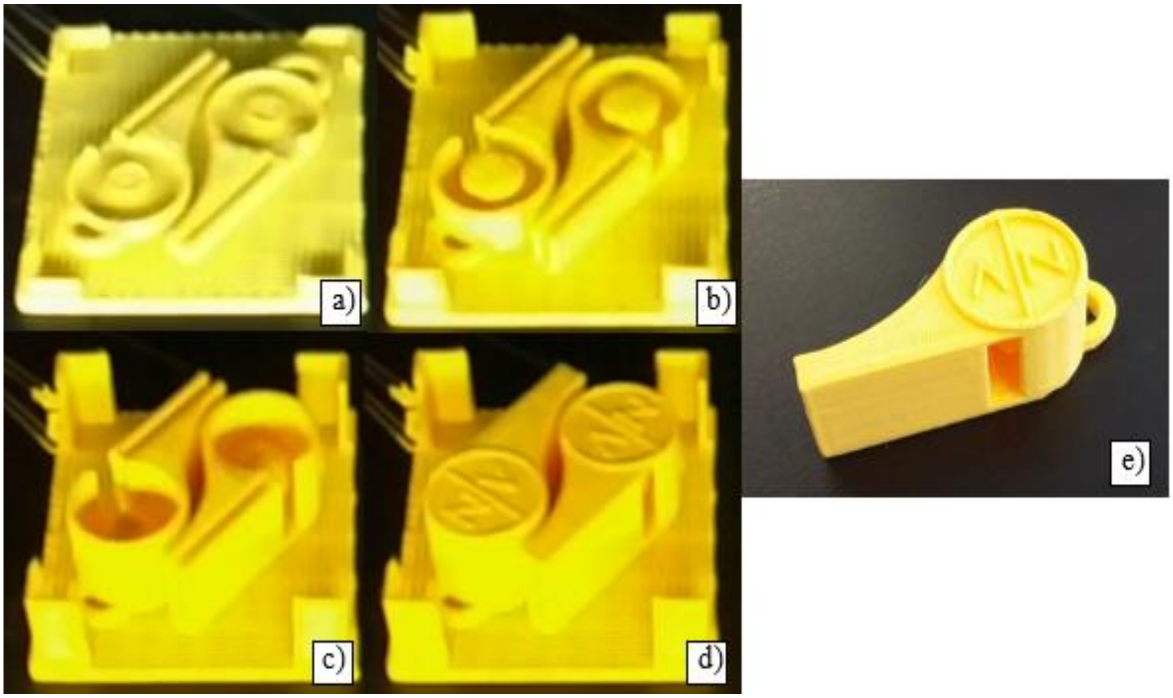

Figure 2-1: (a-d) Time-lapse of two whistles being printed and the final result, (e) Note that a ball is printed inside of the whistle. This is an example of AM being used to make geometries which are impossible to make using conventional methods.

However, some disadvantages of AM over conventional manufacturing methods include:

- ❖ **Process control is challenging.** There are many input settings that have to be fine-tuned for a part to come out according to specifications [18]. Minor deviations in ambient temperature or humidity can have major consequences in the final part quality.
- ❖ **Throughput is low.** Compared to mass production, AM is slow. For sufficiently large production quantities it may be cheaper to adopt processes like injection molding.
- ❖ **There are materials limitation**. Not all materials are available for use. The list of useable materials is steadily growing, but this may still be a limitation for niche applications looking to use a specific material [18].

2.2 Types of Additive Manufacturing

There are many different types of AM, and many companies give new names to their processes even though they are arguably the same. Many laymen believe the terms 3D printing and AM to be interchangeable, although this is not accurate. ASTM released a standard for terminology pertaining to AM. In it they define seven categories of AM [19]. As ASTM defines them, the seven categories are:

1. **Binder Jetting** — an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
2. **Directed Energy Deposition** — an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.
3. **Material Extrusion** — an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
4. **Material Jetting** — an additive manufacturing process in which droplets of build material are selectively deposited.
5. **Powder Bed Fusion** — an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
6. **Sheet Lamination** — an additive manufacturing process in which sheets of material are bonded to form an object.
7. **Vat Photo-Polymerization** — an additive manufacturing process in which liquid photo-polymer in a vat is selectively cured by light-activated polymerization.

Note that at NVBOTS the process of choice is material extrusion, but that it is referred to as Fused Deposition Modeling (FDM) or as Fused Filament Fabrication (FFF). According to ASTM, 3D printing is defined as *'the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology'* [19]. As FDM adheres to this definition, it can be classified as 3D printing. Therefore, 3D printing, material extrusion, AM and FDM can all be used to describe the process used in the NVBOTS' current printer, the NVPro.

2.3 General AM Process

Gibson [20] lays out the generic process for AM. Step 1) create a Computer Aided Design (CAD) file representing the part. The geometry has to be fully defined before the second step can be started. Step 2) translate the CAD file into an STL file. This is the standard used as an input for all AM machines. Almost all CAD software packages have a way to export a design into an STL file. Step 3) transport the file to the AM machine. Step 4) machine setup. The machine may need different inputs such as material properties, energy settings, timings or thickness of material. Step 5) Build. This step can be done almost entirely automatically except for errors like running out of material or having a glitch. Depending on the type of AM used, this build will occur via different means. Step 6) Removal. The part has to be removed from the build space. Note that NVBOTS has an automatic part removal feature which gives it a significant advantage over its competitors as it is the only one in the market with this feature. Removal can often be time consuming if the settings are not entered just right, because the part will stick to the build surface. Step 7) Post-Processing. Before the part can be used, it will often require some post processing such as cleaning, heat treatment, or the removal of support material. Figure 2-2 below shows a generalized AM process.

Figure 2-2: Generalized Additive Manufacturing Process [21]

2.4 Applications of AM

There are many applications of AM, ranging from purely visual purposes, such as visual aids for designers or doctors, to functional parts like production parts. Figure 2-3 below shows the use of AM technology in industry. This is based on a survey conducted by Wohlers, asking AM companies what their customers use their technology for. Note that functional parts account for a third of all uses, and is the largest segment. This was not true even as recently as 2011. In the 2011 report by Wohlers, this section only counted for roughly 15% [22], indicating high growth for this segment.

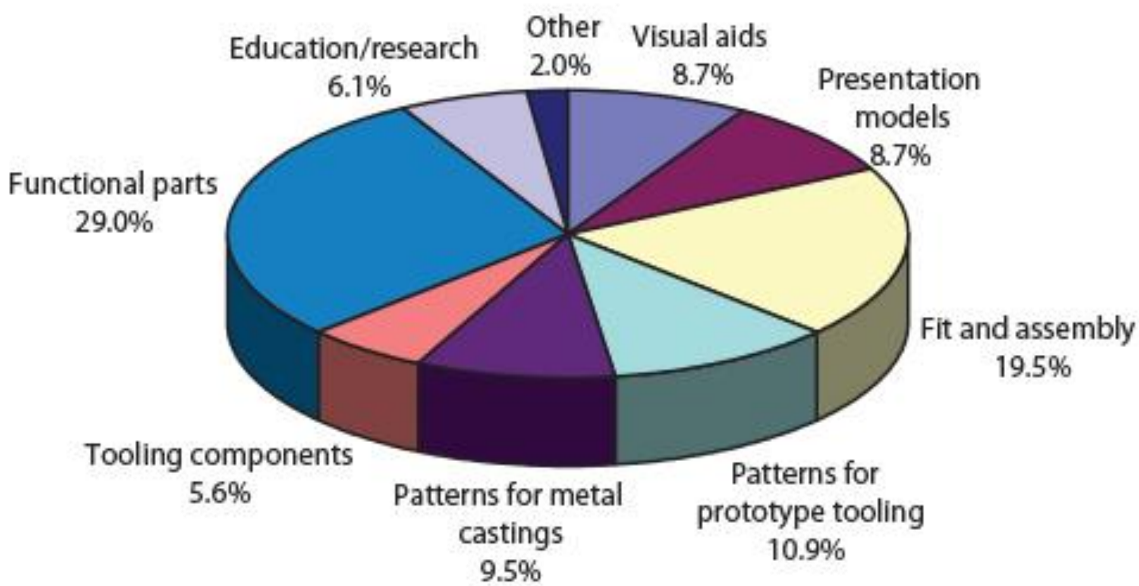

Figure 2-3: Pie chart showing the results of a survey by Wohlers Associates, illustrating what companies use AM technology for [23]

A detailed analysis of these applications is far beyond the scope of this thesis. Instead, readers are directed to other sources such as the annual Wohlers Report, or one of the many textbooks available. However, it is worthy to note that Additive Manufacturing is gaining wide acceptance due to its limitless applications.

2.5 Market Growth

It is estimated that the AM industry grew to $5.165 billion, a growth of 25.9% from the year before [24]. As Table 2-1 shows, a growth of 25.9% is relatively small in comparison to prior years, but nonetheless an incredible statistic for any industry.

Year	Industry Revenue ($ billion)	% growth
2011	1.714	29.4%
2012	2.275	32.7%
2013	3.034	33.4%
2014	4.102	35.2%
2015	5.165	25.9%

Table 2-1: AM industry revenue and growth. [24]

Wohlers is expecting this growth trend will largely continue, and that by 2017 the industry will reach $8.8 billion – an average of 30% annual growth for the next two years. It also estimates that by 2021 the industry will be at roughly $26.5 billion [24]. The trends in AM technology are therefore very positive. Using AM technology for rapid prototyping is a relatively mature application [24]. The future lies in production, with major benefits such as reduced reliance on tooling, high flexibility, and unique part geometries for better performance. Figure 2-4 shows the business opportunity instore for companies like NVBOTS.

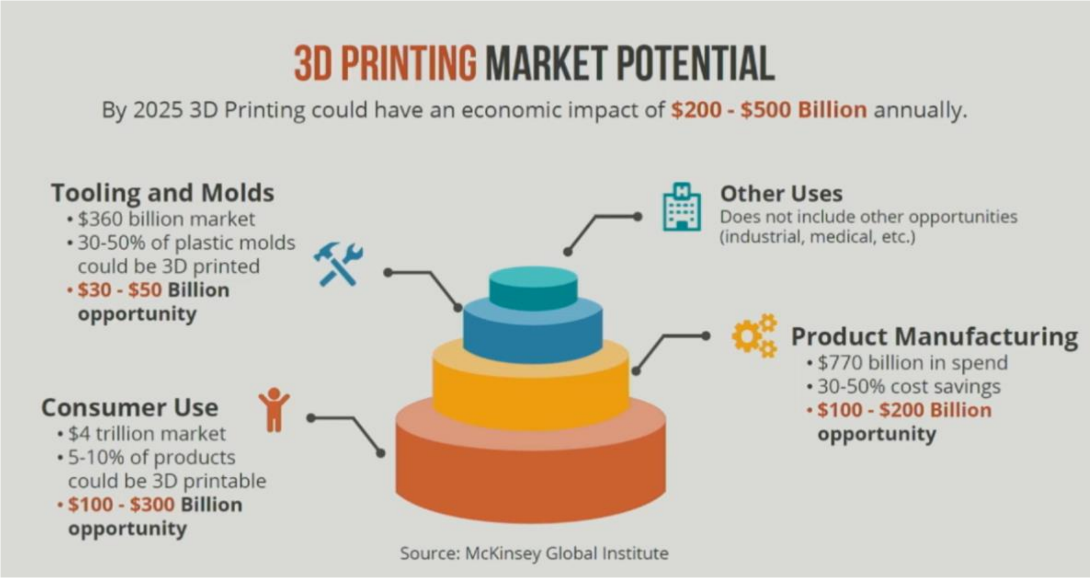

Figure 2-4: Market Potential of 3D printing by 2025 [25]

Chapter 3
Initial Research and Key Findings

3.1 Overview

At the onset of this project there were no obvious symptoms of errors at NVBOTS. Printers were being assembled roughly within their promised time frame and were of satisfactory quality for the customers. However, this lack of obvious symptoms does not mean that the company was ready to ramp up their production by an order of magnitude. Identifying areas that need work to prepare for the scale up was the first step in the project, and required a survey of the entire company. This was done by conducting interviews with some of the key employees at NVBOTS, going through documentation, and building a printer from scratch. It was after going through this activity that the team narrowed down the problem areas to inventory management and manufacturing systems. Hence, it is highly recommended for companies that are looking to scale up to do a similar activity as it will help identify the potential problems that could hinder a smooth transition.

3.2 Interviews with Employees

To get a better understanding of NVBOTS, its business model, its products and its operations, one of the first things the M.Eng team did was to conduct interviews with all the key players across various departments including Engineering, Manufacturing, Operations, Software Development, Sales and Servicing. The idea behind these interviews was to get background information about NVBOTS, to get familiar with the people and their roles, to identify critical problems that the company was facing and potential problems that could arise while scaling-up.

Interviews usually lasted roughly 30-60 minutes. The interviews were informal and had a lot of open-ended questions to encourage discussion. A list of possible questions were usually sent in advance to most of the interviewees so that the meetings could be more efficient. The following paragraphs summarize the key takeaways from these interviews with various departments:

- **Sales and Marketing Team:** The sales team believed starting with a niche market like the education sector was the best bet for NVBOTS. Their target market to begin with were schools in the Boston and New York regions but were now slowly moving into overseas markets in Australia. Selling to schools was slightly tricky owing to low budgets, long supplier acquisition times and lack of understanding of the product. The main selling points about the NVPro printer were the automated part removal feature and the NVLibrary which included lesson plans, curricula and ready-to-print parts. The sales team expected to sell anywhere between 100 & 200 printers in 2016.
- **Engineering Team:** The engineering team was constantly working to improve the quality of the printer. They received feedback from the customers and then acted on it to ensure those problems don't occur in the future. Since 2014, the NVPro Printer has gone through multiple design iterations to make it more robust, easy to assemble and service. At the time of the interviews the engineering team was developing standard assembling and testing procedures. Filament calibration was a major problem that came up during the interview. The filaments that NVBOTS received from suppliers were prone to material changes across batches. This caused the printed part to either warp or be hard to peel-off the raft. The engineering team was running a DOE to understand what factors affected print quality the most.

  The engineering team along with NVLabs was also working on developing the high-speed, multi-metal 3D printer. They were focusing on making the design modular so that they could aim for late-stage differentiation and build both the NVPro and the NVMade (metal printer) on the same production line.
- **Manufacturing Team:** Once a work order to build a batch of printers was issued, the manufacturing team would start assembling printers and were capable of assembling up to 12 printers in 2 weeks. The production team liked building the sub-assemblies and the final

printers in batches, as they felt it was easier to read a procedure once and repeat it multiple times. There were currently only two people working on the production floor, some of whom also had other responsibilities beyond production. This limited the number of printers that could be assembled in a year. To add to this, there were limited number of tools and little formal structure on the production floor. Furthermore, the engineering team continuously introduced changes which was sometimes difficult for production team to cope with. The production team strongly felt that restructuring the production floor, organizing the work benches, having a well written standard operating procedures and established flow of materials, would help when NVBOTS scales-up.

- **Operations and Servicing Team:** The main role of this team was to schedule production, ensure availability of inventory, build supplier relationships, dispatch workers in order to perform servicing on the field, keep track of failure costs, and ship finished printers in a safe and hassle-free manner to the final customers. Currently, there was no efficient system in place to ensure proper tracking of incoming and outgoing parts from the inventory. Also, the order placed by the purchasing team was on an ad-hoc basis. This sometimes resulted in stockouts of raw-material causing delays and stoppages in production.

  Servicing was usually dealt over the phone unless it was absolutely necessary to send servicing men to customer's location. The team actively kept track of servicing costs and reasons for failure. This information was passed onto the engineering team so as to mandate corrective action.

- **Software Development Team:** Print jobs and queues could be managed only through the NVCloud platform that interfaced with the 3D printer. The role of the software development team was to ensure that all printers were connected to the cloud and functioned efficiently. The dashboard displayed temperatures of the printbed and nozzle, provided live feed of the printer, and indicated the filament levels. Recently, there have been many network issues and bugs which the team is trying to fix. To make this setup more efficient they have partnered with Resin IO, a startup that provides a platform to encompass client, server and device software. The team also wanted to develop a custom ERP software, which could be very handy when NVBOTS scales up.

3.3 Building 3D Printers

In addition to conducting interviews of key players at NVBOTS, the team also built an NVPro printer. It was important to be familiar with the company's product and its production process to be able to effectively contribute to their improvement. Considering that the production process of the printers mostly consisted of common assembly steps as opposed to complex manufacturing processes, it was reasoned that it would be feasible for a printer to be built by the team as a learning exercise. In fact, the team ended up building two NVPro printers and derived three major benefits. First, it gave access to data that NVBOTS had not yet collected. Second, it gave a deep appreciation for the engineering and design of the printer. Third, whenever a procedure was unclear it was immediately brought to the attention of the engineers, who then clarified the requirements and made the changes on their documents.

During the first printer build, the primary objective of the build was to understand the nuances of the assembly process. However, recommendations for improving the SOPs were noted during the printer build exercise, and were submitted to the engineering team towards the end of the exercise. The recommendations consisted of making the assembly instructions as explicit as possible to avoid any ambiguity, standardizing the format of the SOP sheets to increase their readability, and standardizing the sentence structuring of the instructions, to name a few. These recommendations were used by NVBOTS to improve the subsequent versions of the SOPs.

The second printer build was done in order to collect data with respect to the timing of each operation, to identify the tools required, to understand the work order system, to verify and understand the quality checks. This build was crucial as the team wanted to identify bottlenecks in the process, estimate production capacity of the plant, find out how long it would take to make a printer and to verify if the SOP's were robust enough.

Figure 3-1 below summarizes the most important timing data. Note that the figure below does not include picking nor post processing. It takes roughly 10.5 man-hours to build a printer, including all the assembly steps, picking and post processing for printed parts. It is important to note that the timing is strictly for the execution of the procedure and does not include the time required for searching for tools, reading and understanding the procedures.

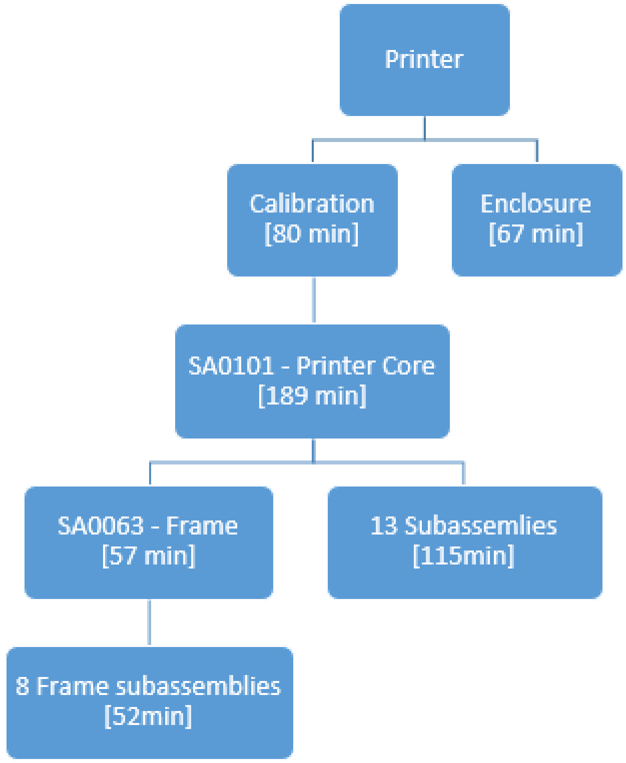

Figure 3-1: BOM tree of a NVPro REV G printer with the corresponding times. Note that this does not include the time for picking, nor the time (~40 min) required for post processing of printed parts.

In total, data was collected on roughly 400 procedures, across 39 items (36 subassemblies, and 3 printed parts requiring post processing). The vast majority of procedures needed little specialized equipment. 1.5mm, 2.0mm and 2.5mm hex wrenches, a Philips head screwdriver, an arbor press and needle-nose pliers were amongst the most used tools. There were 231 SKUs and about 720 parts that went into a making a printer, out of which 70 SKUs and about 450 parts were fasteners.

A significant amount of time was spent before each procedure to locate all required tools. For some frequently used tools, like the 2mm hex wrench, only one or two existed on the production floor. As a result, not every workbench had its own tools and it became difficult to locate these. Numerous times the procedures called out to use a fixture. However, the location of these fixtures was not obvious, leading to significant searching time. Although this searching time is not included in the data, it is something NVBOTS should be aware of.

3.4 Identification of Key Problem Areas

After having conducted the interviews and having spent a significant amount of time on the production floor, the team was able to identify potential problem areas. Especially, the printer building activity gave a lot of insights as we spent numerous weeks on the production floor. This gave a weekly snapshot of the production floor, which pointed out some interesting issues. For example, the procedures were constantly being updated, and in some cases the parts were updated alongside it. This caused some confusions and disruptions, and indicated that the Engineering Change Orders (ECOs) could be developed further. Inventory stockouts occurred frequently, often for multiple parts at a time. The stockouts often meant that the workflow had to be adjusted, both for our build as well as for the production team. Lack of inventory management was therefore highly disruptive to the production floor, and the schedule ended up being dynamic and constantly readjusted. Furthermore, the total workload was highly unbalanced. Some weeks barely anything occurred on the production floor, but then the next week employees were very busy. Partly this unbalanced workload was as a result of the inventory mismanagement and partly due to unexpected demand spikes.

Eventually, we narrowed down to inventory management and manufacturing systems as the most important problem areas and decided to focus on these problems. The problems related to these areas are written in detail in Chapter 1. However, some of the other problems that NVBOTS must be aware of are as follows:

- **Quality definition and quality testing**: There did not exist any formal definition of quality specifications to quantify the goodness of a printer or of parts printed on the printer. For the printed parts, to a large extent, the quality testing process was based on their visual inspection. It was reasoned that a lack of a quantifiable quality definition could be an obstacle as the company scaled up its production and diversified into the commercial market space. Addressing this problem would also include the creation of formal quality testing procedures to qualify a printer based on predetermined target quality specifications.
- **Filament calibration**: NVBOTS' printers are based on the FDM additive manufacturing process, which requires the use of consumable plastic filament drawn from discrete spools. The quality of printed parts is highly dependent on the material characteristics of these

filaments. Currently, NVBOTS sourced its filaments in batches, and there was notable variation in filament characteristics from batch to batch. Compensating for this variation required time consuming calibration of the printers. The disruptions in production due to lack of printed parts caused by filament calibration could be an obstacle as NVBOTS scales-up.

- **Design for Manufacturing**: Currently, 20 parts that go into making a printer are parts printed in-house. The rationale behind using in-house printed parts was to provide flexibility during the initial design phase of the printer. However, the printing process is inherently slow, which could cause significant time delays as production ramps up. Addressing this problem area would involve exploring alternate ways of fulfilling the functional requirements of these parts in a design for manufacturing (DFM) study.
- **Design for Assembly**: During the initial printer build, there were many instances of inconvenient and difficult assembly steps that sometimes required several retries to do correctly. This significantly increased the printer assembly time, which could adversely affect the production rate during ramp up. A Design for Assembly study would address ways to improve the assembly process of the printer.
- **Servicing**: During failures of a printer in the field, NVBOTS used to send out its own personnel for servicing. As production ramps up, NVBOTS' servicing capabilities would have to scale up at an equal pace. Additionally, field failures were not being tracked to their root causes by NVBOTS and this has to be done in the future.
- **Shipping**: As NVBOTS expands its distribution overseas, its product shipping capabilities would have to scale up at the same pace. NVBOTS did not have a structurally robust shipping container for safely shipping its printers overseas. A viable logistics partner could help solve this problem.
- **Gantry Tolerances**: Research from previous projects [26][27][28] at NVBOTS showed that the tolerances of the gantry were well within the target specifications. While this demonstrates the high quality of gantry components, it also reveals that NVBOTS could potentially relax the tolerances of the gantry components, which would help reduce the overall cost of gantry.
- **Standard Operating Procedures**: The labour intensive nature of the assembly process and the lack of proper standardization of procedures could adversely deteriorate the quality from printer to printer as production is ramped up. Though NVBOTS is addressing this issue, making this a priority and rewriting robust SOPs is the need of the hour.

3.5 Quality Control Experiment

Following the informational interviews of key players at NVBOTS, the printer build, and identification of problem areas, the lack of a formal definition of printer and printed part quality was identified as an issue that needed to be addressed before NVBOTS' production ramp up. Consequently, the team wanted to explore if this was a potential area for a project given the current needs of NVBOTS.

A statistical analysis experiment was conducted on three NVBOTS' printers in an effort to provide a starting point for creating a quantifiable measure of goodness of printers, and checking the variation in performance of the printers. The results of the experiment would also provide the engineers with exploration areas of possible improvements. On an analytical level, the objective of the statistical analysis experiment was to study the variation in performance (dimension of a printed part) among different printers, at different locations within a printer, and within the inherent printing process. An Analysis of Variance and Nested Variance analysis was performed for different samples printed on the three printers.

The results showed that the printers demonstrated good performance and that there was minimal variation among printers (less than 10 microns). Whether this performance was good or not needed to be determined by NVBOTS based on the market they wished to target. Considering that NVBOTS implemented more rigorous quality control tests for printers following this experiment and that the performance of the printers was reasonably good, the team decided to focus only on the two important problem areas namely, inventory management and manufacturing systems.

3.6 Current Situation: Inventory Management

After having narrowed down the problem areas, the team split up to focus on specific problems. The author of this thesis worked on inventory management and further investigated to get a better understanding of the inventory situation at NVBOTS. The following paragraphs outline these findings.

NVBOTS had a very robust coding system for its parts. It used an alphanumeric coding method wherein the first two letters indicated the part type and the next four numbers were unique to that particular part. An example of their coding system is FR0023 where FR stands for fasteners and 0023 is the unique code for M2 washer (Stainless Steel). Currently, there are about 230 unique parts in the latest version of the NVPro 3D printer. Each of these parts had a specific location within the inventory room. Some of the SKUs like fasteners had multiple locations on the assembly workbenches and the refurbishing/servicing workbench. The locations were more or less well named and marked. The location information of these parts were documented in an excel sheet.

Being a startup, NVBOTS hadn't invested in a good ERP software. They currently used a primitive MRP software with limited functionality called Odoo. Odoo was used to keep track of the inventory levels, order delivery dates and receipts. It was observed that Odoo was not well updated and hence did not reflect their exact inventory position. This lack of knowledge of the quantity on-hand for SKUs led to stockouts of certain raw-materials which caused stoppages in production. To add to this, NVBOTS did not conduct any cycle counts to update the system from time to time.

In small companies like NVBOTS, lack of sufficient data to assist in decision making is also a problem. NVBOTS lacked a framework for proper data collection. Information with regards to the bill of materials cost, supplier lead times, previous sales data, future demand data, and others were not well documented. This further augmented the problem when orders for parts had to be placed. Currently, orders were being placed in an ad-hoc manner without much consideration for lead times, ordering costs, volume discounts or any other metric. The order sizes were roughly based on the estimated production for the next couple months or so. There was a lack of structured scientific approach to determining how much to order and when to order. More often than not the triggers for placing these orders were because of stockouts being reported by the production team to the purchasing team. However, some SKUs had enough quantity to last an entire year. This was also problematic as NVBOTS constantly updated the design of the printers, leading to scrapping of these expensive parts.

When orders were received, they were placed on the incoming shelf. After the order was checked against the purchase order (PO) for quantity, it was subjected to quality checks. Once verified as good, the parts were placed in their respective locations in the inventory room. After placing parts into the shelves, the sign-in sheets were updated into the Odoo system. The incoming side of inventory was handled by a dedicated person and happened in a hassle-free manner. The biggest problem lied with the outgoing inventory. Parts were taken out of the inventory for multiple reasons including for production, development, servicing and for marketing purposes. Whenever a part was being taken out it was required to be entered in the sign-out sheets. It was observed that this practice was not followed by everyone leading to unfilled sign-out sheets. Thus, the Odoo system did not truly reflect the quantity in the inventory room and reconciling for lost inventory was a difficult task.

The inventory room was not well maintained. The primary reason was the lack of dedicated inventory personnel to ensure good housekeeping. The locations, though well named, had certain discrepancies. Sometimes parts earmarked for other SKUs were being stored in their location, leading to confusion. Unwanted boxes, parts and documents were scattered within the inventory room. There was a need for implementing 5S system within the inventory room. Also, the location of the parts in the room wasn't according to any scheme. It was haphazardly stored. This made picking parts for assembly operations a very time-consuming task, as the production team had to move across multiple racks to pick parts for a simple sub-assembly.

Another problem at NVBOTS was the lack of a proper vendor qualification framework. Being a startup, they pretty much accepted any vendor that offered to supply them with the required parts at reasonable pricing. On analysing the purchase orders and packaging slips, it was noticed that most vendors did not deliver within the given deadlines and some of them had very high lead times. Though this was not a problem until now, NVBOTS cannot afford to make any mistakes with respect to vendor selection in the future as it could be disastrous for them. They need to identify a list of criteria for comparing vendors. This will help them identify risky vendors and separate them, forge contracts with good vendors and have multiple sources for a single part type, if needed.

The need of the hour was to put a list of policies and procedures in place with specific responsibilities assigned to certain individuals. There had to be a way to enforce discipline to ensure proper tracking and updating of inventory levels in the Odoo software. A proper framework for data collection needed to be established. Even the ordering needed to be more robust and based on systematic methods and on the planned production schedules. It was also important to implement some sort of housekeeping within the inventory room. To add to this, vendors needed to be vetted properly before being qualified as NVBOTS' vendors. In conclusion, a framework for inventory management and vendor section had to be put in place.

The following chapters deal with some of the above mentioned problems, describing the problem solving methodology adopted, results obtained and recommendations suggested.

Chapter 4
Inventory Classification

4.1 Overview

Inventory classification is the process of segregating inventory items into more or less "homogenous" groups based on certain characteristics of the items such as demand, annual usage value, storage space requirements, et cetera. The main purpose of inventory classification is to simplify the management of inventory, thereby reducing the time and effort spent by an inventory manager to ensure better control of inventory.

Usually companies deal with a huge variety of parts, either raw materials or finished goods inventory. There might be thousands of SKUs that the inventory manager might have to manage in terms of when to order, how much to order and how to store the parts. It gets more complicated in firms which do not use an MRP/ERP software to manage inventory. In these situations, classifying inventory into groups with common characteristics helps in manging them. It also helps in directing attention to important SKUs, where there is an opportunity for optimization and cost saving rather than focusing on relatively unimportant SKUs.

It is true that we cannot treat all SKUs the same way and have a common ordering policy for them. At the same time, it is very difficult to treat each SKU as a single entity and have a specific policy for it. It is therefore essential to understand the characteristics of SKUs and try to group them either based on the nature of demand, cost of the product, type of product, or some other characteristics.

4.2 Common Inventory Classification Methods

Some of the commonly used methods to classify inventory are ABC analysis, FSN analysis and VED analysis [29]. They are outlined in the following paragraphs.

ABC analysis which is an acronym for “Always Better Control” [29], is an adaptation of Pareto’s Law [30]. Pareto studied that in Italy 80% of the wealth was held by 20% of the total population. He believed this reflected a universal principle and formulated the axiom that “significant items in a given group normally constitute a small portion of the total items in the group and that majority of the items in the total will, in the aggregate, be of minor significance” [29]. This axiom fits well in most inventory situations where 20% of the total SKU’s account for 80% of the total costs. Typically, ‘A’ category items account for 15-20% of the SKU’s and represent 80% of the total costs, ‘B’ category items account for 30-35% of the SKU’s and represent 15% of the total costs, and ‘C’ category items account for 50% of the SKU’s and represent 5% of the total costs. Figure 4-1 below depicts a typical ABC analysis.

To perform ABC analysis, all the SKUs are ranked in decreasing order of the total annual usage value which is the multiple of annual demand and unit price for the SKU. Then the SKUs with cumulative sum of usage value within the top 80% are characterized as ‘A’ items and so on. This characterization helps managers to focus on ‘A’ items which are of highest value and hence obtain the largest savings. Similarly, they can focus less on ‘C’ items which are relatively cheap.

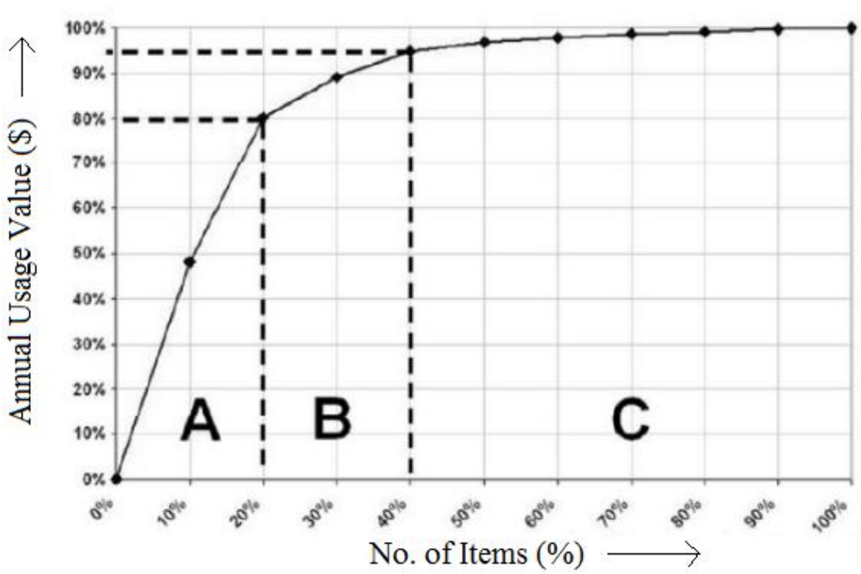

Figure 4-1: Diagram for ABC plan [29]

FSN analysis is another method of inventory classification where F stands for fast moving, S for slow moving and N for non-moving parts. This analysis helps in reducing inventory costs. For example, parts that haven't been used or issued for a long time can be completely removed from the system, slow moving items can be significantly reduced in quantity while keeping a sufficient stock of the fast moving items [29].

VED analysis works the same way as well, where the parts are characterized as valuable, essential and desirable and then necessary steps are taken to control inventory for those parts [29].

In addition to the above mentioned methods, there are other ways to classify inventory like grouping them based on vendors or based on lead time or based on the space requirements or special needs of certain inventory, et cetera.

4.3 Initial Observations

At NVBOTS raw-material inventory was categorized based on their part type such as fasteners, motion components, printed parts, adhesives, et cetera and were stored in the inventory room based on their space requirements, as XL (extra-large), L (large), M (medium) and S (small). Each of these part types had a unique code which helped in easy identification and storage. However, this categorization was more for internal purposes so as to ensure easy picking and assembly operations. It was also interesting to note that most SKUs had long shelf-lives, while part types like adhesives and thread-lockers had lower shelf-lives which needed to be treated differently and mandated shelf-life tracking.

While studying the raw material inventory at NVBOTS it was seen that most parts required to assemble the printers were procured from external suppliers. Out of the 230 SKUs about 20 SKUs required for assembling the printers were 3D printed in-house and were considered part of the raw-material inventory. Essentially, parts could be classified as either externally procured or internally produced and hence it was important to treat them differently. Similarly, the vendors could be further broken down into domestic and international vendors. A study on the lead times of suppliers, number of SKUs supplied and their pricing policies could further yield interesting results and a potential for classification based on vendors.

4.4 Methodology

After analysing the raw-material inventory, necessary data pertaining to demand, annual usage, lead time and unit price of the SKUs was collected (refer Chapter 5 for data collection method).

Logically, it made sense to classify inventory as "Externally Procured" and "Internally Produced". Printed parts (PP: NVBOTS code) would be the only part type under the "internally produced" category. Unlike the other components which were obtained from external suppliers, printed parts needed to be planned and produced in-house. Decisions pertaining to how much to produce in each batch, how many production machines (3D printers) to be used and when they need to be produced needed to be determined. Also, triggers for printing more parts, issuing work-orders, scheduling quality checks were to be decided. These decisions are very different from procuring parts from outside suppliers which would involve issuing PO's and RFQ's, making a decision based on the price, lead time, ordering costs and other parameters.

Out of the remaining part types, Adhesives (AD: NVBOTS code) were very peculiar. Most of the SKUs under part type AD had very low shelf-life, usually between 6-9 months. Hence, these parts needed to be separated from rest of the components that were externally procured. In addition to demand and usage, expiry date also needed to be tracked for these parts.

The remaining SKUs did not have any obvious inherent characteristics and hence were considered for analysis using a Unit Price vs Lead Time graph. This is an innovative approach to classify inventory based on the trends obtained on plotting a graph with y-axis being the unit price of each SKU and x-axis being the supplier lead time to procure the component. By following this approach, a graph as shown in Figure 4-2 was obtained. The intensity of the plotted points indicates overlapping SKUs, darker the circular dot, more are the number of SKUs. There was no obvious trend visible and the data points were all over the place. There were low priced parts with low and high lead times, and similarly there were high priced parts with low and high lead times. This is slightly vague considering that we haven't defined what constitutes low lead time and what the threshold for low priced parts is. Since NVBOTS considers parts above $10 as high priced parts and lead time above 10 days as high lead time, the graph is not very useful. However, if the plot showed any obvious trends, then grouping based on these trends could have been a possibility.

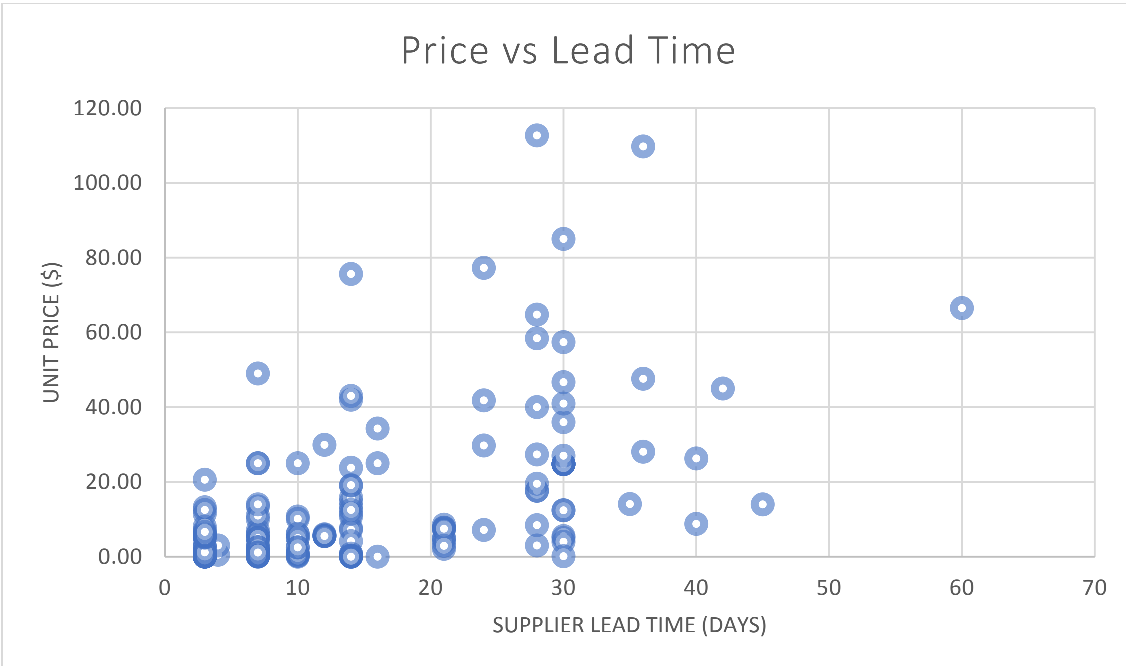

Figure 4-2: A graph depicting unit price on y-axis and supplier lead time on x-axis

Considering that the above approach didn't help much in classifying inventory, ABC analysis was applied to the remaining SKUs. In order to do so the annual demand and unit price data of each SKU was collected. Then the annual usage value for each SKU was calculated using the formula below.

$$Annual\ Usage\ Value = Annual\ Demand * Unit\ Price \quad (4\text{-}1)$$

Since the ABC analysis doesn't have any strict threshold for each category, the classification into A, B and C was decided by NVBOTS based on the scheme mentioned in Table 4-1 below. For example, 24% of the SKU's account for 75% of the total annual usage value for 'A' category items.

Category	Annual usage value	% of total SKUs
A	75%	24%
B	20%	27%
C	5%	49%

Table 4-1: Threshold set by NVBOTS for each category

Then, all the SKUs were arranged in decreasing order of the annual usage value and cumulative annual usage column was generated as shown in Table 4-2, the top 75% of the annual usage value which accounted for 24% of total SKUs was categorized as A, next 20% which accounted for 27% of total SKUs was B and the remaining 5% that accounted for 49% of the total SKUs was C.

Item #	SKU	Cumulative Annual Usage Value	Category
1	FP0032	4.00%	A
2	CB0013	7.89%	A
3	FM0021	10.91%	A
4	CB0010	13.65%	A
5	FM0044	16.33%	A
6	EC0091	18.69%	A
7	FP0033	20.99%	A
.	.		A
.	.		A
56	EC0084	75.35%	A
57	MC0014	75.97%	B
58	MC0005	76.57%	B
59	FM0051	77.14%	B
60	MC0009	77.69%	B
61	MC0006	78.24%	B
.	.	.	B
.	.	.	B
119	PP0004	94.83%	B
120	FP0027	95.19%	C
121	MC0020	95.36%	C
122	FR0125	95.54%	C
123	FM0036	95.72%	C
124	FM0035	95.90%	C
125	FM0034	96.07%	C
.	.	.	C
.	.	.	C
231	EC0079	100.00%	C

Table 4-2: ABC Classification based on Cumulative Annual Usage Value

Figure 4-3 below further reinforces and pictorial depicts the annual spending on different category of items for a demand of 180 printers. It was seen that maximum amount was spent on ‘A’ items (~75%) as compared to ‘B’ (~20%) or ‘C’ (~5%) and hence priority had to be given to ‘A’ items over ‘B’ and over ‘C’. This grouping of SKUs helps inventory managers to focus and have robust ordering mechanisms for ‘A’ items since they are expensive and account for a large portion of a company’s spending as compared to ‘B’ or ‘C’ items which are relatively less expensive and hence less stringent checks have to be put in place for them. This classification is very useful especially for startups like NVBOTS that have to deal with hundreds of SKUs and lack a sophisticated ERP system or dedicated inventory personnel. It is important to note that the numbers in the graph below are scaled appropriately in order to conceal the true spending of NVBOTS.

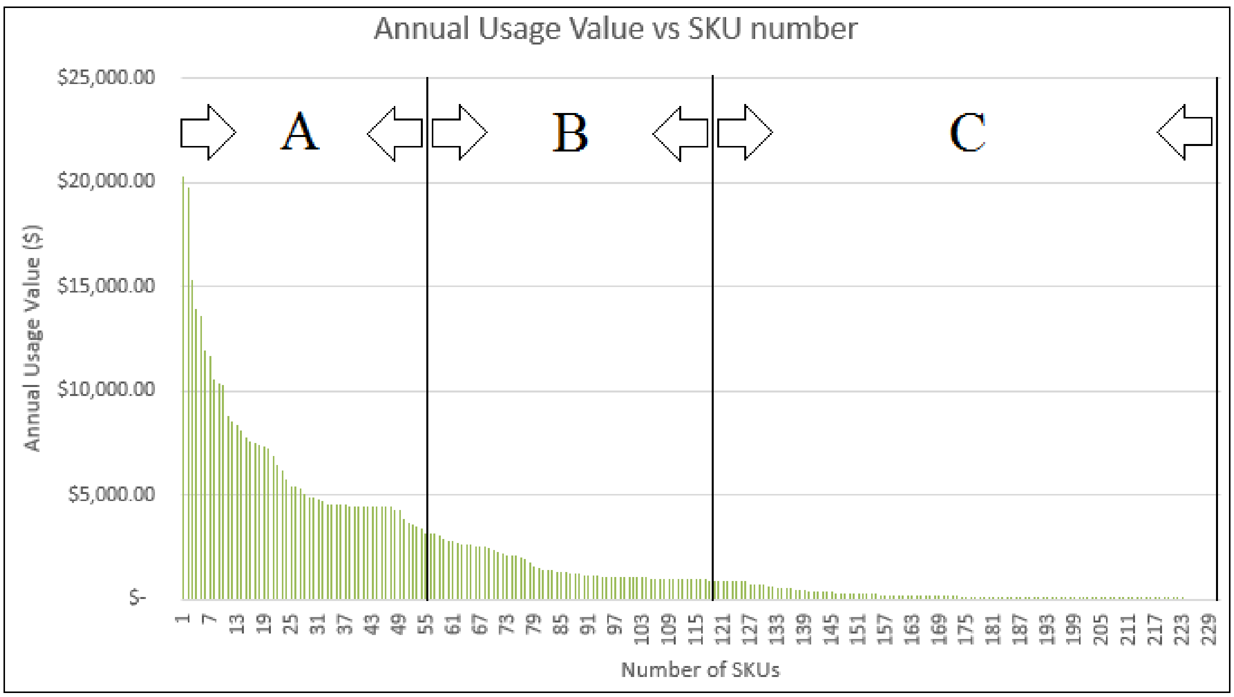

Figure 4-3: A graph of Annual Usage Value vs Number of SKUs

4.5 Summary

In conclusion, all inventory in a firm aren’t the same and hence cannot be treated the same way. Some inventory are more valuable than others. Hence, it is required to categorize inventory in order to save both man-hours spent in ordering parts and also the total cost spent in acquiring the necessary inventory.

Raw-material inventory at NVBOTS was classified into specific groups so as help manage them better. This classification will assist NVBOTS to employ better storage facilities and ordering strategies based on the type and importance of the parts, so as to optimize total costs. Figure 4-4 below summarizes this classification.

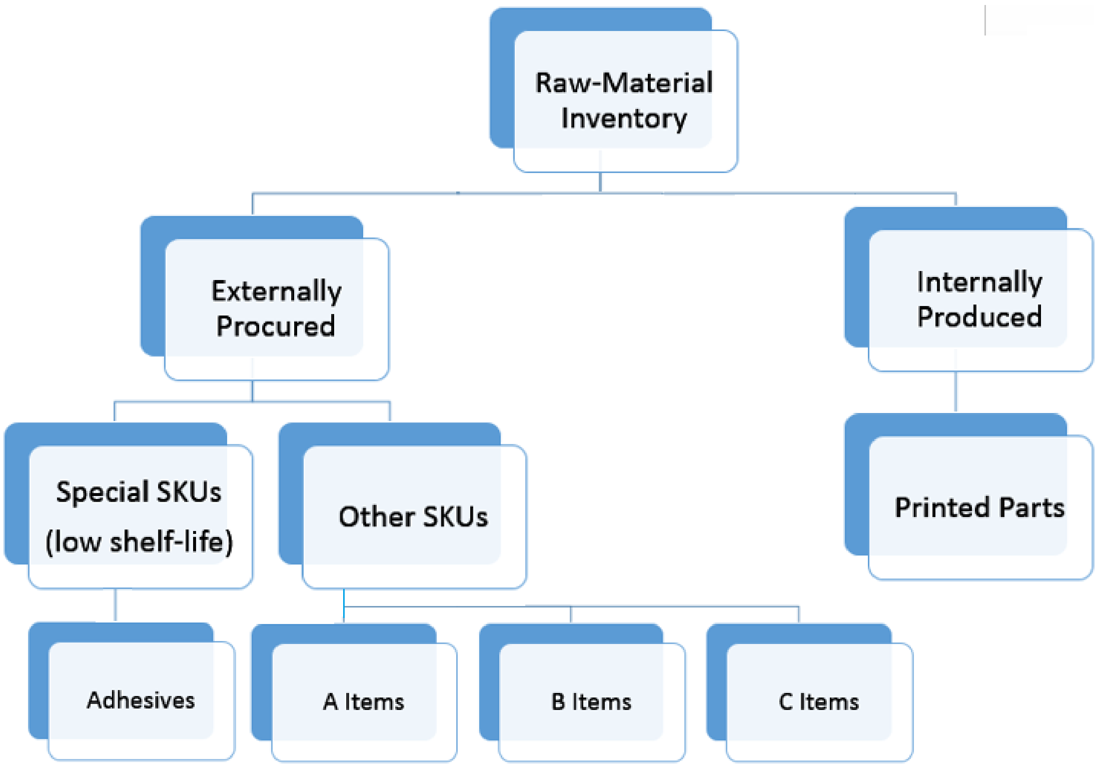

Figure 4-4: Summary of SKU Classification at NVBOTS

Chapter 5
Inventory Management: Literature Review

5.1 Overview

Inventory management is a broad term encompassing the process of planning, organizing and controlling inventory, simultaneously minimizing investment while balancing demand and supply [31]. It includes activities pertaining to tracking of inventory, storage, deciding on the order quantity and timing of ordering.

Inventory management is very crucial to any manufacturing organization, big or small [29]. All industries need to value inventory management and carry it out in the right manner, otherwise it has potential to destroy companies. It plays an important role in the day to day functioning of companies, if done correctly it can ensure efficient tracking of stock levels, reduce carrying costs and improve cash flows by ensuring availability of required parts [32].

The main reason for holding inventory is to smooth business and production processes by acting as a buffer in case of uncertain supply and demand [33]. Inventory Management helps in establishing the required stock levels for different SKU's based on their respective demands, determining when and how much to order, and ensuring that customers demand is satisfied while keeping costs relatively low.

It is also important to treat the SKU's as different entities and have a plan of action for each of them. There are many different inventory models that can be used based on the available data, type of SKU and the situation. Traditional methods include Periodic Review System & Continuous Review System [29] while modern methods pertain to Just-in-Time ordering and ordering based on MRP (Material Resource Planning).

5.2 Literature Review of Inventory Models

Considering that NVBOTS had neither any prior inventory management practice nor sufficient data, it made sense to use traditional inventory models rather than complicating things. It was more about establishing a reasonable starting point instead of trying to optimize. The following sections outline some of the inventory models that could be applied to the inventory categories at NVBOTS.

5.2.1 Economic Order Quantity (EOQ) Model

Economic Order Quantity model is one of the simplest and most widely used inventory models. It is essentially a trade-off between holding cost and ordering cost. A large order size reduces the number of orders thereby helps save on ordering cost but increases the locked up capital and hence the holding costs [34]. The aim of EOQ model is to determine the optimal order size that helps minimize the overall cost. Figure 5-1 below shows the how the order size influences the total cost.

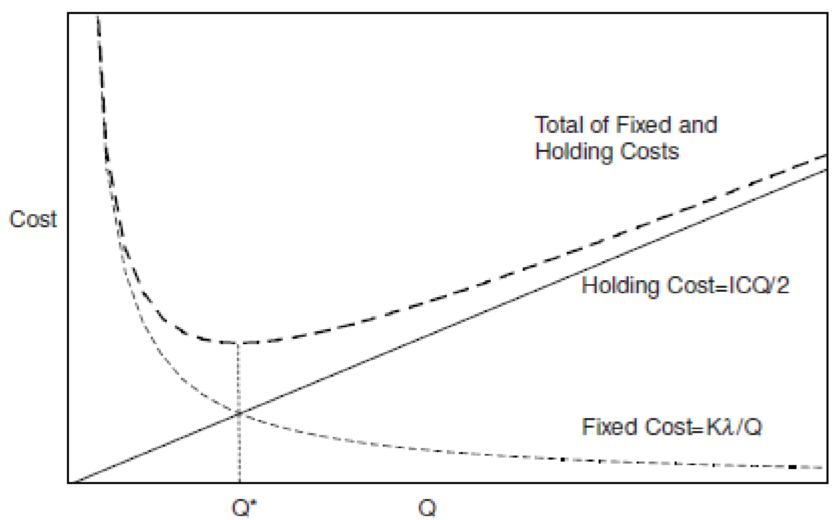

Figure 5-1: Fixed and Holding costs as a function of order quantity [35]

Like any other model, there are a lot of assumptions that are made in this model. Some on the assumptions include that demand and lead time is deterministic, material is instantaneously received, there are no quantity discounts and no stockout costs. The assumption related to instantaneous delivery can be fixed by appropriately determining reorder point so as to account for the lead time demand. The reorder point may also include additional safety stock. Figure 5-2 below shows the EOQ – ROP policy and the equations that follow are based on sources [29] & [36].

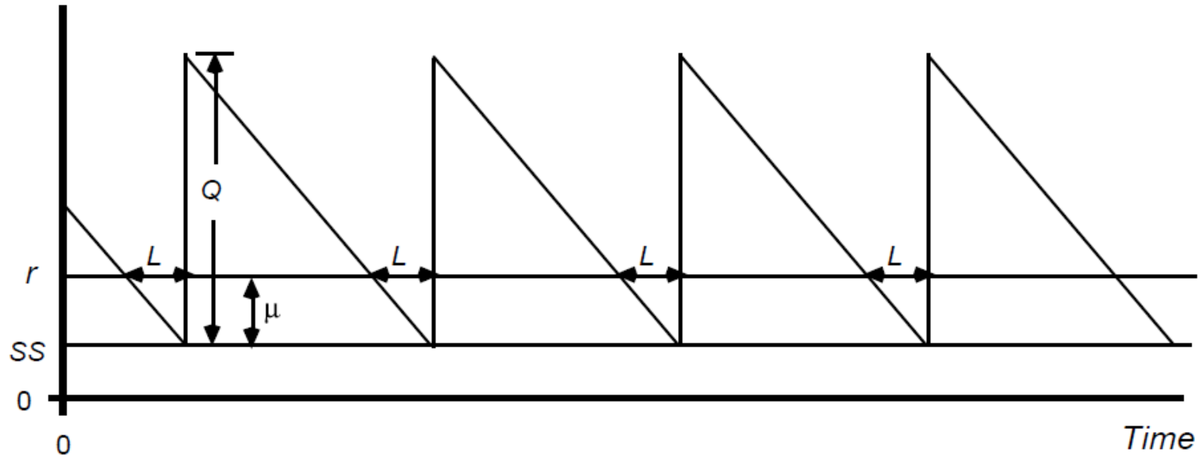

Figure 5-2: EOQ-ROP policy, where L is Lead Time, r is Reorder Point, SS is safety stock [37]

- **Inputs to the model**
  - For EOQ:
    - D = Annual demand (units/year)
    - K = Ordering cost ($)
    - h = Annual holding cost/unit ($/unit/year)
    - P = unit price ($/unit)
  - For ROP:
    - μ_{LT}= Average demand during lead time (units)
    - SS = Safety stock (units)
    - z = Service level
    - LT = Lead time (days)

      μ_d= Demand during lead time (units)
    - σ_d= Standard deviation of demand during lead time (units/day)
    - σ_{LT}= Standard deviation of lead time (days)
- **Outputs from the model**
    - Q^* = Optimal order quantity (units)
    - TC = Total cost ($)
    - ROP = Re order point (units)

- **Equations**
  - $h = 15\% * P$ (5-1)
  - $Q^* = \sqrt{\frac{2*D*K}{h}}$ (5-2)
  - $TC = Parts + Ordering + Holding\ costs = P * D + \frac{D*K}{Q^*} + h * \left(SS + \frac{Q^*}{2}\right)$ (5-3)
  - $ROP = \mu_{LT} + SS = \frac{LT}{365} * D + z * \sqrt{LT * \sigma_d^2 + \mu_d^2 * \sigma_{LT}^2}$ (5-4)

5.2.2 Economic Production Quantity (EPQ) Model

This model is a variation of the EOQ model used when an order for parts is not placed with an external supplier but rather is produced from within the plant. EPQ determines the optimal lot size in which parts need to be produced based on the trade-off between setup costs and holding costs [38]. EPQ model is more useful when a company has a longer planning horizon with repetitive rotational schedule. It provides an intuitive way of calculating the lot size and sequence in order to optimize total cost.

When a company is producing parts, a lot of information pertaining to the demand rate, processing times, setup costs are needed. This information is captured more comprehensively in an EPQ model as opposed to an EOQ model. The EPQ model as described by Pinedo [38], can be used for a single machine producing a particular type of part. When there are multiple part types that are produced on a single machine, then it gets more complicated. The following equations assist is calculating the optimal lot size and cycle length (period during which the optimal lot size for each part is produced on the machine plus any idle time) as indicated in [38].

- **Inputs to the model**
  - D_j = Demand rate for part j (units/day)
  - P_j = Production rate (reciprocal of processing time) for part j (units/day)
  - h_j = Holding cost ($/day/part)
  - n = Number of types of parts produced on a given machine
  - c_j = Setup cost for part j ($) (sequence independent)
  - U = Unit price ($/unit)

- **Outputs from the model**
  - Q_i = Lot size for part i (units)
  - CL = Cycle Length (days)
- **Equations**
  - $\sum_{j=1}^{n} \frac{D_j}{P_j} \leq 1$ (Feasibility Check) (5-5)
  - $CL = \sqrt{(\sum_{j=1}^{n}((h_j * D_j * (P_j - D_j))/(2 * P_j))^{-1} * \sum_{j=1}^{n} c_j}$ (5-6)
  - $Q_i = D_i * \sqrt{(\sum_{j=1}^{n}((h_j * D_j * (P_j - D_j))/(2 * P_j))^{-1} * \sum_{j=1}^{n} c_j}$ (5-7)
  - $Idle\ Time = CL * \left(1 - \sum_{j=1}^{n} \frac{D_j}{P_j}\right)$ (5-8)

Figure 5-3 shows an example of EPQ scheduling for a machine which makes 4 different types of items. Once Item 1 has been produced, then Item 2 is processed on the machine and so on, until the determined lot size is produced. After reaching the lot size for each item, the inventory level will decrease due to the arriving demand and when the inventory level of Item 1 reaches zero, a new cycle will begin.

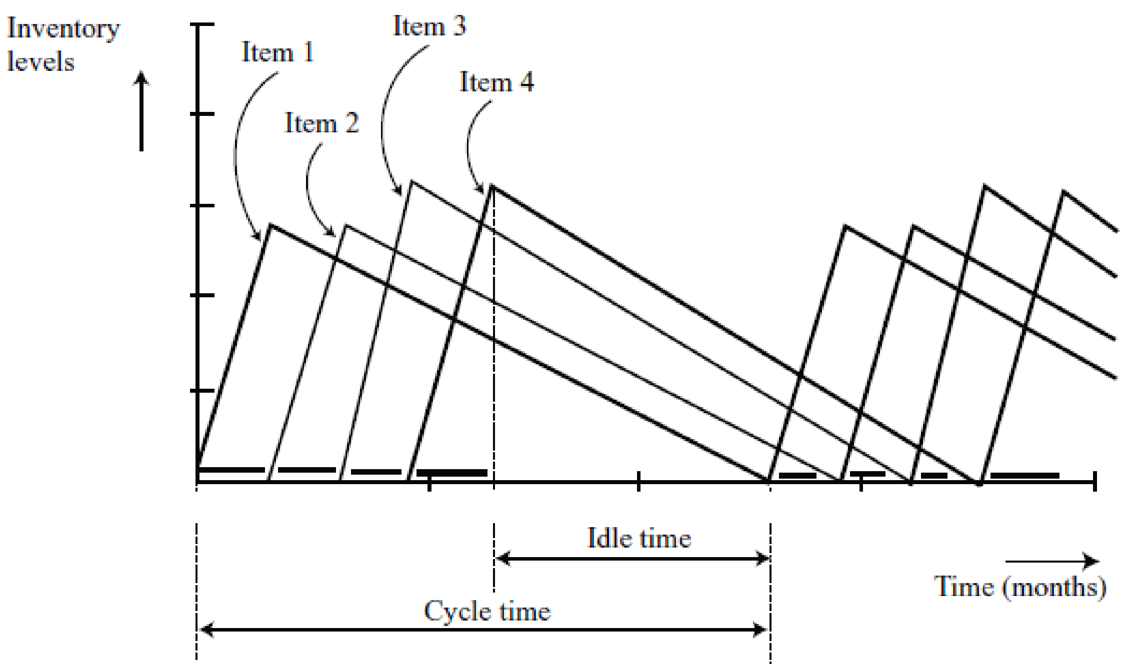

Figure 5-3: Rotation Schedule EPQ model example [38]

5.2.3 QR Model

The QR model also known as (s,Q) policy is an extension of the EOQ model used when the demand is stochastic [37], where Q is the order size and R is the reorder point. The model assumes that inventory is monitored constantly and hence it is a continuous inventory review system [37]. Figure 5-4 illustrates the working of a QR model, where an order is triggered when the inventory level reaches the reorder point and it takes lead time for the predetermined order size to arrive.

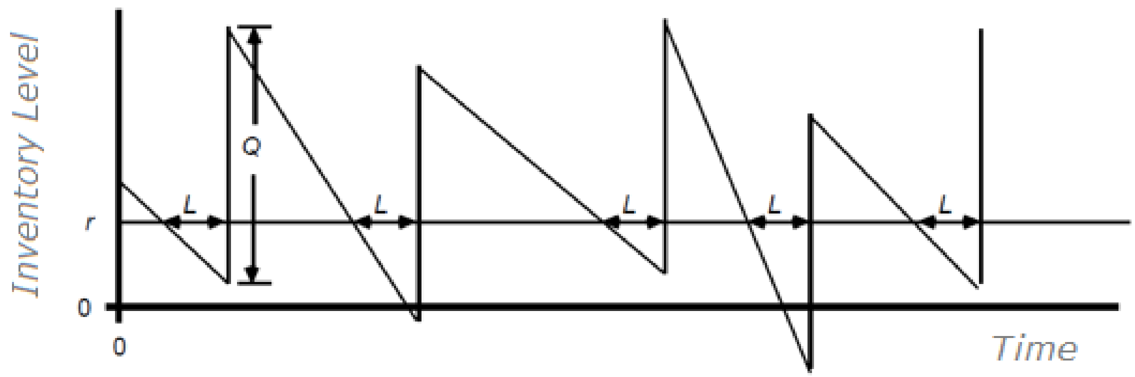

Figure 5-4: Illustrates the working of a QR model, where L is lead time, r is reorder point, Q is order size [37]

In the QR model, in addition to inventory holding and ordering costs, stockout costs are also considered. Thus, it is a trade-off between holding cost, ordering cost and stockout cost, so as to minimize the total cost. Most assumptions stated while describing EOQ model hold true except those pertaining to deterministic demand and instant receipt of goods.

In the QR model, a request for an order is triggered when the inventory falls to a predetermined level known as the reorder point. The reorder point accounts for the demand during lead time and also additional some safety stock. When the stock levels reaches reorder point R, an order for Q^*(optimal order quantity) is placed. The equations and the algorithm to be followed in order to run this model are described in [37] & [39], as shown below. It is important to note that the following equations are valid only if the demand is normally distributed.

- **Inputs to the model**
    - D = Annual demand (units/year)
    - SD = Standard deviation of annual demand (units/year)

- K = Ordering cost ($)
- h = Annual holding cost/unit ($/unit/year)
- P = Unit price ($/unit)
- s = Stockout cost/unit ($/unit)
- LT = Lead Time (days)
- z = Service level
- F(R) = Fill Rate
- n(R) = Expected shortage per cycle (units)
- L(z) = Loss function
- μ = Demand during lead time (units)
- σ = Standard deviation during lead time (units)
- SS = Safety Stock (units)

➢ **Outputs from the model**

- Q = Order quantity (units)
- R = Re order point (units)
- TC = Total cost ($)

➢ **Equations**

- $Q = \sqrt{\frac{2*D*(K+s*n(R))}{h}}$ (5-9)
- $\mu = \frac{D}{365} * LT$ (5-10)
- $\sigma = \sqrt{\frac{SD*SD}{365} * LT}$ (5-11)
- $R = Z * \sigma + \mu$ (5-12)
- $n(R) = \sigma * L(z)$ (5-13)
- $F(R) = 1 - \left[\frac{Q*h}{s*D}\right]$ (5-14)
- $z = NORMSINV\ [F(R)]$ (5-15)
- $L(z) = \frac{1}{\sqrt{2*3.14}} * \exp(-0.5 * z * z) - z * (1 - NORMDIST(z))$ (5-16)
- $SS = R - \mu$ (5-17)
- $TC = Cost\ of\ components + Ordering\ Cost + Holding\ Cost + Stockout\ Cost$

  $TC = P * D + \frac{D*K}{Q^*} + h * \left(SS + \frac{Q^*}{2}\right) + s * n(R) * \frac{d}{Q}$ (5-18)

- **Algorithm for running the model**
  1. Determine Q_0 using EOQ formula.
  2. Find F (R_1) & z values.
  3. Determine R_1 & n (R_1).
  4. Find Q_1.
  5. Repeat steps 2-4 for Q_2, Q_3 …., until $R_n = R_{n-1}$.

5.2.4 Base Stock Inventory Model

Base stock policy is a type of periodic review inventory model, where orders for replenishment are made at specific intervals of time [40]. The interval of time that elapses before an inventory evaluation occurs is referred to as the review period. The order placed during the review keeps changing from time to time based on the consumption since the previous review period [40]. The only decisions to be made are with regards to the length of the review period and the initial base amount to be put into the system, which is based on the nature of demand and supplier lead times.

This model assumes that there is no ordering cost and that any number of orders can be placed with a supplier during a year. Also, base stock model accounts for the demand during the replenishment lead time and tops up the inventory level to the maximum pre-determined amount after every order. The following equations are based on [40] & [41] and hold true when the demand is normally distributed.

- **Inputs to the model**
  - r = Review period (days)
  - LT = Lead time (days)
  - z = Service level
  - μ = Mean annual demand (units)
  - σ = Standard deviation of demand (units)
  - P = Unit price ($/unit)
  - PI = Pipeline inventory (units)
  - CS = Cycle stock (units)
  - h = Annual holding cost/unit ($/unit/year)

- **Outputs from the model**
  - SS = Safety Stock (units)
  - B = Maximum inventory level (units)
  - TC = Total cost ($)
- **Equations**
  - $CS = \frac{r}{365} * \frac{\mu}{2}$ (5-19)
  - $PI = \frac{LT}{365} * \mu$ (5-20)
  - $SS = z * \sigma * \sqrt{\frac{r+LT}{365}}$ (5-21)

    If standard deviation for lead time is known then the equation shown below can be used to determine safety stock instead of equation (5-21).

    $SS = z * \sqrt{LT * \sigma_d^2 + \mu_d^2 * \sigma_{LT}^2}$, where σ_{LT}^2 is the standard deviation of lead time, σ_d and μ_d is the lead time standard deviation and mean demand.
  - $B = \frac{r+LT}{365} * \mu + SS$ (5-22)
  - $TC = Holding\ Cost + Cost\ of\ components = (CS + PI + SS) * h + P * \mu$ (5-23)

The behaviour of the base stock model is depicted in Figure 5-5, shown below. At periodic intervals in time, orders are placed so as to ensure that when they arrive, the inventory level reaches the base stock. Usually, the replenishment leads to an inventory level slightly above or below the base stock level, since the demand is not deterministic but rather normally distributed.

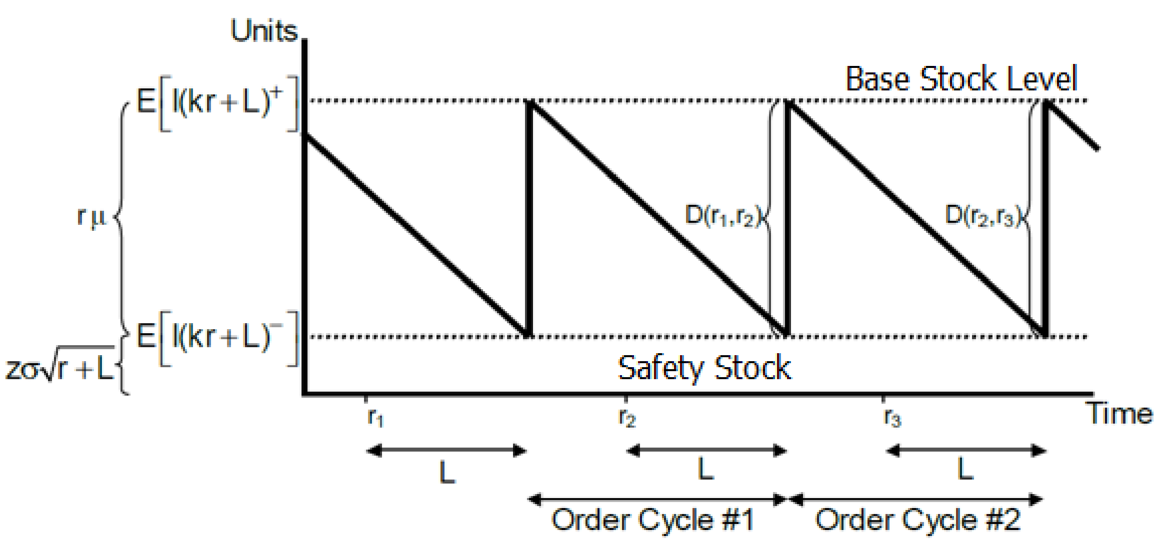

Figure 5-5: Expected behaviour of base stock policy [40]

Chapter 6

Inventory Management: Methodology & Results

6.1 Data Collection

In order to test the models in Chapter 5 for the various categories of raw-material inventory at NVBOTS, it was necessary to collect some data. Considering that NVBOTS didn't have any organized database with information on demand, ordering patterns, supplier lead times, unit price of parts, et cetera, it was vital to collect this data and establish a framework so as to ensure future data collection. The following paragraphs explain how the data required in order to run the inventory models was collected.

6.1.1 General Data

Annual Demand Data:

NVBOTS did not have information with regards to its past sales and even if they did, that data would be irrelevant considering the small number of 3D printers they had sold. NVBOTS did not have any official forecasts, but the sales team expected the demand for their 3D printers to grow rapidly. The demand could be either from external customers looking to buy the latest version of NVPro printer or from the development team within NVBOTS or from external customers wanting to upgrade their older versions of the 3D printer. After speaking with the sales team and the Director of Operations at NVBOTS, the consolidated expected mean demand and standard deviation for the year was as shown in Table 6-1. It is also important to note that the demand for the SKUs are dependent on the demand for the printers but due to the lack of master production schedule and data on processing rate of subassemblies, an MRP approach could not be used.

Product	Annual Demand	
	Mean	Std. Dev.
NVPro 3D Printer	180	18
Encoder Subassembly	40	4
Hot-End Subassembly	500	150
Extruder Cable Harness	40	4

Table 6-1: Annual Demand Data

Service Level:

NVBOTS had a total of 231 raw-material SKUs that were used to assembly the NVPro 3D printer. Hence, all the parts were equally important in terms of their availability for production purposes and so NVBOTS decided on a 95% service level for all raw-material SKUs.

Annual Holding Cost %:

Holding cost includes cost of capital, insurance, obsolescence, depreciation, taxes, storage and handling costs. It is usually expressed as a percentage and is in the range of 15-35%, depending on the type of industry. The following formulae [42] were used find a ball-park estimate of the holding cost %.

$$Inventory\ Carrying\ Cost\ (\%) = \frac{Cost\ of\ owning\ Inventory\ per\ year\ (\$)}{Inventory\ Value\ (\$)} \tag{6-1}$$

$$Cost\ of\ owning\ Inventory/yr = Capital + Service + Storage + Risk\ costs \tag{6-2}$$

The capital cost is the return possible if the money was invested elsewhere. Assuming an annual return of about 4% on capital, for an inventory value of $50,000, the capital cost would be $2000. The service cost which includes insurance, tax and physical handling costs can be approximated as 5% of the inventory value, giving us $2,500. The storage cost is the cost of space, which in the case of NVBOTS is about $300 per month for the inventory room, so the annual storage cost is about $3,600. The obsolescence and depreciation can be assumed to be about 5% of the inventory value yielding $2,500. Therefore, the total cost of owning inventory using equation (5-25) is about $10,600. Using equation (5-24), the inventory carrying cost % is about 21%. However, NVBOTS recommended using an annual holding cost of 15% for running the inventory models. In order to find the holding cost for each part, 15% of its unit price is used.

Supplier Lead Time:

Supplier lead time information is one of the most important data when it comes to inventory management. NVBOTS hadn't collected any information with regards to lead time. Without this information it would be very difficult to determine how much and when to order. In order to find the supplier lead time, a manual scan of the purchase orders yielded the ordering date and the packaging slips indicated the delivery date. The time from ordering to delivery of the product was considered as lead time and used for further analysis. This was a very tedious process considering that there were 231 SKUs spread across 75 vendors, whose purchasing and delivery information had to be looked at in order to find the lead time. Now that we have collected this information, it would be very easy in the future for NVBOTS to update this and estimate standard deviation of lead time. This information will help NVBOTS to identify risky suppliers and to tailor ordering strategies accordingly.

Unit Price of the SKUs:

Though the unit price of components was well known by NVBOTS, there was no particular document that included the price of all SKUs. The bill of materials cost of all parts used to assemble the printer was unknown as well. In order to obtain this information, we glanced through the many excels sheets used by the firm and generated a document containing updated unit price information for each SKU.

There was no information with regards to the cost of the printed parts that were produced in-house. NVBOTS treated printed parts as "zero cost" components. However, this wasn't true. The following methodology was used in order to calculate the cost of the printed parts:

$$Cost\ of\ PP\ (\$) = Cost\ of\ Filament + Cost\ of\ Labour + Cost\ of\ Electricity \qquad (6\text{-}3)$$

Where,

$$Cost\ of\ Filament\ (\$) = Filament\ used\ (Kg) * Cost\ of\ Filament\ (\$/kg) \qquad (6\text{-}4)$$

$$Cost\ of\ Labour\ (\$) = Man\ hours\ spent\ (hrs) * Cost\ of\ labour\ per\ hour \qquad (6\text{-}5)$$

$$Cost\ of\ Electricity\ (\$) = Print\ Time\ (hr) * Power\ Used\ (Kw) * Cost\ per\ Kwh \qquad (6\text{-}6)$$

Using the above methodology, the cost of printed parts was calculated. A sample set of the printed parts and their costs are shown in Table 6-2 below. Also, it is important to note that some approximations were made with respect to power consumed, man-hours spent and filament used.

Part Number	Printing Time (hrs)	Power Consumed (Kw)	Cost ($/Kwh)	Total Cost of Electricity ($)	Filament Used (g)	Cost of Filament ($/Kg)	Total Cost of Filament ($)	Man-Hours Spent (min)	Cost of labor ($/hr)	Total Cost of Labor ($)	Overall Printed Part Cost ($)
PP0004	0.28	0.20	0.20	0.01	3.02	20	0.06	12	25	5.00	5.07
PP0040	2.80	0.20	0.20	0.11	67.77	20	1.36	24	25	10.00	11.47
PP0041	3.88	0.20	0.20	0.16	70.01	20	1.40	28	25	11.67	13.22
PP0043	7.55	0.20	0.20	0.30	151.76	20	3.04	22	25	9.17	12.50
PP0044	2.86	0.20	0.20	0.11	37.43	20	0.75	12	25	5.00	5.86
PP0050	2.25	0.20	0.20	0.09	34.71	20	0.69	12	25	5.00	5.78
PP0054	2.36	0.20	0.20	0.09	43.70	20	0.87	12	25	5.00	5.97
PP0055	1.17	0.20	0.20	0.05	22.20	20	0.44	12	25	5.00	5.49
PP0057	1.11	0.20	0.20	0.04	13.73	20	0.27	12	25	5.00	5.32

Table 6-2: Printed Parts cost calculation

6.1.2 Data Specific to EPQ Model

Demand Rate:

EPQ model is well suited for parts that are produced within the firm, i.e. printed parts in case of NVBOTS. As mentioned earlier, the annual demand for NVPro printers was about 180. In order to make 180 printers, 180 of each type of printed part was required. However, there was high percentage of defective printed parts produced. On speaking with the production team, this defect rate was found to be as high as 25%. In order to account for this, the production needed to be 25% higher than the given demand, which translated to about 240 units. Assuming a 5 day working week, this demand translated to about 1 printed part per day. Therefore, the demand rate for each type of printed part was 1 printed part per day.

Production Rate:

NVBOTS had an organized database with information on the time required to print each of the PPs. The printing times were analyzed and it was seen for a given printed part, filament batch, slicer configuration and a given production printer, the time required to print was fairly consistent. The histogram in Figure 6-1 shows many instances of printing times for the part PP0042.

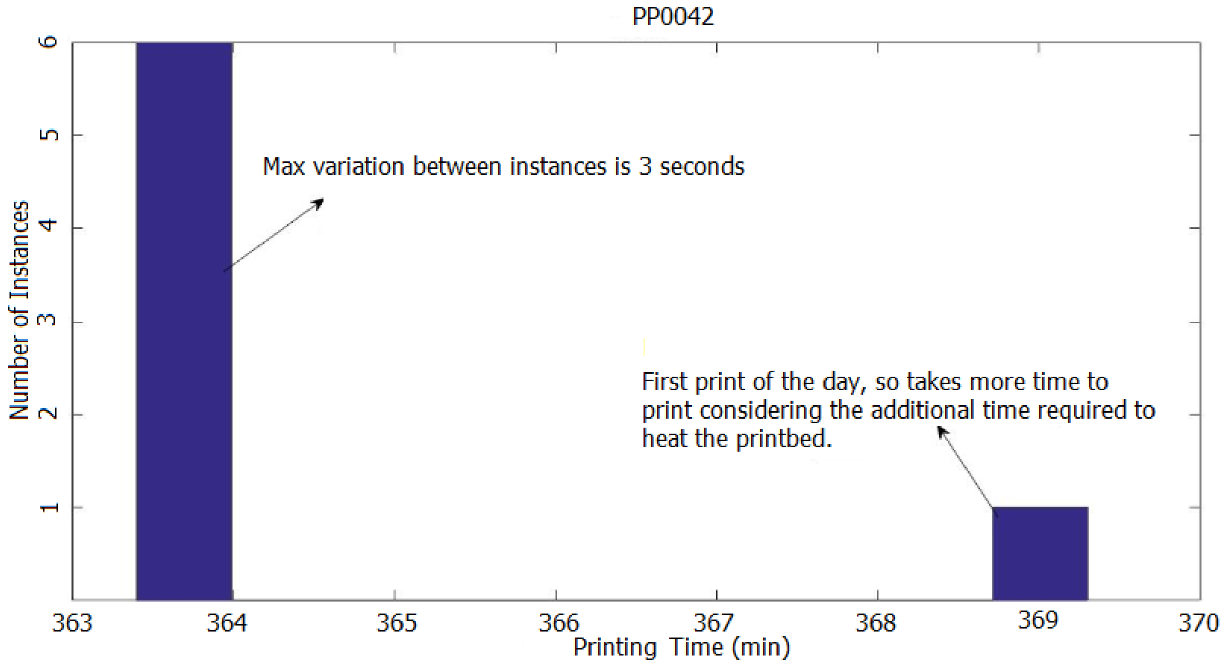

Figure 6-1: Histogram depicting printing time for PP0042

It can be seen from the graph that the printing time for PP0042 is around 364 minutes, with a maximum variation of 3 seconds between the 6 instances. There also appears to be an outlier on the histogram. This is the first print of the day on the printer and it takes more time since it includes the time to heat printbed to the required level. Once the printbed is at the required temperature, it takes about 364 minutes to print the part and hence this time was considered as the printing time for PP0042. Similar analysis was done for the other parts and the printing time was obtained for each PP.

The production rate could be calculated by taking the reciprocal of the printing time for each type of printed part and multiplying that with the number of hours of operation in a day. At NVBOTS, the number of hours of processing print jobs was about 16 hours. The formula to find production rate is as shown below.

$$Production\ Rate\ (units/day) = \left(\frac{1}{Printing\ Time\ hrs}\right) * Production\ hours\ in\ a\ day \quad (6\text{-}7)$$

Annual Holding Costs:

As mentioned earlier, the annual holding cost is about 15% of the unit price of the part. However, in case of EPQ model this 15% will not only be on the cost of the part but also on the cost of the equipment used to makes those parts. In case of NVBOTS they use 4 NVPro 3D printers to make the printed parts. Hence, the annual holding cost should also include 15% of the cost price of the NVPro printers.

Setup Costs:

The setup costs basically involve the costs of preparing the machine to process a different type of part. In case of 3D printers, this can be approximated as the cost to ensure that the printbed is heated enough to start printing and the cost of labour to send print jobs, monitor jobs, install new spools of filament and then remove the printed parts from the 3D printer so as to make space for the next set of parts.

At NVBOTS, the setup time was assumed to be the same for each type of printed part. The setup time was approximated as 12 minutes, which translated to a setup cost of about $5. This setup cost is only an approximation used for the purpose of finding lot sizes by using the Economic Production Quantity model.

6.1.3 Data Specific to Base Stock Model

Review Period:

The review period is the time between two successive inventory quantity evaluations. It is usually determined by a firm. It is usually expressed in days. The review period can change from one SKU to another and from one vendor to another. In case of NVBOTS, the review period for each vendor was decided by the Director of Operations. The review period is chosen such that it is small for more expensive items and large for cheaper items. Table 6-3 below shows a sample set for parts and their respective review periods.

Part Number	Part Category (A-B-C)	Review Period (Total Days)
EC0018	A	20
FM0001	A	10
EC0081	B	20
FI0001	B	20
FM0029	B	20
FI0007	C	60
FP0017	C	60
FR0004	C	60

Table 6-3: A sample list of parts and their review periods

6.1.4 Data Specific to QR Model

Ordering Cost:

It is the cost associated with placing each order. It usually includes order checking, telephone, labour and transport costs associated with each order. In case of NVBOTS, the Director of Operations suggested the using $5 for each order placed with vendors over the phone and $2 for orders placed on the internet.

Stockout Costs:

It is the cost associated with stopping production due to lack of parts, loss of customer goodwill and future sales. For the purpose of use in the QR model, the stockout cost was approximated as the product of unit price and lead time, but capped to a maximum of $10. There was no specific reason for capping it to $10. It was considered to be a reasonable estimate.

6.2 Inventory Management: For Printed Parts (PP)

Among the categories of raw-material inventory, printed parts were the only part type that feature under "internally produced" category at NVBOTS. Unlike other inventory models that were useful for procuring parts from external suppliers, Economic Production Quantity and Economic Lot Sizing models were well suited for scheduling internal work. These models help determine the lot sizes according to which parts must be produced. It is essentially a trade-off between holding costs and setup costs. Considering PPs are produced in-house, it makes sense to use EPQ model to determine the lot sizes. At the same time, EPQ helps in deciding the number of production printers required to meet the demand for printed parts.

At NVBOTS, printed part production was not scheduled and the lot sizes were random. Each type of printed part was produced in different lot sizes and there was no methodology behind the lot sizing. Also, the lot sizes kept changing from cycle to cycle and the production printers were not assigned to any particular part type. It is important to note that NVBOTS wished to push the utilization of the printers to 65%. This was due to the fact that the printers often stopped working, had software issues and produced defective pieces. By working with a utilization of about 65%, NVBOTS would have enough idle capacity on hand to make up for any lost production time and still be able to meet the demand.

6.2.1 Application of EPQ Model to PPs

Once the required data for the model were collected, an excel sheet was setup in order to run the EPQ model as described in Section 5.2.2. The summation of the ratios of demand and production rate for all PPs was calculated and it was seen that $\sum_{j=1}^{n} \frac{D_j}{P_j}$ was equal to 3.47. The EPQ model for a single machine can be used only if $\sum_{j=1}^{n} \frac{D_j}{P_j} \leq 1$. Therefore, in order to accommodate all the printed parts, NVBOTS needed atleast 4 production printers so as to ensure that $\sum_{j=1}^{n} \frac{D_j}{P_j} \leq 1$ for each of the printers. However, NVBOTS did not want the utilization of any printer to be above 65%. The number of printers needed to achieve this rate of utilization could be calculated from the formula below.

$$No.of\ machines\ required = \frac{\sum_{j=1}^{n} \frac{D_j}{P_j}}{Utlization} \quad (6\text{-}8)$$

It was seen that 6 productions printers were required in order to meet the demand needs of NVBOTS, with a utilization of utmost 65% for each printer.

The next step was to determine how to allocate the 20 printed parts to the 6 production printers. This was done by allotting printed parts based on the subassembly they featured in, ensuring that $\sum_{j=1}^{n} \frac{D_j}{P_j}$ for given production printer did not exceed 1. For example, printed parts used in the removal subassembly, removal support and removal motor mount, were both assigned to the same production printer.

Table 6-4 shows the application of EPQ model to one of the production printers at NVBOTS. The lot sizes for each printed part and the cycle length for the printer were calculated based on the formulae described in Section 5.2.2 and are as shown in the table below.

Part Number	Production Rate Pj (parts/day)	Demand Rate Dj (parts/day)	Dj/Pj	Holding Cost ($/day/part)	Setup Cost ($)	Cycle Length (days)	Lot Size (parts)
PP0038	38.10	1.00	0.026	0.347	5.00	5.663	6
PP0047	10.67	1.00	0.094	0.347	5.00	5.663	6
PP0053	19.05	1.00	0.053	0.347	5.00	5.663	6
PP0044	5.59	1.00	0.179	0.348	5.00	5.663	6
PP0046	6.15	1.00	0.163	0.348	5.00	5.663	6
	Total Dj/Pj =		**0.514**				

Table 6-4: EPQ model applied to a production printer at NVBOTS

The model yielded a lot size of 6 for each of the above mentioned printed parts, considering the demand rate was the same for all of them. The cycle length was about 5.7 days. It means that every 5.7 days, the given printer will produce a batch of 6 parts for each of the above shown SKUs (PP0038, PP0047, PP0053, PP0044 and PP0046). The printed parts can be produced in any order but once a particular printed part is selected, the entire lot size is produced before moving onto the next SKU. A similar methodology was applied to determine the lot sizes for the other 15 PPs that were scheduled to be printed across 5 production printers.

It is important to keep in mind that Pinedo's EPQ model is not perfect. It does not take into account raw material usage and hence doesn't optimize for filament in case of NVBOTS. Also, Pinedo's model is applicable to a single machine and hence cannot be used to optimize across several machines. Pinedo model assumes the demand to be constant and deterministic, and so it is well suited for make-to-stock environments. In spite of these constraints, EPQ model provides a reasonable estimate of lot sizes and cycle length so as to minimize the holding and setup costs.

Currently NVBOTS operated with 4 production printers. In order to meet the demand forecasted, NVBOTS needed to add atleast 2 production printers (so as to operate with a utilization of less than 65%). Even with 4 printers they might be able to meet demand but this would mean a high utilization of about 90% which is very hard to achieve considering the frequent problems, quality issues and stoppages in production.

In addition to informing NVBOTS about the requirement for more production printers, the EPQ model helped in providing a starting point with respect to lot sizing. A lot size of 6 suggested by the EPQ model for the above PPs seemed reasonable considering that production of NVPro printers also occurred in batches of 6 and the cycle length more or less coincided with a working week at NVBOTS. Also, there is no need for any safety stock since the parts produced are considered to be available immediately. However, if needed certain amount of safety stock can be kept on hand in order to account for production stoppages. This can be calculated using second half of equation (5-4), where lead time can be substituted with expected machine downtime (in days).

It is important to note that the data for setup costs and holding costs used in the EPQ model are approximations and so there is a possibility for the batch size to be slightly different. However, the main purpose was to move away from ad-hoc scheduling to a more structured way of determining lot sizes, which EPQ model helped in.

6.3 Inventory Management: For Adhesives (AD)

Adhesives (AD) are another category of raw-material inventory at NVBOTS. They have low shelf-life compared to other SKUs and hence are treated as a separate category. Unlike the other SKUs, adhesives could be treated as consumables. The annual demand and spending on these ADs were relatively low, however it was important to plan their purchasing in order to prevent wastage due to expiration of ADs.

Common inventory models like EOQ, QR and base stock policies might not be applicable as these models do not take shelf-life into account. Hence, the ordering strategy for adhesives must be based on their shelf life and so it was important to track the shelf-life of such components.

Table 6-5 below shows a sample template that can be used to track expiration dates of products. Excel sheet can be setup to colour code SKUs that are about to expiry and need reordering.

Part Number	Annual Demand (bottles)	Lead Time (Days)	Expiry Date
AD0001	2	5	9/31/2016
AD0007	4	5	12/1/2016
AD0010	4	5	12/1/2016
AD0014	4	5	8/14/2016
AD0022	9	5	2/31/2017

Table 6-5: Shelf-Life Tracking Template

It was recommended to NVBOTS to use spot-order methodology for ordering adhesives i.e. orders should be placed a week prior (to account for lead time) to when the product expires and the excel sheet should trigger that order by color-coding the SKU that needs reordering, instead of having safety stock on-hand. In cases where the adhesive was expected to be consumed within the expiry date, it was decided that the production team must inform the purchasing team a week in advance. However, on speaking with the production team we learnt that consumption of an entire bottle prior to expiration was a rarity. Spot-ordering ADs will help track shelf-life and ensure NVBOTS does not have excess inventory that would otherwise result in wastage due to expiration.

6.4 Inventory Management: For Other SKUs

The other SKUs refer to the raw-material inventory that were categorized as A, B and C items. In order to decide the ordering strategy for these items, QR and base stock inventory models were considered. The QR model is a continuous review inventory model. The QR model like the EOQ model, takes into account ordering costs and holding costs in addition to stockout costs. Essentially, it is a trade-off between the three costs where a predetermined order Q is placed when the inventory level drops to R. On the other hand, base stock policy is a periodic review model where orders are placed at predetermined intervals of time. The order quantity for each order is different and aims at replenishing the stock level to the initial decided base stock level.

All the data required to run the two models were collected as explained in Section 6.1. Once the data were collected, an excel sheet was setup with formulae of both QR and base stock models, as mentioned in Section 5.2. Both models were then applied to all the SKUs. The results were studied and a decision regarding the ordering strategies for each category was then made.

Table 6-6 below shows the demand, lead time and unit price of 18 SKUs that were considered for analysis by the two models. It is important to note that the model was applied to all SKUs, but only 18 SKUs are depicted in the table below for the sake of simplicity.

Part Number	Part Category (A-B-C)	Annual Demand (units)		Lead Time (Days)	Unit Cost ($/unit)
		Mean	Std. Dev.		
EC0076	A	180	18	11	34.30
FM0002	A	180	18	21	24.80
FP0006	A	180	18	20	19.54
MC0001	A	180	18	5	25.00
MT0003	A	180	18	10	19.15
SA0032	A	680	168	5	32.00
CB0002	B	180	18	9	5.54
FI0001	B	180	18	10	7.61
FM0019	B	180	18	10	14.75
FP0010	B	180	18	20	8.45
JP0001	B	180	18	9	5.50
MC0003	B	360	36	7	5.94
EC0011	C	180	18	5	1.48
FI0002	C	180	18	5	2.00
FM0034	C	680	168	5	5.00
FP0014	C	180	18	2	0.50
FR0031	C	1440	144	5	0.17
MC0004	C	360	36	7	0.74

Table 6-6: Demand, Lead Time and Unit Price information for 18 SKUs

6.4.1 Application of the QR model to A, B and C items

Table 6-7 shows the application of QR model to the selected 18 SKUs. The order size Q obtained would help in deciding order quantity while the reorder point R determines when an order needs to be placed. Though it might not be practical to apply the QR model to all of A, B and C categories, it is worthwhile to study the overall costs, average inventory units and locked-up capital needed to employ such an ordering strategy. Hence, the excel sheet ran the model to all SKUs in order to facilitate comparison with Base stock model for the respective SKUs. The results shown in the table below are based on the formulae mentioned in Section 5.2.3.

Part Number	Part Category (A-B-C)	Ordering Cost ($/order)	Stockout Cost ($/unit)	Order Quantity (units)	ROP (units)	Average Inventory (Units)	Annual Holding Cost ($)	# of orders/ year	Total Ordering Cost ($)	Total Stockout Cost ($)	Total Cost of QR Model ($)
EC0076	**A**	5	10	20.39	13.79	16.11	82.87	8.83	44.14	8.31	6309.32
FM0002	**A**	5	10	24.26	23.26	20.61	76.66	7.42	37.10	8.03	4585.79
FP0006	**A**	5	10	26.91	22.30	21.96	64.38	6.69	33.45	5.98	3621.01
MC0001	**A**	5	10	22.97	7.60	15.63	58.63	7.84	39.18	3.88	4601.70
MT0003	**A**	5	10	26.51	12.97	19.33	55.53	6.79	33.95	4.13	3540.60
SA0032	**A**	5	10	47.89	55.54	66.46	319.01	14.2	71.00	43.93	22193.90
CB0002	**B**	5	10	47.77	12.48	30.45	25.31	3.77	18.84	1.01	1042.35
FI0001	**B**	5	10	41.07	13.74	27.38	31.25	4.38	21.91	1.53	1424.50
FM0019	**B**	5	10	29.96	13.20	21.28	47.09	6.01	30.04	3.11	2735.24
FP0010	**B**	5	10	39.65	23.32	29.35	37.20	4.54	22.70	2.43	1583.33
JP0001	**B**	5	10	47.94	12.48	30.54	25.20	3.75	18.77	1.00	1034.97
MC0003	**B**	2	10	42.28	23.60	34.90	31.09	8.51	17.03	1.81	2188.33
EC0011	**C**	5	7	90.94	8.84	50.86	11.29	1.98	9.90	0.20	287.79
FI0002	**C**	2	10	49.83	9.42	30.88	9.26	3.61	7.23	0.25	376.74
FM0034	**C**	5	10	103.56	65.95	104.71	78.53	6.57	32.83	6.01	3517.37
FP0014	**C**	2	1	98.64	4.36	52.21	3.92	1.82	3.65	0.05	97.61
FR0031	**C**	5	1	758.63	70.42	422.15	10.76	1.90	9.49	0.18	265.24
MC0004	**C**	5	5	182.14	23.57	104.79	11.63	1.98	9.88	0.23	288.14

Table 6-7: Results of QR model applied to A-B-C categories

6.4.2 Application of Base Stock Inventory Policy to A, B and C items

Table 6-8 shows the application of the base stock model to the same 18 SKU's. The model helped determine the safety stock and base stock level to be established for each SKU.

Part Number	A-B-C Item	Review Period (Days)	Cycle Stock Cost ($)	Safety Stock - SS (units)	SS Holding Cost ($)	Avg. Inv. (Cycle+SS) (units)	Pipeline Inventory Cost ($)	Base Stock (units)	# of orders in a year	Total cost ($)
EC0076	A	20	35.48	10.27	52.86	17.17	40.55	31.95	13.05	6368.14
FM0002	A	10	12.83	10.27	38.22	13.72	54.98	31.95	26.1	4700.52
FP0006	A	10	10.11	10.04	29.42	13.49	40.43	30.73	26.1	3727.66
MC0001	A	20	25.86	9.16	34.36	16.06	12.93	26.4	13.05	4638.41
MT0003	A	20	19.81	10.04	28.83	16.93	19.81	30.73	13.05	3580.7
SA0032	A	20	125.06	85.52	410.51	111.58	62.53	150.66	13.05	22423.4
CB0002	B	10	2.87	7.9	6.56	11.35	4.91	20.71	26.1	1142.04
FI0001	B	20	7.87	10.04	11.46	16.93	7.87	30.73	13.05	1462.25
FM0019	B	20	15.26	10.04	22.21	16.93	15.26	30.73	13.05	2772.98
FP0010	B	10	4.37	10.04	12.72	13.49	17.48	30.73	26.1	1686.08
JP0001	B	10	2.84	7.9	6.52	11.35	4.88	20.71	26.1	1134.74
MC0003	B	60	36.87	30.03	26.76	71.41	8.78	122.64	4.35	2219.51
EC0011	C	20	1.53	9.16	2.03	16.06	0.77	26.4	13.05	335.98
FI0002	C	60	6.21	14.78	4.43	35.46	1.03	59.6	4.35	380.37
FM0034	C	20	19.54	85.52	64.14	111.58	9.77	150.66	13.05	3558.7
FP0014	C	60	1.55	14.45	1.08	35.14	0.11	57.3	4.35	101.45
FR0031	C	20	1.41	73.31	1.87	128.48	0.7	211.24	13.05	314.03
MC0004	C	20	1.53	19.1	2.12	32.89	1.09	56.53	13.05	336.39

Table 6-8: Results of Base Stock inventory model applied to A-B-C categories

As can be seen from the table above, base stock model was run for all SKUs for the purpose of studying the implications of such a policy. Based on formulae mentioned in Section 5.2.4, the total cost of the model for each SKU is shown in the table. It is important to note that base stock model assumes that there is no ordering cost, however in case of NVBOTS there exists a cost for placing each order and hence this cost was also considered and the total cost equation was slightly modified to accommodate ordering cost. Base stock model might not be a practical option for all categories (A, B & C), however it is worthwhile to compare the results with that of the QR model.

6.4.3 Comparison of QR & Base Stock model for A, B and C categories

The following set of graphs compares the results from base stock and QR models for all of the A, B and C categories items at NVBOTS, for a demand scenario of 180 NVPro printers (Note: the numbers depicted in the graph are scaled and modified appropriately in order to conceal the actual spending of NVBOTS). The quantitative parameters considered for comparison include the average inventory and locked-up capital held, total costs and number of orders placed in a year.

Average Locked-up Capital:

Locked-up capital refers to the amount of cash tied up in the form of inventory in the warehouse. Liquid cash is important for every business, however if a firm has too much inventory then a large amount of cash which could otherwise be put to better use, will not be available. Hence, the lower the amount of locked-up capital, the better it is for a company. Figure 6-2 shows that the total average locked-up capital is lower for base stock model for all 3 categories.

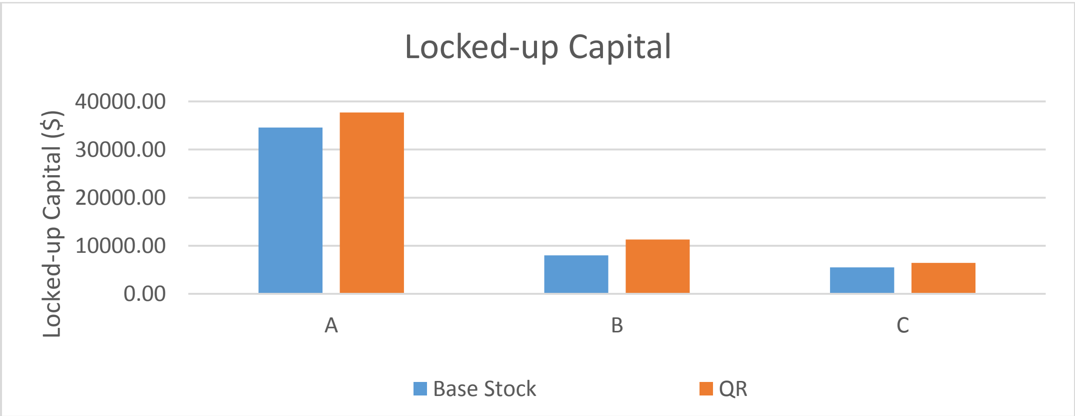

Figure 6-2: Average locked-up capital for A,B&C categories based on Base Stock & QR models

Though the difference in the amount of locked-up capital between QR and Base stock models is not a lot (~$7000), this could make a huge difference for startups that usually have cash constraints. The average locked-up capital is higher in case of QR model since the average inventory on-hand is higher. In QR model the order sizes are bigger and the frequency of orders are smaller compared to base stock model. Hence, on average, there is more inventory on-hand in case of QR model resulting in more locked-up capital. The on-hand inventory for various SKUs across categories are shown in Figure 6-3, Figure 6-4 and Figure 6-5. For most SKU's it is seen that the on-hand inventory is higher for QR model than Base stock model.

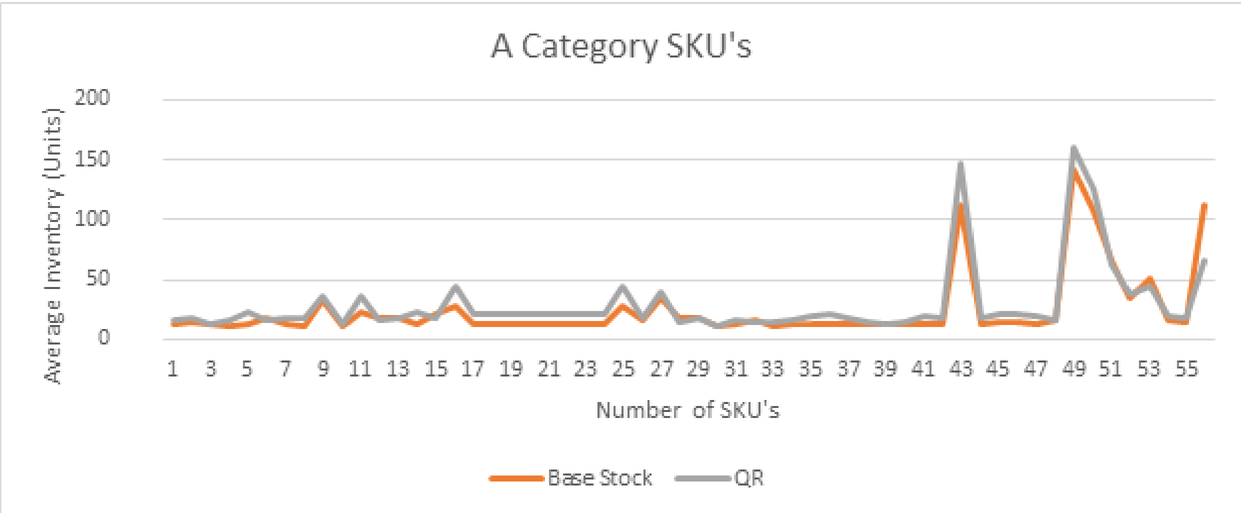

Figure 6-3: Average units of Inventory for A Items for QR and Base stock models

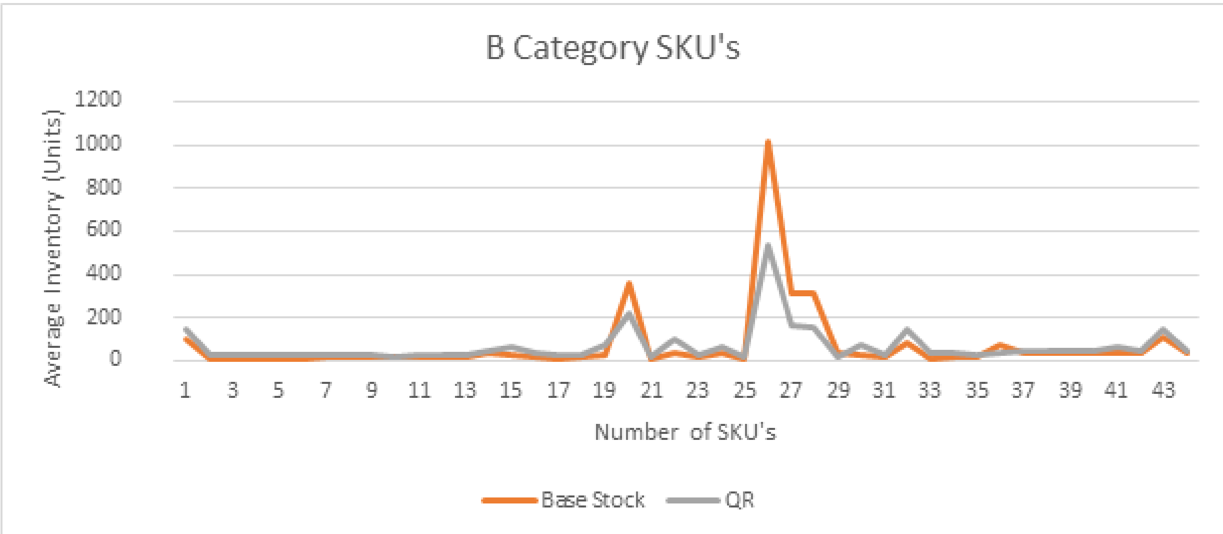

Figure 6-4: Average units of Inventory for B Items for QR and Base stock models

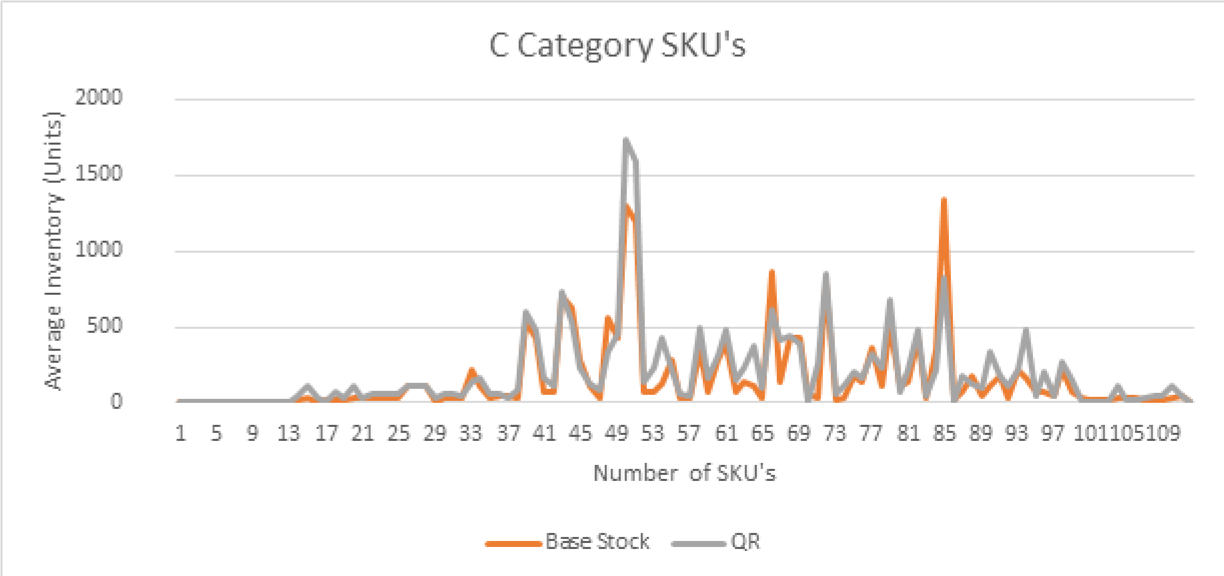

Figure 6-5: Average units of Inventory for C Items for QR and Base stock models

Total Cost for acquiring parts (excluding cost of components):

Total cost for base stock model includes holding costs for cycle stock, safety stock and pipeline inventory, and ordering costs. Total cost for QR model includes ordering costs, inventory holding costs and stockout costs. Since the cost of components is the same for both models, it has been excluded from the total cost shown in the graph below.

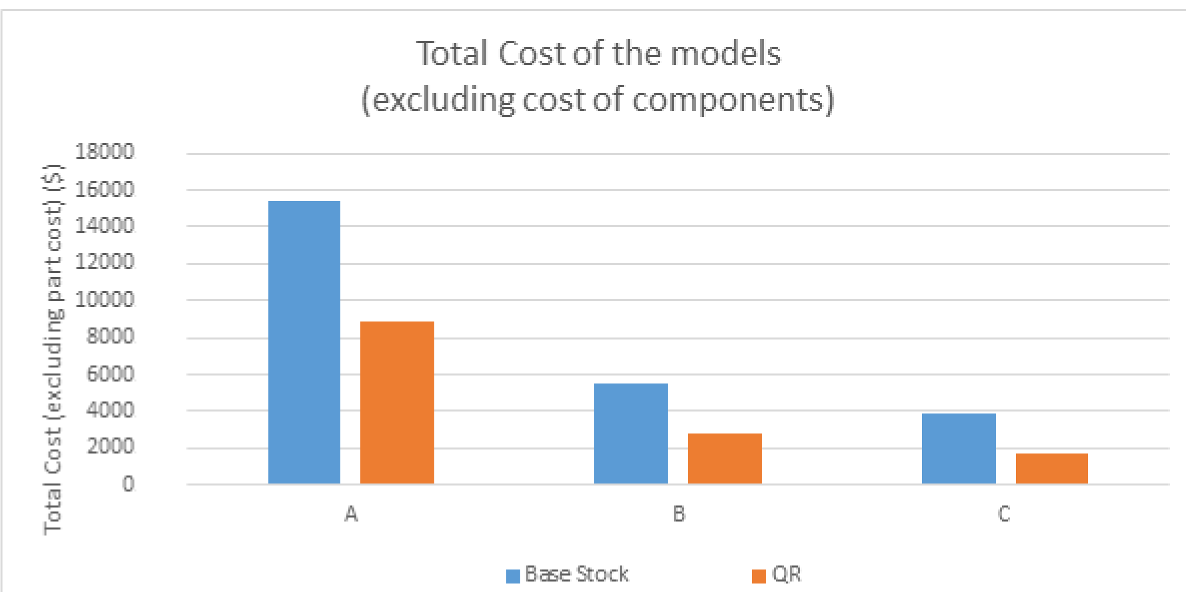

Figure 6-6: Total costs comparison between Base Stock and QR model

It is seen from Figure 6-6 that the total cost (excluding component cost) is lower for QR model compared to base stock model, for all categories. The total difference (all categories) in the costs between the two models is as high as $10,000. As the number of orders increase, the ordering costs also increase. Since the frequency of orders is higher in case of base stock model, the overall cost is higher for base stock model due to higher ordering costs.

Number of Orders placed in a year:

The number of orders placed in a year is determined by diving the annual demand by order size in case of QR model. For base stock model, the number of orders in a year can be approximated by dividing the number of days in a year by the review period for that SKU. Based on the review periods chosen, it was seen that the number of orders in a year was higher in case of base stock models across all categories. This makes sense considering that in base stock model there is a need for tighter control and hence small order sizes are placed more frequently.

The result of the number of orders placed for the two models across categories are shown in Figure 6-7, Figure 6-8 and Figure 6-9. The number of orders placed for base stock model is higher than that of QR model for all of A, B and C category items.

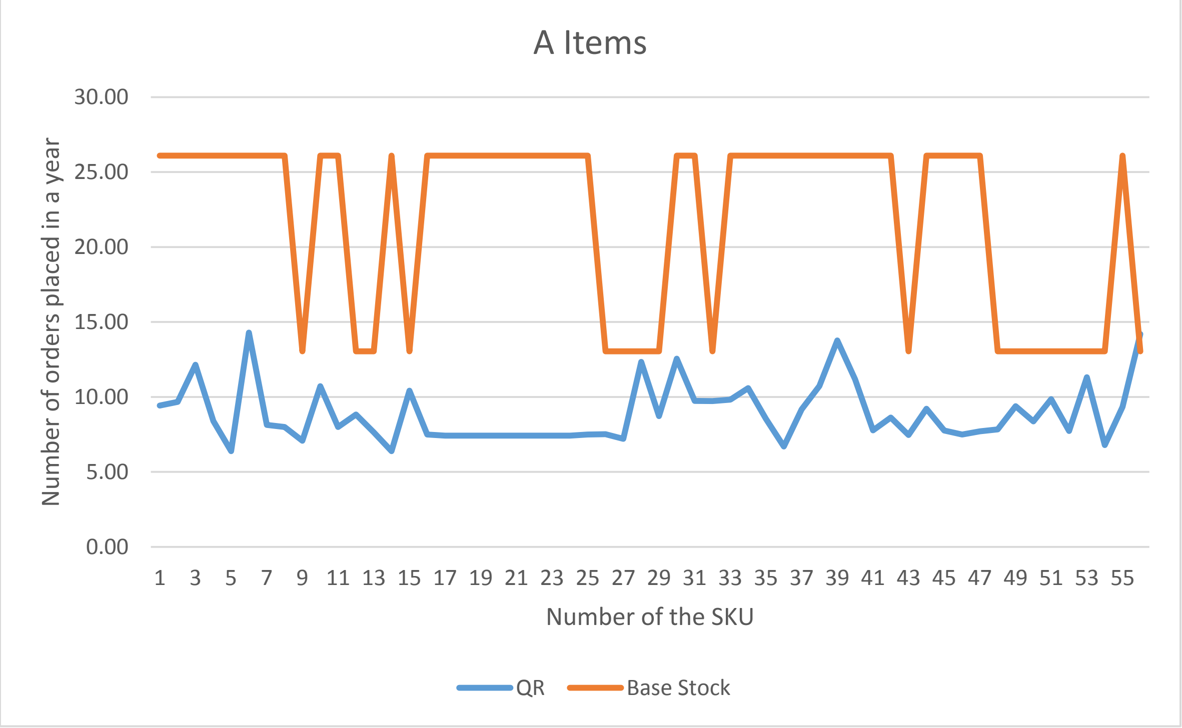

Figure 6-7: Number of orders placed in a year for A items

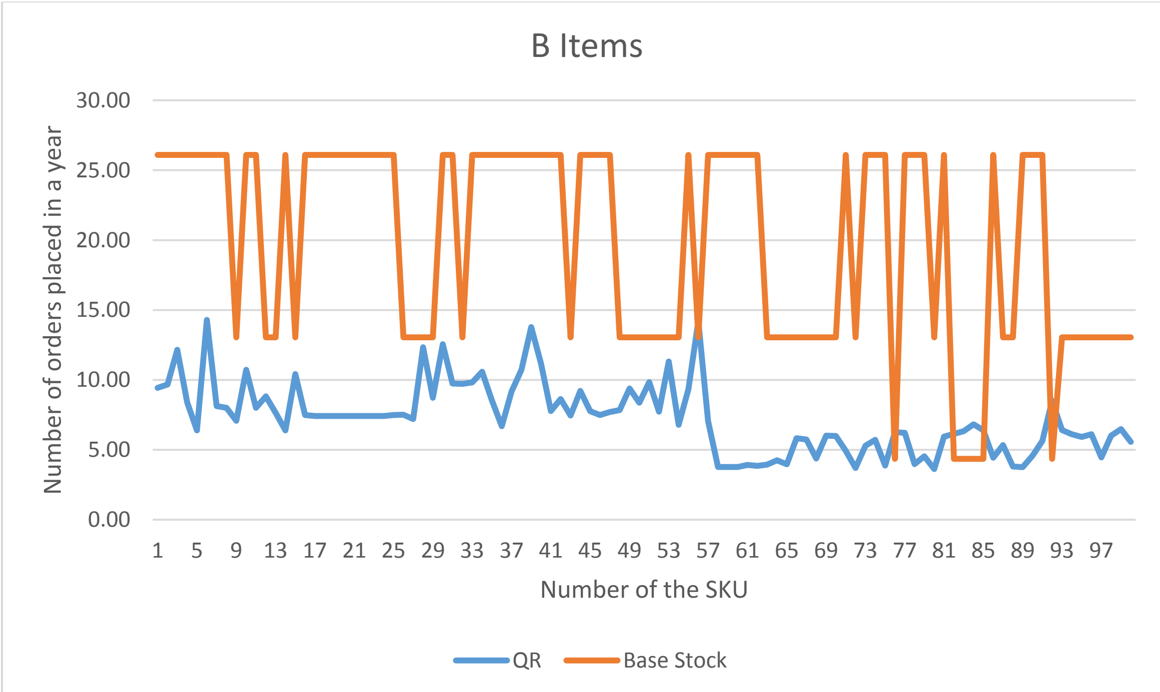

Figure 6-8: Number of orders placed in a year for B items

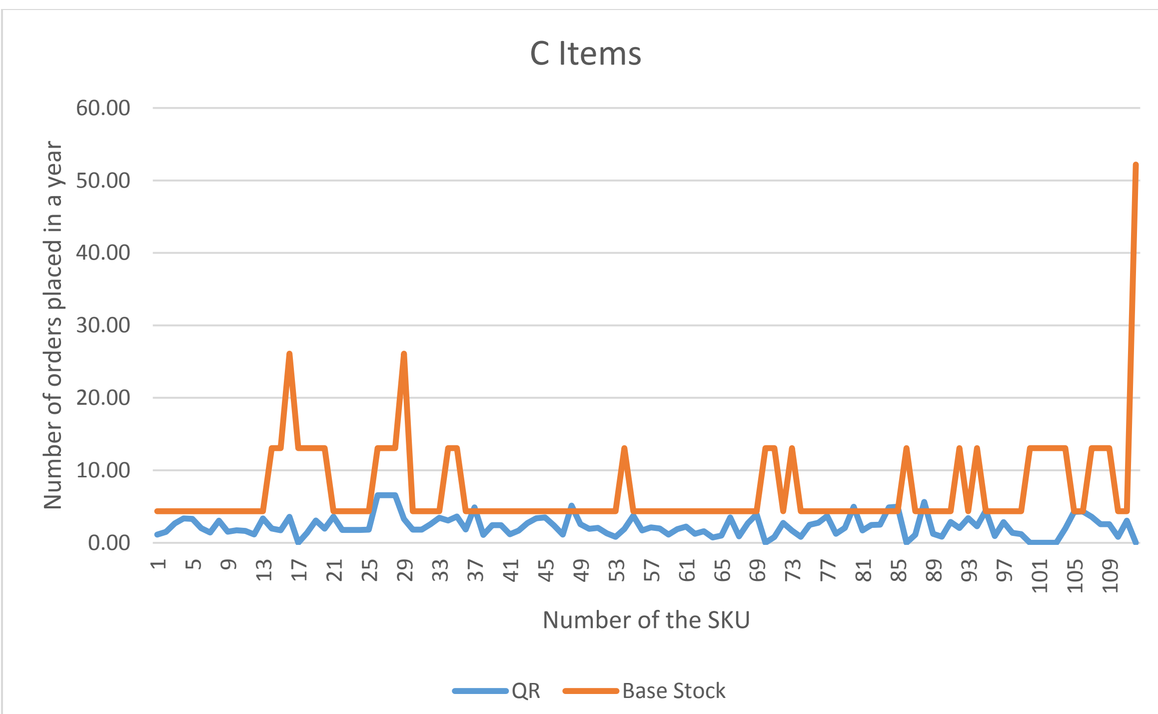

Figure 6-9: Number of orders placed in a year for C items

6.4.4 For A Items: Base Stock Inventory Model

For any company, ‘A’ items are usually the most valuable and expensive. ‘A’ items have significant impact on a company’s inventory costs and hence need tight control. It is important to carefully plan and monitor the inventory levels for such items. ‘A’ items usually are stored in separate locations, with little on-hand inventory but frequent ordering policies. Companies usually use Just-In-Time ordering strategies for A items. However, for startups like NVBOTS it is very hard to use JIT practices owing to a less well-established and reliable supply chain.

Base stock policy is a periodic review model and hence the ordering frequency can be determined by the firm. Since ‘A’ need tighter control, the firm can choose a review period that is small so as to ensure frequent ordering. In base stock model, the orders are placed regularly so the order quantities are generally small. Considering that ‘A’ items occupy a large amount of space, small order size reduces the storage requirements. Also, since the order sizes are small, less working capital is required. This really helps firms that have funding limitations.

It is easier to adjust ordering sizes in base stock model and hence changes in demand can be accommodated better. Regular ordering based on demand also prevents accumulation of obsolete inventory. Most importantly, from the vendor’s point of view it is easy to manage considering that the orders are at regular intervals of time which allows vendors to plan in advance. This also helps firms in consolidating orders for various SKUs procured from a given vendor and also help in forging long-term contracts.

In addition to the above mentioned qualitative analysis, the comparison of the QR and base stock model yielded the following quantitative information. Though the overall cost to procure parts is about $6000 higher in case of base stock model, the amount of locked-up capital needed is much lesser. The ordering costs can be somewhat offset if the firm enters into a contract with the vendors, thereby lowering total costs. Also, in case of base stock model the stock levels can be monitored periodically rather than continuously, as done in QR model. Based on the above analysis, it was decided to employ base stock ordering strategies for ‘A’ category SKUs at NVBOTS. The final results including the review period, recommended safety stock and base stock levels and average order size for a few ‘A’ items are shown in Table 6-9 below.

Part Number	Review Period (Days)	Recommended Safety Stock (units)	Base Stock Level (units)	Inventory Position (units)	Order Size (units)
EC0076	20	10.27	31.95	12	12
FM0002	10	10.27	31.95	28	-11
FP0006	10	10.04	30.73	28	-11
MC0001	20	9.16	26.40	14	9
MT0003	20	10.04	30.73	43	-19
SA0032	20	85.52	150.66	32	106

Table 6-9: Base stock policy recommendation for A category SKUs

The table above is based on the formulae in Section 5.2.4. Inventory position is the sum of current stock level and pipeline inventory, and the numbers mentioned in inventory position column indicates the level as on 6/1/2016. Once the safety stock and base stock levels are determined, to find order quantity, the following formulae is used:

$$Order\ Size = Base\ Stock - Inventory\ Position + Expected\ demand\ during\ LT \quad (6\text{-}9)$$

At each review period, the order size is determined based on the inventory position and so the order size is not the same every time. The negative values in order quantity indicates that there is more on-hand inventory than determined by base stock level and therefore an order for that SKU might not be placed in that review period. This means NVBOTS has excess stock for some of the SKUs which could potentially be cut down if base stock strategy is used rather than determining order sizes in an ad-hoc manner.

Since the current method of ordering at NVBOTS was unsystematic, it is very difficult to compare existing to proposed inventory strategy. Also, there was no well-defined safety stock levels and hence the recommended safety stock level obtained from base stock model could not be compared to existing safety stock levels. However, it was noted that the average locked up capital for ‘A’ items at NVBOTS was about $60,000. If base stock policy is used, locked-up capital can be brought down to $40,000. This freeing-up of $20,000 worth of funds will further help the cause of a startup like NVBOTS. Also, by following a systematic approach like base stock model they can not only reduce the amount of working capital required from week to week but also ensure that there are no production stoppages due to stockouts.

In order to validate the results of the base stock model, a simulation was run using FlexSim model software. For more details on the modules and features of the simulation, refer to Jain's [1] thesis. The graphs that follow are applied to SKU EC0076, whose review period, maximum stock level and safety stock levels are shown in Table 5-9. For the sake of running the simulations, review period and lead time were converted to minutes assuming 480 minutes of working time (8 hour shift). The green line indicates the base stock level, red line the current inventory level and blue line indicates the amount of safety stock.

Figure 6-10 shows the inventory level for EC0076, with base stock level equal to 32 and safety stock level being 11. Every 9600 minutes (review period) an order is placed which arrives after 5280 minutes (lead time). Order size is not the same and is recalculated every time as explained earlier. In a deterministic demand scenario, when the replenishment arrives, the inventory level will exactly be base stock level. However, the demand scenario below is normally distributed, sometimes the demand during lead time is lower than expected and hence it shoots beyond base stock level. Some other times, the demand during lead time is higher than expected, in those cases it will just fall below base stock level. As it can be seen from the graph below, the model seems to be working well with no stockouts, thereby validating the calculated safety and base stock levels. Also, the inventory consumed has dipped into safety stock only once in 50,000 minutes so far, indicating that the demand during that period was higher than expected.

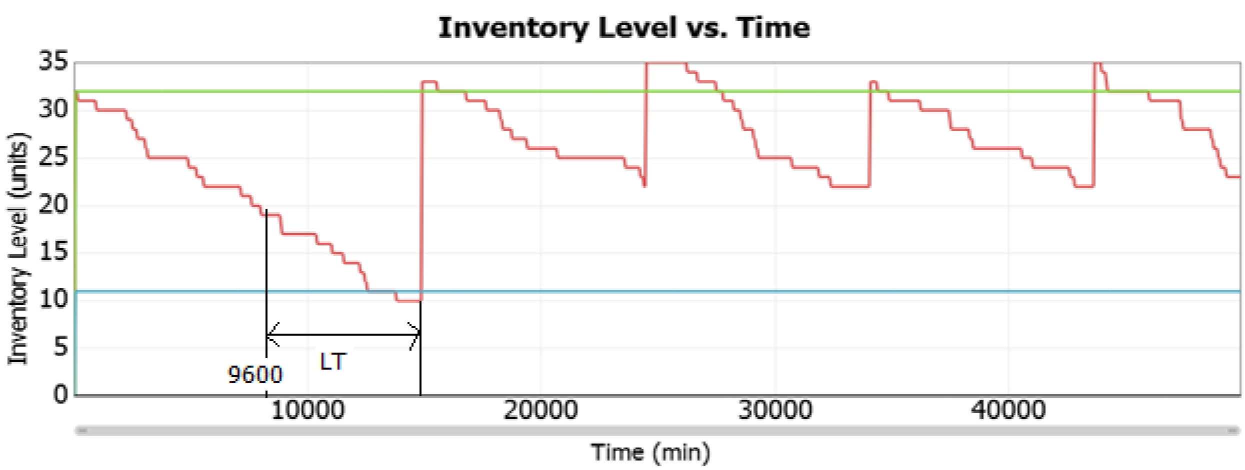

Figure 6-10: Inventory level vs Time graph, obtained using Base Stock model for EC0076

The lead time used in the model above was 11 days. Often this lead time is not a constant and may vary. If the lead time decreases it might not be much of a problem, however if it increases then it could cause stockouts. In order to understand the impact of a change in lead time and to study its sensitivity, the same model was run for EC0076 with all other parameters unchanged except lead time.

When the lead time was decreased to 5 days as shown in Figure 6-11, the orders arrived sooner and hence less inventory was consumed in a given review period resulting in inventory level higher than established base stock level after order arrived. It was also seen that the stock levels did not dip into safety stock indicating that there was sufficient inventory on-hand, which was the result of shortened lead time.

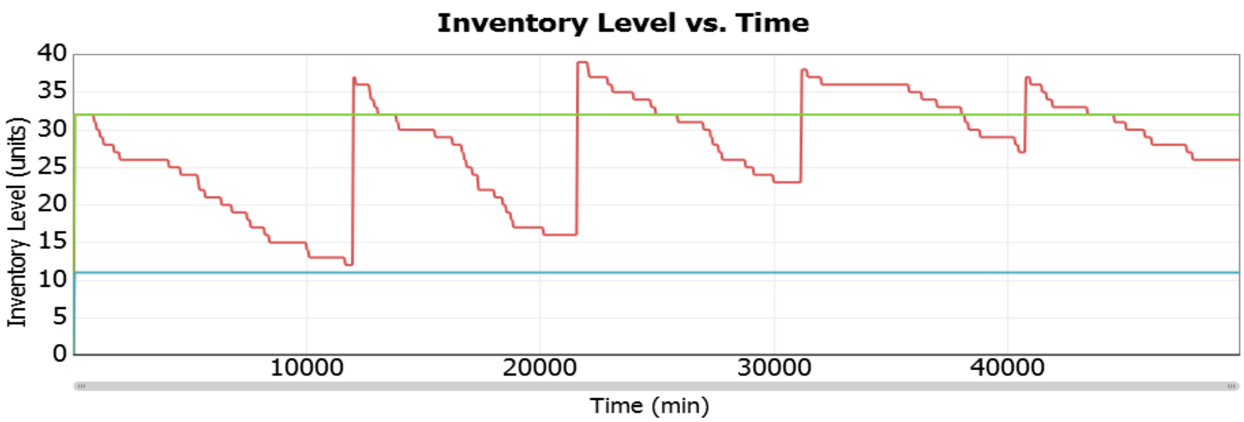

Figure 6-11: Inventory level for EC0076 when lead time changes to 5 days

When the lead time was increased to 20 days as shown in Figure 6-12, it resulted in stockouts. The inventory level often dipped into safety stock due to the late arrival of orders. Also, it was noted that after receiving an order, the inventory level was still below base stock level because the consumption during lead time was higher due to the increased lead time.

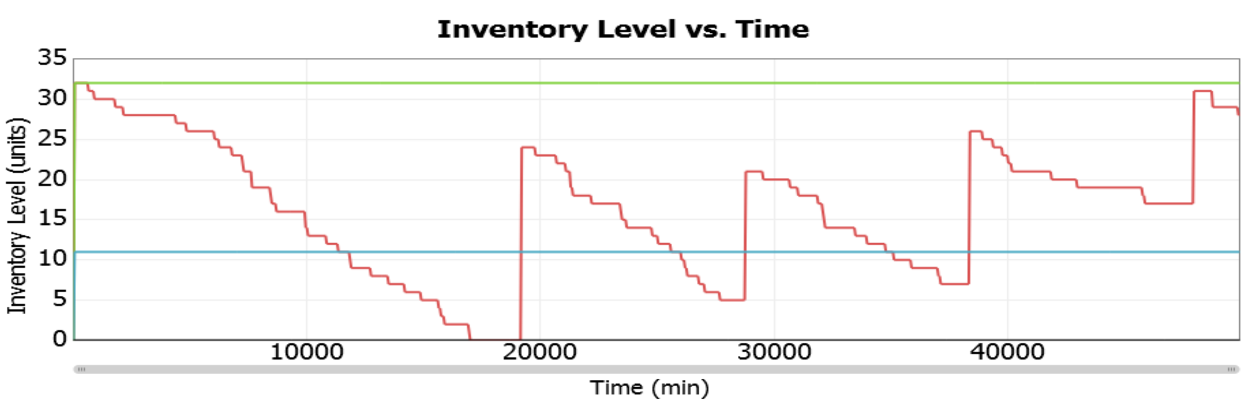

Figure 6-12: Inventory level for EC0076 when lead time changes to 20 days

It was seen that the base stock strategy designed with the original lead time of 11 days was able to meet demand whenever lead time decreased. When lead time was slightly increased, the demand was still almost completely met. However, when the lead time was almost doubled, there were stockouts. The above analysis indicates that the base stock and safety stock levels established are more or less robust to slight variations in lead time.

6.4.5 For B Items: Base Stock Inventory Model

'B' items are not as important as 'A' items but more important than 'C' items. It is usually very tricky to decide an inventory ordering strategy for 'B' items considering that they are intermediate to 'A' and 'C'. Some firms employ base stock model while others resort to QR model. NVBOTS being a startup and having working capital constraints wished to have tight control over 'B' items as well. Base stock model due to its frequent ordering and other advantages as mentioned in Section 6.4.4 was favored compared to QR model. Quantitative analysis in Section 6.4.3 showed amount of locked-up capital required for base stock model was lesser than QR. However, base stock model will be $2,000 more expensive than QR, to meet the same annual demand. This is due to higher ordering costs caused by frequent deliveries. Table 6-10 below shows the base stock and safety stock levels for a few 'B' category items based on the formulae in Section 5.2.4.

Part Number	Review Period (Days)	Recommended Safety Stock (units)	Base Stock Level (units)	Inventory Position (units)	Order Quantity (units)
CB0002	10	7.90	20.71	11	4
FI0001	20	10.04	30.73	477	-453
FM0019	20	10.04	30.73	5	19
FP0010	10	10.04	30.73	12	5
JP0001	10	7.90	20.71	11	4
MC0003	60	30.03	122.64	27	86

Table 6-10: Results from applying Base stock model to B category items

As it can be seen from the table above, safety stock and base stock levels were determined. Inventory position mentioned above is the stock level plus pipeline receivables as on 6/1/2016. The order size is recalculated at each review period based on equation (5-32). It is seen that the order size for a few SKUs was negative, indicating that an order need on be placed as there is more inventory that established base stock level.

In order to validate the results obtained, a simulation was run on FlexSim software. For more details with regards to the simulation and modules used, refer Jain's thesis [1]. The simulation was run for the SKU CB0002, with the data from the table 5-10. The green line indicates base stock level and blue line indicates safety stock level.

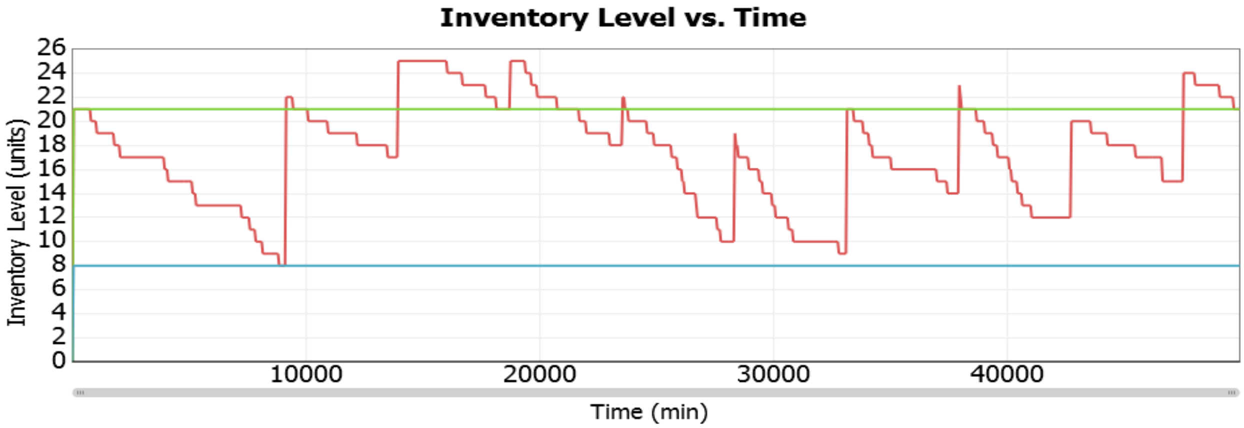

Figure 6-13: Inventory level vs Time graph for CB0002, based on base stock model

Figure 6-13 above shows the application of base stock model for CB0002. It was seen that for the established base stock level of 21 units and safety stock of 8 units, there were no stockouts. Thus, validating the numbers calculated and shown in table 5-10. The inventory level hardly dipped into safety stock and post replenishment level was close to base stock level. However, for the same data if the lead time doubled from the original 9 to 18 days then the graph would be as shown in Figure 6-14, where there are often stockouts due to longer lead time.

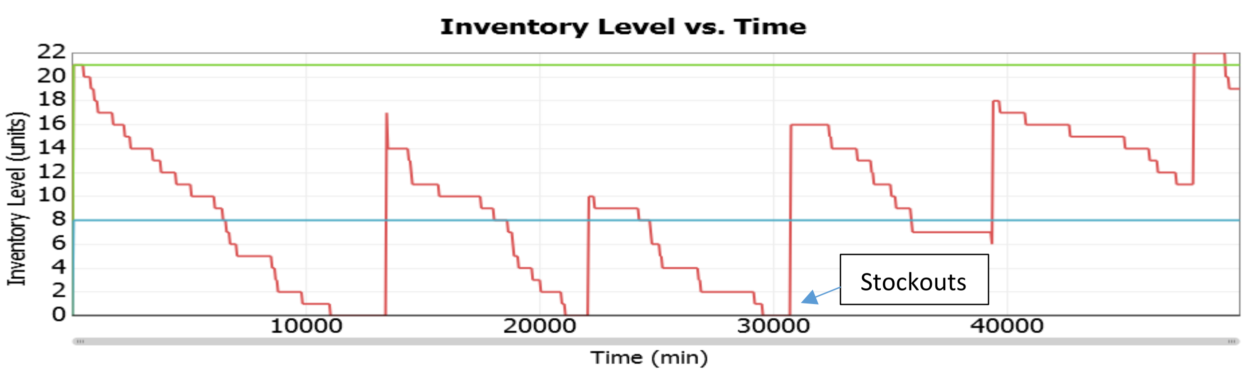

Figure 6-14: Inventory level graph for CB0002 with LT of 18 days

6.4.6 For C Items: QR Model

'C' items are the least expensive raw-material inventory in any firm. They usually account for 5-10% of the total annual usage value. It is important to note that the availability of 'C' items are equally important for NVBOTS. Most fasteners and low value items fall under this category. It is good to have a large amount of inventory on-hand for 'C' items as they do not significantly influence overall inventory costs. Most firms order 'C' items in bulk once in a six months or so. Some firms buy them in economic order quantities and firms particular about including stockout costs use QR models. For startups like NVBOTS it might not be advisable to order once in 6 months, owing to frequent design changes which might mandate scrapping a few SKUs and ordering in such large quantities requires more working capital.

QR model is a continuous review model where the same order size is placed every time the stock levels fall to certain level known as the reorder point. QR model helps in minimizing costs and also the number of orders placed. Usually, 50% of the SKU's in a firm are 'C' category items and so if they are to be ordered frequently as in a base stock model, it would be a hassle to manage them. Hence, models that have minimum number of orders are favorable for 'C' items. Also, since it is the same order quantity every time, the inventory manager doesn't have to calculate the amount to be ordered. The quantitative analysis indicated that on comparison with base stock model, QR has a lower overall total cost requirement for procuring the same amount of inventory. Owing to the quantitative, qualitative and nature of startups, it was decided to choose QR model for ordering 'C' category parts.

Table 6-11 below shows the final recommendations based on QR model for 6 selected 'C' items at NVBOTS, where Q indicates the order size and R is the reorder point.

Part Number	Q	R
FI0002	49.83	9.42
FM0034	103.56	65.95
FP0014	98.64	4.36
FR0031	758.63	70.42
MC0004	182.14	23.57

Table 6-11: Order size and Reorder Point based on QR model for 'C' items

The results shown above were based on formulae mentioned in Section 5.2.3. In order to validate the findings, a simulation on FlexSim software was run. For details on the simulation and modules used, refer to Jain's thesis [1]. The graph shown in Figure 6-15 below is for SKU FR0031, whose lead time is 5 days, order quantity is 759 units and reorder point is 71units. The green line indicates the reorder point.

Figure 6-15: Inventory Level vs Time for SKU FR0031, using QR model

It appears from the graph as though the demand is deterministic, however the demand is normally distributed. It is seen that the QR model seems to be working fine. It hardly dips into safety stock, the order quantity is the same and the order is placed when the inventory level drops to ROP. It is also noticed that there are no stockouts. To understand the impact of the three levers that determine the results of the QR model (lead time, reorder point and order quantity), the following graphs were plotted.

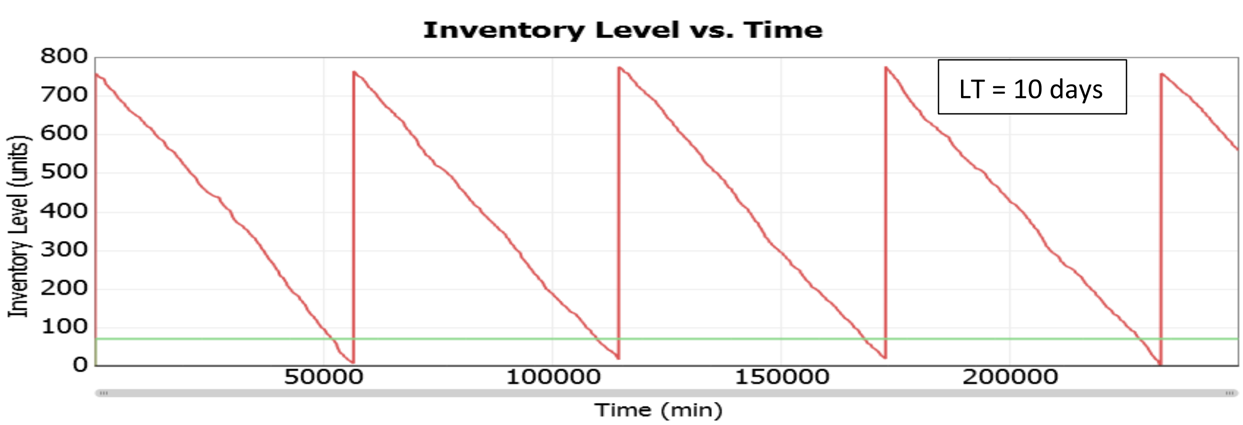

Figure 6-16: Inventory Level vs Time for SKU FR0031, using QR model – LT 10 days

Figure 6-16 shows the graph with the original Q and R but with double the lead time. It is seen that the inventory level dips further into safety stock than before due to delay in arrival. However, there are still no stockouts and so the model is robust even when the lead time is doubled.

In order to understand the impact of R, it was reduced by half the original amount and the model was run. The graph shown in Figure 6-17 indicates that when the reorder point was reduced from 71 to 36, there were stockouts. This is due to the fact that the reorder point is much lower and hence the triggers for orders are sent much later, resulting in a late delivery of raw-materials which often causes stockouts. Hence, it is important to set appropriate triggers ROP.

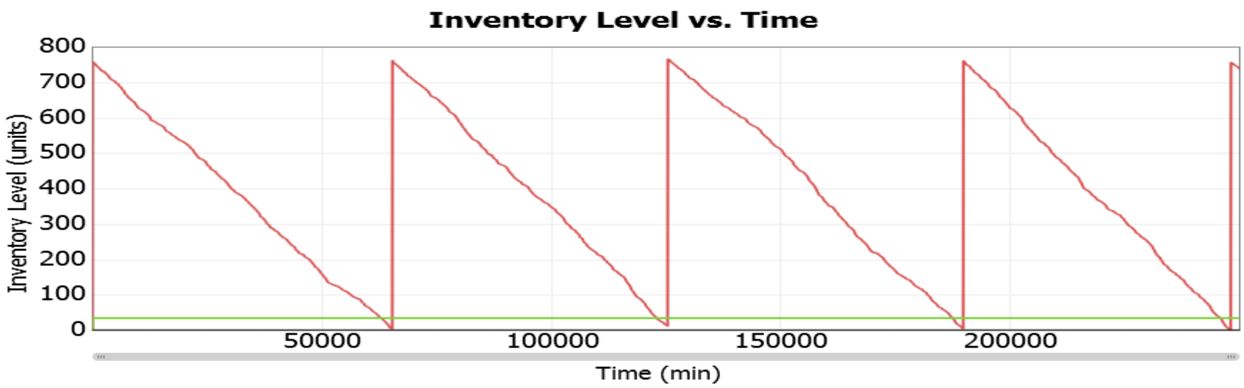

Figure 6-17: Inventory Level vs Time - SKU FR0031, using QR model with ROP reduced by half

Next, the order size was varied while the lead time and ROP remained the same. The graph in Figure 6-18 shows the inventory level when Q was reduced by half and it was noticed that the model seemed to be working perfectly fine. However, it is important to note that the total cost to procure parts is no longer optimal, due to increased ordering costs caused by more deliveries of lesser quantity.

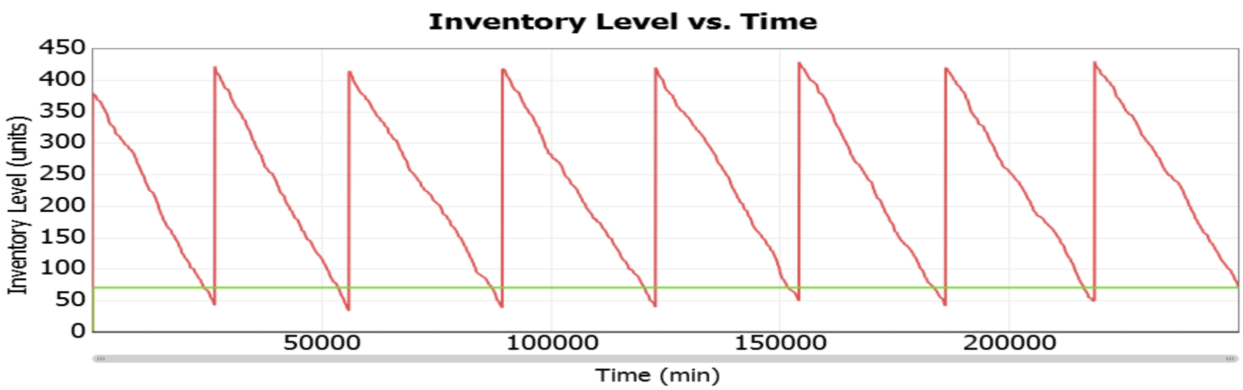

Figure 6-18: Inventory Level vs Time - SKU FR0031, using QR model with Q reduced by half

It is important to note that whenever the lead time demand is greater than the order quantity, QR will fail to work because even after receiving fresh stock, the inventory level will be less than that of reorder point. This is due to the fact that QR models is essentially aiming for minimum total cost. Though it considers lead time, priority is to keep the costs low.

6.5 Summary and Final Recommendations

It was seen that NVBOTS lacked a systematic approach to ordering parts. Information with regards to demand, supplier lead times, unit price of components, ordering costs, and other data were not well documented. This resulted in frequent stockouts of raw-material inventory. Currently, orders were placed in an ad-hoc fashion resulting in excess inventory for a few SKUs and very little for others.

In order to solve the inventory management problem at NVBOTS, existing inventory methods were studied. These included EOQ, EPQ, QR, Quantity Discount and Base Stock models. Some advanced inventory methods such as JIT was also considered. All models were analyzed from the point of view of a startup, keeping in mind the constraints of a startup. The main purpose was to establish a system that allowed data collection and to decide on ordering strategies for the various categories of inventory.

Having understood the needs of NVBOTS and having studied the qualitative and quantitative aspects of the various inventory models, the following recommendations were made.

- ❖ Economic Production Quantity (EPQ) model for Printed Parts (PP): PPs were produced in-house and the lot sizes needed to be determined. EPQ model helped to not only determine lot sizes but also the number of production printers required in order to meet the demand.
- ❖ Shelf-Life Tracking for Adhesives (AD): For ADs it was decided to track shelf-lives and spot order a week in advance so as to allow enough time for the adhesives to be delivered.
- ❖ Base Stock model for ‘A’ and ‘B’ items: NVBOTS wanted to order these expensive in small batches, frequently. Hence, the review period was set as suitable to NVBOTS. Based on the data, the recommended safety and base stock levels were established. Orders were placed at set intervals of time and the order quantity varied based on the inventory position.

- QR model for ‘C’ items: Using QR model, the order size and the reorder points for all C items were established. QR model helped take into account stockouts and was also the least cost model.

It is important to note that the improvements from current method to proposed method is hard to quantity considering that the current method was random and the required data was not available.

Chapter 7
Physical Control of Inventory

7.1 Overview

Physical control of inventory refers to knowing exactly what is in the inventory, where it is located and how much of each type is there. This information is useful in order to set safety stock levels, ROP and to facilitate in placing orders as determined in Chapter 6. The activities under physical control of inventory include storekeeping, inventory room layout, efficient tracking of incoming and outgoing materials, updating the systems to reflect the current inventory position, good housekeeping practices within inventory room, proper labelling and storage of parts at specified locations [43].

To ensure efficient inventory tracking and physical upkeep, it is necessary to have a set of policies agreed upon by the entire organization, which outlines the material flow in and out of the system, responsibilities to individuals, maximum inventory to be held at any time and other important metrics. The following paragraphs outline a simple set of procedures that can help to structure an efficient inventory tracking and control system.

Firstly, it is necessary have a unique code for each SKU so as to easily identify the part. The code can either be all numbers or alphanumeric, as decided by the company [43]. Then it is necessary to identify where these SKU's are located. All locations should be named properly so as to easily pinpoint any part. Some SKU's may have multiple storage locations, it is important to tabulate this information and have a database which contains the location information of all the stock keeping units (SKU). A preliminary stock count at all of these locations is highly advised.

This information must be immediately transferred either to excel sheets or to any ERP software used by the company.

Secondly, there must be a strategy in place for upkeep, handling inventory, issues and disposals [29]. Proper documentation must be put in place so as to ensure that the inventory levels in the system truly depict the inventory levels in the warehouse. Any discrepancy here can be disastrous for the company. Some of the common practices for inventory personnel include receiving materials, checking them against purchase orders for quantity, coordinating quality checks, separating the rejected goods, then formally signing in the accepted parts into the system as well as the physical locations and ensuring that new materials are put at the back of the rack to ensure FIFO (first in first out), keeping the purchasing team informed about any shortages and uneven trends, and ensuring good housekeeping at all inventory storage locations [29]. For outgoing inventory, it is necessary to have inventory sign-out sheets and make it mandatory for anyone taking anything out of the inventory storage location to update them. In more sophisticated companies, this can be done through barcoding & ERP softwares. Basically, both incoming and outgoing inventory records must be maintained and updated into the system, as real-time as possible.

Implementing 5S in the inventory storage facility is highly recommended. Firstly, sorting all wanted material from unwanted material is important. If there are any obsolete inventory, old documents or broken storage boxes, they must be removed and replaced by necessary items [44]. Then, clearly labelling and marking zones within the inventory room for each SKU is important. Ensuring that the place is kept clean is the duty of the inventory personnel. A list of standard practices must be posted on a bill board within the room and everyone in charge of inventory must be educated about these practices. Once this system is set in place, regular audits to ensure everything is as expected must be conducted [44].

Thirdly, once the above procedures are put in place it is necessary to re-evaluate the storage locations to further optimize the system. It is important to understand which parts are fast moving and which are not, which require more space, which parts need to be stored together or isolated due to their physical characteristics and which parts to be located close to each other to facilitate easier picking for assembly operations [29]. It may also be useful to group and store parts based on ABC classification. This way the expensive parts can be better secured by providing limited access to their stored locations. All of the above activities involves understanding the materials and its properties, and thereby laying out the inventory room in the most optimal manner.

Lastly, it is important to draft a list of policies with respect to inventory control outlining how often cycle counts for each SKU needs to be conducted and how to deal with discrepancy in the inventory levels [45]. It is very useful to conduct cycle counts periodically to identify missing parts, ascertain reasons to that and try and fix the problem for reoccurring. Inventory is considered as “money” in most organizations and hence it is vital to track them efficiently.

7.2 Recommended Practices for NVBOTS

Inventory at NVBOTS was neither tracked nor stored efficiently. This often led to problems while ordering parts due to the lack of knowledge of the current inventory position. The inventory room layout was not according to any scheme. This significantly increased the time for picking raw-materials required to assemble printers. There was no proper methodology to update the incoming and outgoing inventory numbers into the Odoo (MRP) software. There was no predetermined timing for conducting a firm-wide inventory counting nor was there a methodology to reconcile for lost inventory. To add to this, inventory room was accessible to almost all individuals at NVBOTS, causing more confusion and making it harder to establish discipline. To deal with these problems, the following recommendations were made to NVBOTS.

7.2.1 Tracking Inventory

Currently, NVBOTS relied on inventory sign-in and sign-out sheets to keep track of incoming and outgoing inventory. These sheets were then weekly uploaded onto the Odoo software in order to obtain the current stock levels. The problem with this system was that sometimes people taking parts from the inventory would forget to sign them out. Since there was no dedicated inventory personnel, it was very hard to enforce discipline. Also, since the sheets were updated into Odoo on a weekly basis, the lack of knowledge of the stock levels in the interim caused delay in order placements.

Established companies usually have a bar coding system that automatically updates the inventory levels in the software. In other firms, dedicated inventory personnel handle incoming and outgoing inventory and hence they can more or less efficiently track inventory and held accountable. However, for startups like NVBOTS, the above mentioned methods could mean more investment.

Firstly, it was recommended that instead of everyone at NVBOTS having access to inventory room, a dedicated member from each of the production, servicing, development and other teams should have access. Secondly, exploring economical ways other than using sign-out sheets that could provide real-time inventory tracking should be considered. With regards to this, it was suggested that instead of using sign-out sheets, people picking inventory should send an email to person in charge of updating Odoo software indicating the part picked, quantity and purpose. If this policy is enforced, the person updating the Odoo software can do so immediately, thereby reflecting the true inventory status.

Another method to track inventory was by using QR codes. In this method, every SKU location would have a QR code and whenever a part was being withdrawn, the person could scan the code using QR scanner app on his/her phone and then fill out an online form with regards to quantity and purpose of inventory withdrawal which would then be formatted into an editable excel sheet. The software required for this was readily available at NVBOTS and hence this option was worthwhile considering.

It is also important to note that NVBOTS did not wish to use any visual cards in the inventory room in order to indicate low stock levels and trigger orders. Instead, they wanted the inventory updating system to be so robust that they could completely rely on the inventory status depicted in Odoo software and base the order replenishments on those levels. Hence, the main purpose of the above suggestions are to ensure that the tracking and updating inventory status is near perfect.

7.2.2 Inventory Counting and Reconciliation:

NVBOTS didn’t have a practice of conducting stock checks. This resulted in lack of information with regards to what is exactly present in the inventory. Stock checks help in recalibrating the system to reflect actual inventory status. It also helps to identify obsolete stock and indicates the value of stock held from time to time, which might be useful information for accounting purposes.

Once a reasonable inventory tracking system was put in place, it was recommended that NVBOTS initially do stock checks every month in order to see if there was a large discrepancy between the numbers in the Odoo software and the actual inventory in the inventory room. If the discrepancy is within certain limits then it might be worthwhile to take stock counts once a quarter rather than every month. Also, another reasonable method could be to enforce a rule to conduct cycle counts every two weeks for ‘A’ items as they are most valuable, every month for ‘B’ items and quarterly for ‘C’ items which are of the lowest value. However, there is no need to do this since NVBOTS has the advantage where all of its inventory can be counted within 6 hours, unlike other big firms which have to close down its operations temporarily in order to count existing stock.

Once the stock counts are taken, the next step is to compare with the stock levels in the Odoo software and to accounts for the discrepancy. If the numbers in the actual inventory are less than those in the system, then it could be caused due to theft, damaged parts, or improper system updating, et cetera. Sometimes the number in the stock might be more than those in the system, this might be due to improper updating of the Odoo software caused either by loss of inventory sign-out sheets or negligence of the inventory personnel.

It is important to reason out the cause for discrepancy, if any, and ensure that it doesn’t arise in the future. No matter how perfect a system is, there are bound to be discrepancies, hence most firms set thresholds beyond which if the inventory is found missing or found to be in excess, serious actions are mandated. Considering NVBOTS is a startup, a low threshold of 5% was recommended for ‘A’ and ‘B’ items, and 10% for ‘C’ items.

A template that can be used to reconcile for lost inventory is shown in Table 7-1. Negative number in “Difference” column indicates less actual inventory than mentioned is system and positive number indicates more actual inventory than in the system.

Item	Stock Level	Counted Quantity	Difference (%)	Need to Investigate?
A1005	100	91	-9.0%	Yes
B7324	55	54	-1.8%	No
A4509	18	16	-11.1%	Yes
C3467	24	31	+29.2%	Yes

Table 7-1: Inventory Reconciliation Sheet [46]

7.2.3 Inventory Storage System and 5S:

NVBOTS had a unique code and storage location for each of its SKUs. However, the storage of these SKUs in the inventory room was not according to any particular scheme. Currently, all raw-material inventory were stored in inventory room in racks according to their size as XL (extra-large), L (large), M (medium) and S (small). There was no methodology as to what constituted a large or a small part. People relied on visual inspection to make this classification. Also, within the racks, the SKU were not stored according to any order, they were randomly placed in these racks. In addition to this, demand and space requirements weren’t considered while allocating space for the raw-material inventory.

The following simple methodologies were suggested for storing parts in the inventory room. First, size, safety stock, maximum stock level and other information with regards to parts must be collected and then they must relatively be positioned based on the total space requirements as XL (extra-large), L (large), M (medium) and S (small). Then, within each of the racks parts must be stored in alphabetical order of the SKU codes. This helps in easy location and organization of the inventory room.

A second method was also suggested. In addition to space considerations, this involved organizing the inventory room based on subassemblies. Considering that parts were picked subassembly wise, locating parts of a particular subassembly close to each other will not only reduce the time required but also the effort spent in moving across various shelves and racks. Parts that are common to subassemblies can be stored in a separate location. This way, anyone wanting to pick parts for a particular subassembly just needs to visit the rack where that subassembly SKUs are stored and the common storage rack where the SKUs common to subassemblies are stored. This method is especially useful when the volume of production increases and picking becomes the bottleneck. In order to ensure First-in-First-out (FIFO) for all SKUs, it was decided that whenever inventory was being stored onto the shelves, it would be placed on the back of storage location and parts being removed from inventory would be taken from the front of the shelves.

The inventory room lacked good housekeeping practices. The inventory room at NVBOTS was often cluttered with cardboard boxes, packaging material, et cetera. Though the locations were more or less well marked, sometimes a location earmarked for a particular SKU was used to store another SKU. This often led to confusion and hence implementation of 5S inside the inventory room was very vital.

It was recommended that all unwanted documentation, packaging material, et cetera must be removed from inventory room from time to time and stored in a specific location. The inventory location of SKUs must be updated in the system and followed strictly. The inventory room must be cleaned atleast once a week and responsibility should be assigned to any one individual to ensure good housekeeping within the inventory room. Informing everyone at NVBOTS about the inventory management practices and ensuring that everyone follows them strictly is of utmost priority.

7.3 Summary

Physical control of inventory is a very important aspect of the overall inventory management. This chapter briefly discusses some of the best inventory control practices as applicable to a startup like NVBOTS.

Efficient tracking of inventory is vital to ensure that parts are available when required and overall inventory costs are kept as minimum as possible. Orders can be placed in the right quantity and time only if one knows the exact inventory position of a firm. In order to ensure efficient tracking, proper storage, good housekeeping and 5S practices should be implemented. Most importantly everyone needs to understand the need for efficient inventory tracking and the implications of improper inventory control, as this will help enforce discipline.

Chapter 8
Vendor Selection

8.1 Overview

Vendor selection is process of screening vendors and evaluating them based on certain criteria by employing quantitative, qualitative and business intuition. Vendors have always been an integral part of a company's management policy [47]. Vendor selection is a strategic decision and highly influences a company's competitive advantage [48]. It is especially more important for firms that outsource their manufacturing to screen vendors properly before qualifying them.

Most organizations do not have structured approach to qualifying vendors. More often than not price is the only criteria which is considered while comparing two vendors. But as an organization grows, complexity increases, the choices on offer increases, risk increases, it is important to select the right vendors as they will have a direct and consequential influence on a firm's performance [48].

Vendor selection is often conducted by the supply chain and procurement division. In recent years, supplier management and vendor selection activities have gained prominence owing to the potential savings that can be obtained in cost and time. The main purpose of the vendor selection and rating process is to assist in making a choice between vendors, to identify risky vendors and replace them, and to forge long lasting contracts with good vendors. Usually, these vendors are rated based on certain criteria that is specifically important to the given company. There are many techniques to evaluate vendors, ranging from operations research to neural networks. While most companies employ a vendor matrix technique that is specific for their purpose.

8.2 Steps in Vendor Selection and Rating

The steps involved in a vendor selection process include generating a list of criteria on which to evaluate the vendors, ranking the criteria relatively to each other and then assigning weights to each of the criterion. Then, vendors for a given part or material can be compared against each other based on these criteria. Scores are assigned and then a weighted average calculation is performed, finally to assign a total score to a vendor. Scores maybe assigned by one or more respondents, whose average would be taken. The company also needs to categorize companies as risky, moderate or safe based on these scores and take necessary action. If done correctly, the company will benefit and can work on its core competencies rather than being worried about the supplier network.

Some of the criterion generally used for evaluation of suppliers are competitive pricing, ability to meet specifications and standards, product and service quality, product yields, reliable delivery methods, quality control methods and practices, technical abilities and leadership, ability to provide niche or unique product offering and/or design concept, financial stability and credit strength, compatibility with existing products, adequate distribution/warehousing facilities and resources, spare parts availability, warranty, insurance and bonding provisions, proven performance and experience, sales/service support resources, etc.

Criteria for Selection of Vendor		
S. No.	**Criteria**	**Abbreviation**
1.	Product Quality	PQ
2.	Product Specification	PS
3.	Quality Control System	QCS
4.	Financial Capability	FC
5.	Transportation Facility	TF
6.	Inspection Facility at Works	IF
7.	Production Capacity	PC
8.	Previous Performance	PP
9.	ISO Certification	ISO

Figure 8-1: Criteria for Selection of Vendors [47]

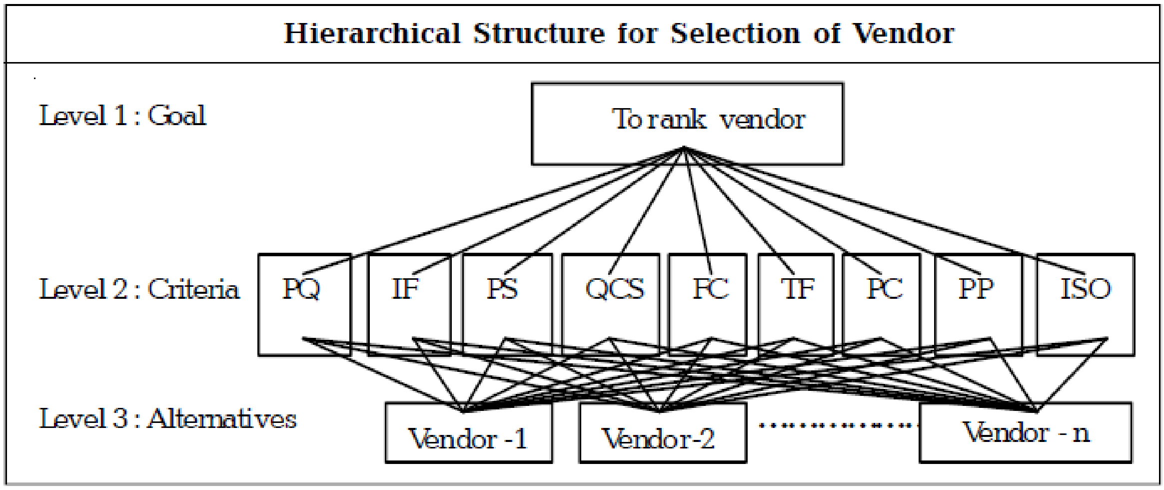

Figure 8-2: Hierarchical Structure for Selection of Vendor [47]

The figures above depict all the steps involved in vendor selection and rating process. Figure 8-1 below shows a list of criteria chosen for vendor selection. Figure 8-2 shows the hierarchical structure for selection of vendors.

Figure 8-3 shows how each of the chosen criteria are compared against each other so as to rank them in the order of importance.

Pair-Wise Comparison Matrix for Selection of Vendor									
To Choose Vendor	**PQ**	**IF**	**PS**	**QCS**	**FC**	**TF**	**PC**	**PP**	**ISO**
PQ	1	5	1	3	3	3	3	3	2
IF	1/5	1	1/3	1	1/3	1/3	1/3	1/3	1/2
PS	1	3	1	1	2	2	2	2	1
QCS	1/3	1	1	1	1/3	2	2	1/3	1
FC	1/3	3	1/2	3	1	3	3	3	2
TF	1/3	3	1/2	1/2	1/3	1	4	1/2	1
PC	1/3	3	1/2	1/2	1/3	1/4	1	1/2	1/2
PP	1/3	3	1/2	3	1/3	2	2	1	3
ISO	1/2	2	1	1	1/2	1	2	1/3	1

Figure 8-3: Pair-Wise Comparison Matrix for Selection of Vendor [47]

Figure 8-4 below shows the normalized priorities based on pair-wise comparison. The criterion are ranked from the most important to the least.

Priority Matrix for Vendor Selection			
Criteria No.	**Criteria**	**Priority**	**Rank**
Cr-1	Product Quality	0.219705	First
Cr-2	Financial Capability	0.157479	Second
Cr-3	Product Specification	0.148237	Third
Cr-4	Past Performance	0.124091	Fourth
Cr-5	ISO Certification	0.086009	Fifth
Cr-6	Transportation Facility	0.084555	Sixth
Cr-7	Quality Control System	0.082475	Seventh
Cr-8	Production Capacity	0.056970	Eighth
Cr-9	Inspection Facility at Works	0.040475	Ninth

Figure 8-4: Priority Matrix for Vendor Selection[47]

Figure 8-5 shows respondents or vendors being scored against the criterion and their respective priorities. A total score is then obtained which can be used for comparison among the various available vendor options.

Table 7: Vendor Selection Model						
Respondents	(Point awarded by the respondents on the 5-point Likert scale against each criterion) x (Priority against each criterion as per Table 6)					
	Point awarded against Cr1x 0.219705	Point awarded against Cr2 x 0.157479	Point awarded against Cr3 x 0.148237	…………..	Point awarded against Cr9x 0.040475	**Total Points**
R1	Say 4 x 0.219705	Say 5 x 0.157479	Say 4 x 0.148237	…………..	Say 3 x 0.040475	**Say T1**
R2	Say 3 x 0.219705	Say 3 x 0.157479	Say 4 x 0.148237	…………..	Say 5 x 0.040475	**Say T2**
R3	Say 5 x 0.219705	Say 5 x 0.157479	Say 5 x 0.148237	…………..	Say 4 x 0.040475	**Say T3**
…… …….. R15	Say 5 x 0.219705	Say 2 x 0.157479	Say 3 x 0.148237	………….. ………….. ………..	Say 2 x 0.040475	**Say T15**

Figure 8-5: Vendor Selection Model [47]

8.3 Methodology Adopted and Results

After discussing with Director of Operations and Director of Finance at NVBOTS, a list of criteria on which to rate the vendors was developed. Then by following the pairwise comparison method shown in Section 8.2, the criteria were ranked against each other and priorities were obtained. Table 8-1 below shows the shortlisted criteria based on which vendors would be selected.

Criteria	Designation
Product Quality & Adherence to specifications	A
Pricing Offered	B
Lead Time	C
On Time Delivery & Order Fulfillment	D
Warranty/Replacement	E
Terms of Payment	F
How easy are they to work with?	G
Financial Stability	H
Flexibility	I
Capabilities/Expertise	J
Geography	K
Can we stay with them in the long term?	L

Table 8-1: Shortlisted Criteria for Vendor Selection

Once the criteria were selected, the Director of Operations and Director of Finance ranked the criteria against each other based on Table 8-2. For example, consider row 1 in Table 8-3 where Criterion A was compared with other criteria. It was seen that A was more important than B and hence given a score of 3 against B and similarly A is marginally more important than C so it was given a score of 2 against C and so on. Also, if you notice row 2 where criterion B is ranked against all other criteria, it seen that against A, the rank is reciprocal of what it was when A was ranked against B. Similarly, all the other rows and columns were filled up. It is important to note all the diagonal elements are 1 since it doesn't make sense to compare the same two criteria.

Order of Importance
1 = equally important
2 = marginally more important
3 = more important
4 = an order of magnitude above

Table 8-2: Order of Importance Index

	A	B	C	D	E	F	G	H	I	J	K	L
A	1	3	2	2	2	3	3	1	2	2	4	2
B	1/3	1	2	1/2	1	3	2	2	1/2	1/3	3	2
C	1/2	1/2	1	1/2	1	3	3	2	1	1	4	1
D	1/2	2	2	1	2	4	1	2	1	1/2	4	2
E	1/2	1	1	1/2	1	3	1/2	2	2	1/2	2	1
F	1/3	1/3	1/3	1/4	1/3	1	1	1/2	1/3	1/3	2	1/3
G	1/3	1/2	1/3	1	2	1	1	2	2	1/3	2	1/2
H	1	1/2	1/2	1/2	1/2	2	1/2	1	2	1/2	3	1
I	1/2	2	1	1	1/2	3	1/2	1/2	1	1/2	2	1/3
J	1/2	3	1	2	2	3	3	2	2	1	3	2
K	1/4	1/3	1/4	1/4	1/2	1/2	1/2	1/3	1/2	1/3	1	1/4
L	1/2	1/2	1	1/2	1	3	2	1	3	1/2	4	1

Table 8-3: Pairwise Matrix for comparing criteria against each other

Having ranked the criteria against each other, the next step was to generate the overall weightage for each of the criterion. In order to do so the following formulae was used:

$$Weightage\ for\ Criterion\ 'X' = \frac{Sum\ of\ Row\ 'X'}{Sum\ of\ all\ elements\ in\ the\ matrix} \tag{8-1}$$

Using the above formulae, the weightage for each criterion was decided and their priority was assigned as shown in Table 8-4

Criteria	Weightage	Ranking
Product Quality & Adherence to specifications	13.95%	1st
Pricing Offered	9.13%	6th
Lead Time	9.56%	4th
On Time Delivery & Order Fulfillment	11.36%	3rd
Warranty/Replacement	7.75%	7th
Terms of Payment	3.66%	11th
How easy are they to work with?	6.72%	8th
Financial Stability	6.72%	8th
Flexibility	6.63%	10th
Capabilities/Expertise	12.66%	2nd
Geography	2.58%	12th
Can we stay with them in the long term?	9.30%	5th

Table 8-4: Weightage for each Criterion

After the weights were established, the next step was to score vendors based on a scale of 5 for each of the above mentioned criterion, where 5 is extremely satisfied and 1 is unsatisfactory. Then a weighted average of those scores are taken to yield a final score out of 5 for each vendor. It is important to note that not all of the criteria are quantitative, some of them are qualitative in nature. Product quality can be easily measured by assessing the specifications requested and comparing them with the product delivered. Price offered and terms of payment can be assessed based on the quotations from vendors. On time delivery and lead time can be tracked based on when the order was placed and when it was received. Qualitative factors like financial stability, flexibility and capabilities in terms of the equipment owned and products that can be offered, can be judged based on visiting them and speaking with other clients of the vendors. "Can NVBOTS stay with a particular vendor in the long-run?", is an important question that needs to be answered and can be assessed based on the vendor's ability to meet growing demand and quality needs of NVBOTS.

In order to facilitate such assessment of the vendors, data related to the above criteria needs to be collected, which is currently unavailable at NVBOTS. However, a sample is shown in Table 8-5 below where two vendors supplying the same SKU were assessed and scored against each other. In order to obtain the total weighted score, the weights column was multiplied with either that of vendor X or vendor Y, and the total was calculated. It was seen from the final scores that vendor X fared better than vendor Y. Thereby, helping NVBOTS in choosing the right vendor.

Criteria	Weights	Vendor X	Vendor Y
A	13.95%	4	3
B	9.13%	4	5
C	9.56%	3	5
D	11.36%	4	5
E	7.75%	5	3
F	3.66%	3	3
G	6.72%	5	4
H	6.72%	5	3
I	6.63%	4	3
J	12.66%	5	5
K	2.58%	4	5
L	9.30%	5	3
Total Weighted Score:		**4.30**	**3.97**

Table 8-5: Vendor Rating

The vendor selection process doesn't stop with scoring vendors. Once they are scored, necessary analysis and corrective actions must be taken based on the scores. For example, based on the scores the procurement team might favor a particular vendor over another and engage in contracts with them. They might try to identify the reason for low scores for existing vendors, if any, and take corrective actions. Vendor rating also provides firms the opportunity to negotiate with vendors by leveraging the stronger vendor. However, it is important to note that the scores assigned to vendors are not a onetime thing, it is necessary to revisit both the criteria and the scores assigned, from time to time.

8.4 Summary

Most organizations do not employ any methodical approach for vendor selection. This is especially true of startups, who often select vendors based on price and quality offered. Though the factors in Table 8.1 are important factors, there might be other more important factors which should be assessed. Also, when companies grow, the complexity in the supply chain also increases. If supply chain and vendor relations are not managed well enough, it could break a company. Hence, it is very important to build good supplier relationships. At the same time it is equally important to assess existing vendors, identify risky vendors and have a systematic approach for selecting new vendors.

Vendor selection provides a systematic methodology to assess vendors and compare them against similar vendors. The process described above is very well applicable to startups as well as big organizations. Once the company can agree upon the criteria based on their needs, selecting vendors becomes a secondary issue. The pairwise matrix method mentioned in this chapter is useful to rank and assign weights to criteria. After the weights have been assigned, then vendors supplying a particular SKU or product are assessed and scored based on the criteria, and a weighted score is assigned to each vendor. Then, decisions based on these scores can be taken, in order to either select a vendor or engage in dual sourcing or contacts or to replace risky vendors. Considering that NVBOTS is experiencing growth and adding more vendors to meet their demands, the methodical approach suggested in this chapter will be very helpful.

Chapter 9
Conclusions, Recommendations & Future Work

9.1 Conclusion

The main motivation of the M.Eng MIT team was to assist and guide NVBOTS in ramping-up their production and manufacturing related activities. This goal was achieved through the collaborative efforts of Jain [1], van Grootel [2] and the author of this thesis. While Jain [1] and van Grootel [2] focused on manufacturing systems, the author of this thesis worked to solve the problems of inventory management.

The primary purpose of this thesis was to help NVBOTS in restructuring their inventory management policies and in establishing a vendor selection methodology. In order to accomplish the goal, some of the key activities included understanding the current inventory practices at NVBOTS, setting up a framework for data collection, determining when and how much of each SKU to order, framing policies for inventory tracking and control and establishing a methodology for selection of vendors. The following paragraphs outline the importance of the above mentioned activities and key learnings.

For any firm, in order to perform any type of analysis, correct data in the right format must be available. It was noticed that at NVBOTS, data was not available in a usable format, it was at a rudimentary level and hence it was tedious to organize the data into useful excel sheets. Data with respect to the annual demand, supplier lead time, unit price of components, inventory holding costs, stock levels, ordering costs, et cetera were collected. All the required data in order to efficiently carry out inventory management activities were listed and tabulated in excel sheets.

After studying the inventory ordering practices at NVBOTS, it was understood that most of the ordering was done on an ad-hoc basis and lacked methodology. Therefore, in order to have a plan of action for each type of SKU, it was required for all raw-material inventory to be classified into homogenous groups based on similar characteristics such as demand and price of components. Once the raw materials were classified into groups, specific ordering strategies based on traditional inventory models such as QR, EPQ and base stock were applied in order to determine the order quantity, reorder points and frequency of placing orders. These models were compared for the total required capital, inventory units and total cost, and then the appropriate policies were determined for each type of SKU.

At NVBOTS, the stock levels were recorded in Odoo (MRP) software. However, due to infrequent updating, it was noticed that there was often discrepancy between the actual stock level and those depicted on Odoo. This caused ordering problems which resulted in stockouts of a few SKUs and excess inventory for others. In order to solve this problem, a few inventory tracking methods have been outlined in the thesis. Also, the thesis outlines some of the best practices for inventory control related to inventory reconciliation, inventory storage and 5S methods.

Lastly, the thesis also outlines a methodology for vendor selection. Vendor selection is very crucial especially for growing companies. It is a multi-criterion decision process where each vendor is evaluated against a set of criteria and scores are assigned. This helps in identifying risky vendors, comparing multiple vendors, for forging contracts, for consolidating vendors and suggesting improvements to existing vendors. Currently, NVBOTS lacked a methodology to evaluate vendors and often qualified vendors based on only cost and quality of the product. The framework described is systematic where NVBOTS decides the criteria on which to rate vendors, then weights are assigned based on the relative importance of each criterion. Once this is established, each vendor is assigned a score against each criterion, a weighted average of the scores are taken in order to yield a single score for each vendor.

9.2 Recommendations

The recommendations made to NVBOTS are summarized in Figure 9-1. For more details with respect to the reasoning behind the recommendations refer Chapter 6, 7 and 8.

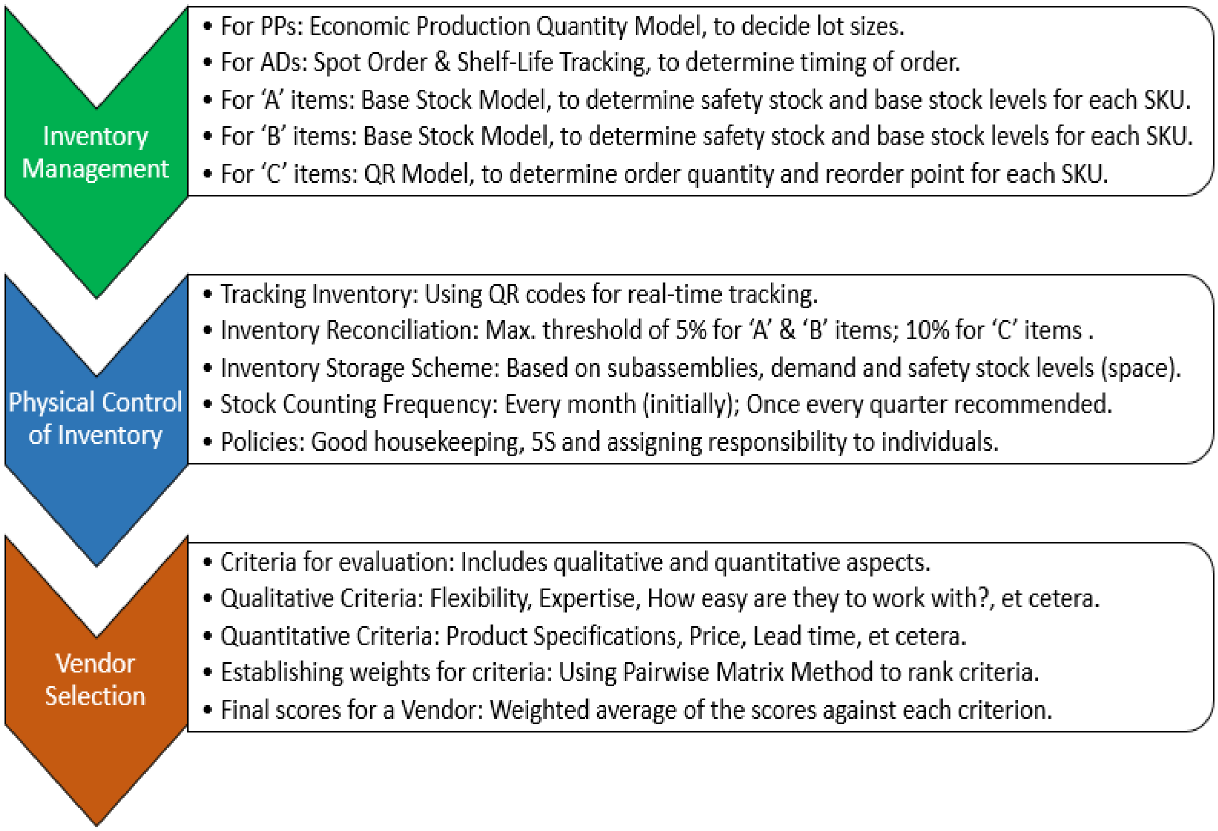

Figure 9-1: Summary of Recommendations

9.3 Future Work

Forecasting and Master Production Schedule:

Currently, there are no official month-wise demand forecasts available. NVBOTS needs to understand the market and predict the demand, especially considering that they are planning on introducing multiple product lines. This will be helpful for production planning purposes. If NVBOTS can develop a Master Production Schedule (MPS) indicating the planned production for an immediate time frame based on forecast and if NVBOTS can integrate production, staffing and inventory requirements, it would help in organizing things and ensuring that all necessary resources are available in time, in order to meet the demand requirements.

Design for Manufacturing of Printed Parts:

NVBOTS currently 3D prints close to 20 SKUs used in the NVPro printer. 3D printing these parts takes a large amount of time and when the demand for the 3D printers increase, this could potentially be a bottleneck. Hence, it is important to redesign these parts so as to make them suitable for conventional manufacturing on a large scale. Also, some of the issues of 3D printing include post processing and manning the 3D printers in order to replace spools, which are both time consuming and labour intensive. A cost benefit analysis must also be performed in order to determine whether it would be better to make them in-house by employing expensive NVPro printers or buy the redesigned parts from external vendors.

Explore available ERP software packages:

Considering that NVBOTS is growing quickly and expanding into new markets, it might be worthwhile for them to invest in an ERP software that will help manage work order management, inventory stock level, receivables and order placements, for tracking sales and customer service issues, for internal work allocation and accounting purposes. Currently, most of these activities are done independently on google documents and excel sheet. Integrating them into a robust and useful software will make things easier for NVBOTS.

Explore Dual Sourcing and Contracts:

Currently NVBOTS relies on single source of vendors for almost all of its SKUs. Especially for custom and critical components it might be worthwhile to consider dual sourcing. In the future, when both competition and demand for the 3D printers increases, having a robust vendor relationship is of utmost important. In order to reduce the risk in the supply chain, dual sourcing should be considered seriously. In case NVBOTS wishes to stick with single sourcing for a few SKUs then they must properly qualify the vendors and ensure that the vendor is capable of meeting the current and future requirements. Also, engaging in long-term with established vendors may be useful to not only reduce costs but in order to establish better vendor relationships.

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