Last-Time-Build Strategies of Spare Parts with the Advent of 3D Printing Technology

by

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ABSTRACT

Forecasting demand and managing spare part inventory has long been a challenge for products that have a very long lifecycle time. With demand being discrete, low and sporadic, understanding of the actual demand is erroneous and hence forecasting the right demand for a Last-Time-Build has been difficult. Managers routinely build buffer stock to avoid missing contractual agreements, with extremely high penalties for running out of stock. Thus, Last-Time-Build strategies have been expensive and non-profit yielding.

With the advent of 3D printing technology and its superiority in terms of the ability to setup shop at a low cost and print parts as and when required, make it a very promising technology in solving the issue of spare part inventory management.

In this thesis, a model-based approach was taken to the decision making of Last-Time-Build. By use of financial modeling and non-linear optimization tools, optimal strategies to best use 3D printing technology have been recommended, under several conditions of demand uncertainty. The most optimal results are achieved when a Hybrid approach is employed. The Hybrid approach is a combination of a Last-Time-Build via traditional manufacturing method that is supplemented with parts printed via 3D printer, to cater to changing demand, at a future point of time. The model helps in determining the best combination of parts that need to be built ahead and the parts that can be built later via 3D printing for various demand projections and a given service level that needs to be met. The sensitivity of each of the different variables involved on the decision making is also highlighted. The higher the uncertainty in demand, the more lucrative is the hybrid approach to solving the problem of spare part inventory management.

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TABLE OF CONTENTS

1 INTRODUCTION ..... - 12 -

2 BACKGROUND ..... - 13 -

2.1 UNDERSTANDING VARIOUS LIFECYCLE STAGES OF A PART ..... - 13 -

2.1.1 Concept and New Product Development ..... - 13 -

2.1.2 Production Lifetime ..... - 14 -

2.1.3 End of Life ..... - 14 -

2.1.4 Service ..... - 15 -

2.2 HOW BIG IS THE SCALE OF THE ISSUE - A SYSTEMS DYNAMICS MODEL APPROACH? ..... - 16 -

2.3 WHAT IS THE ISSUE IN MANAGING EOL AND SERVICE PARTS? ..... - 18 -

2.3.1 Financial Implications ..... - 18 -

2.3.2 Manufacturing Implications ..... - 18 -

2.3.3 Customer Dissatisfaction and Perception of the company ..... - 19 -

2.3.4 Constant resource re-allocation ..... - 19 -

3 PROBLEM DEFINITION AND EXISTING OPTIONS ..... - 21 -

3.1 BUILD AHEAD AND STORE – LAST TIME BUILD ..... - 21 -

3.2 TRANSFER PRODUCTION TO A THIRD PARTY VENDOR AT START OF EOL/SERVICE LIFE ..... - 22 -

3.3 LEVERAGING ADDITIVE MANUFACTURING (3D PRINTING) TECHNOLOGY ..... - 23 -

4 LITERATURE SURVEY ..... - 25 -

5 MODEL AND METHOD ..... - 29 -

5.1 OVERVIEW ..... - 29 -

5.2 ASSUMPTIONS ..... - 30 -

5.3 VARIABLES INCLUDED IN THE MODEL ..... - 31 -

5.3.1 Demand ..... - 31 -

5.3.2 Setup Cost of a 3D printer ..... - 33 -

5.3.3 Per Unit Cost of Production ..... - 33 -

5.3.4 Inventory Management Cost ..... - 34 -

5.3.5 Discount Rate ..... - 34 -

5.3.6 Final Discounted NPV ..... - 34 -

6 CASE SETUPS, RESULTS AND DISCUSSION ..... - 36 -

6.1 CASE 1 – DETERMINISTIC DEMAND – NO 3D PRINTING OPTION – BASE CASE ..... - 36 -

6.2 CASE 2 - DETERMINISTIC DEMAND – OPTION TO 3D PRINT ..... - 36 -

6.3 CASE 2A - DETERMINISTIC DEMAND – OPTION TO 3D PRINT – PER UNIT 3D PRINTED COST VARIES ..... - 38 -

6.4 CASE 2B - DETERMINISTIC DEMAND – OPTION TO 3D PRINT – PRINTER SETUP COST VARIES ..... - 40 -

6.5 CASE 2C - DETERMINISTIC DEMAND – OPTION TO 3D PRINT – DISCOUNT RATE VARIES ..... - 41 -

6.6 CASE 3 – UNCERTAIN DEMAND – NO 3D PRINTING OPTION ..... - 43 -

6.7 CASE 4 – UNCERTAIN DEMAND – OPTION TO 3D PRINT ..... - 44 -

6.8 SUMMARY OF INSIGHTS GAINED ..... - 46 -

7 CONCLUSION AND FUTURE WORK ..... - 48 -

8 REFERENCES ..... - 49 -

TABLE OF FIGURES

Figure 2.1 Different stages of a product lifecycle ..... - 13 -
Figure 2.2 Table summarizing values of variables during different lifecycle stages ..... - 15 -
Figure 2.3 Illustration to help understand the stock and flow concept ..... - 16 -
Figure 2.4 Simple System Dynamics Model to understand impact of this problem ..... - 16 -
Figure 2.5 Graph showing the need to better manage EOL/Service Parts ..... - 17 -
Figure 5.1 A Typical Lay Shaft ..... - 30 -
Figure 5.2 Example of an exponentially decreasing demand curve used in model ..... - 32 -
Figure 5.3 Demand Variation and probability of each demand occurrence ..... - 32 -
Figure 5.4 Fluctuation in demand resulting in different demand curves ..... - 33 -
Figure 5.5 Variables, units and assumed base values ..... - 35 -
Figure 6.1 NPV comparison between Case 1 and Case 2 ..... - 37 -
Figure 6.2 Graph illustrating demand fulfillment in hybrid strategy ..... - 37 -
Figure 6.3 Effect of variation of per unit cost of a 3D printed part on the Net savings ..... - 38 -
Figure 6.4 Variation in Net savings with variation in the per unit cost of 3D printed parts ..... - 39 -
Figure 6.5 3D printer introduction delayed with increase in cost per unit of 3D printed part - 39 -
Figure 6.6 Effect of variation in one-time setup cost of 3D printer ..... - 40 -
Figure 6.7 Deep Dive into understanding results of effect of setup cost variation ..... - 41 -
Figure 6.8 Effect of variation of Discount Rate on optimal hybrid strategy ..... - 42 -
Figure 6.9 Increasing discount rate quickening the process of 3D printer introduction ..... - 42 -
Figure 6.10 Number of parts to build ahead to support 99% service level ..... - 43 -
Figure 6.11 Higher cost to cover uncertainty in demand ..... - 44 -
Figure 6.12 Savings in hybrid strategy in spite of uncertainty ..... - 45 -
Figure 6.13 Higher savings in hybrid method as uncertainty increases ..... - 46 -

ABBREVIATIONS

LTB	Last Time Build
NPD	New Product Development
OEM	Original Equipment Manufacturer
EOL	End Of Life
OTD	On Time Delivery
MOQ	Minimum Order Quantity
NPV	Net Present Value
SLS	Selective Laser Sintering
3D	3 Dimensional
CAD	Computer Aided Design
IP	Intellectual Property
NUB	Number of Units Built

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1 Introduction

Managing the End-Of-Life and Service periods for a product is a very big challenge for OEMs when these products are used in end-products that have very long lifetimes – in the order of 20 years or above. For various industries such as automotive, airlines, industrial machinery and military vehicles, the OEMs are typically bound by contract to have the spare parts available for extensively long periods of time. Spare parts inventory is thus needed for maintenance and repair of final products, vehicles, industrial machines and equipment, frequently requiring high investments and significantly affecting customer satisfaction. Inventory management is complex due to the large number of different items in a portfolio and low intermittent demands. Spare parts inventories are different from other types of inventories in companies. Some important factors in the management of these inventories include:

- The great majority of such parts have intermittent demand and;
- The increasing complexity of products and the life cycles reduction generate an increase on the amount of active codes and risk of obsolescence.
- Mismatch in lead times from OEM to customers versus sub-suppliers to OEMS, frequently results in delays and final customer unhappiness. This could adversely affect the relations when bidding for new businesses with the same customers.
- Finally, customers have rising expectations concerning quality of associated products and services. The occurrence of failure is already a concern and the delay in repairing due to lack of spare parts worsens clients' negative perception;

Firms with a well-aligned spare parts logistics strategy can add value for their customers beyond primary product benefits, thus building long-term customer loyalty and achieving high profit margins. Firms across different different industries now recognize spare parts supply not only as a legal obligation, but also as a chance to offset stagnating or declining revenues and to increase profits in their primary product markets. Thus, spare part management is becoming extremely critical and companies have to look at leveraging radically newer methods & technologies apart from the traditional ones such as better forecasting and better warehouse management.

2 Background

Before delving into the problem at hand, there is a need to discuss the necessary background for a typical product development cycle, the demand profile and the cost and price intricacies. A simple yet detailed system dynamics model helps understand how the portfolio of a OEM could be overloaded with EOL/Service parts warranting a lot more focus. Finally, the issues related to ineffective management of spare parts is detailed to help appreciate the scale and impact of the problem and the need to solve it effectively.

2.1 Understanding various lifecycle stages of a part

The product lifecycle of a part can be broadly divided into 4 sections based on the volumes of production and the percentage of the parts used in a new product versus as a replacement part in a used product.

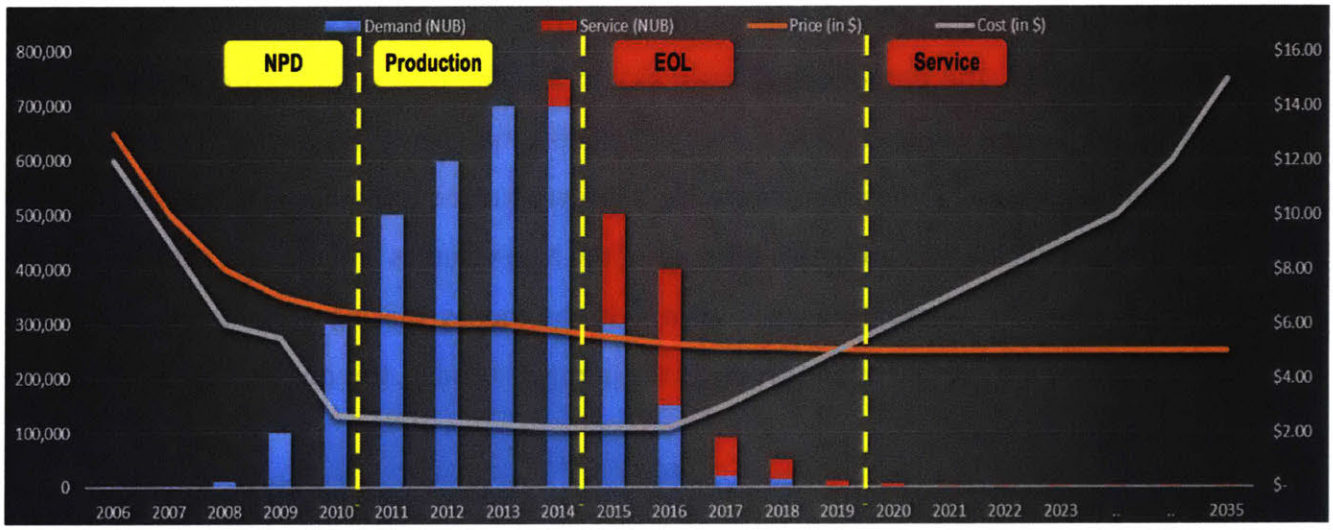

Figure 2.1 Different stages of a product lifecycle

The 4 different stages in a product lifecycle are shown along with the typical cost and price values over each of these stages. The blue and the red color on the columns indicate the portion of the demand that is used in new end-products versus as a spare part. Please note the red (spare part) section dominates as the product enters EOL and Service stages of the lifecycle.

2.1.1 Concept and New Product Development

This is the phase where a part is being designed and developed by the OEM in collaboration with the customer. The specific requirements are being implemented and prototypes of the parts are

being tested in-house in simulated conditions as well as with the customers in actual usage conditions. Once the customer is happy with the product, OEM starts to bring up the high volume production lines into force, gearing for the high demand that is expected to materialize.

The cost per unit produced is high, but so is the price charged to the client. The client however accepts this high price since the volumes are low and they understand that there is a development cost involved which is not just the cost of the materials. However, with the volumes ramping up, the fixed costs get distributed and the cost and price both start coming down.

This phase, depending on how fast the end product is planned to be brought into market, may last between 1-3 years.

2.1.2 Production Lifetime

This is the phase when volumes are high and the end product is in mass production. Depending on the popularity of the end product and the number of parts used in each product, the volumes could even be in 10s or 100s of millions per year. This is the phase when the OEM enjoys the maximum profits. The economies of scale kick in and the cost is reduced dramatically. Even through the price is reduced, OEM enjoys the highest margins in this phase. This is the golden period of the product – the volumes are high, the production is in full swing, margins are high, the sub-suppliers are also profitable because of the high volumes and the part gets the required attention from the product manager since it is the money making unit. Depending on the popularity and the number of end products the part gets used in, this phase of the product could last between 3-6 years.

2.1.3 End of Life

End of Life is the next phase of the product. In this phase, the part has already been in production for a few years. The volumes are now steadily declining. The end product is also getting older and may soon be replaced by a newer model. The part for itself has now a newer successive generation which has incorporated the latest technologies and advancements in manufacturing thus necessitating replacement. A higher percentage of the demand is now being used as replacement parts in used products rather than new products. The tools and machines for

manufacturing the parts are getting older and have frequent maintenance schedules to keep them in shape. The cost is beginning to rise, since the volume based discounts are not as effective and the fixed costs including maintenance are on the rise. But the price is more or less constant. This phase may last between 2-4 years

2.1.4 Service

Finally, several years since this part was first manufactured, it will not be used in any new end product. The end product ceases to be manufactured. The volumes drop drastically compared to the peak volumes from the production phase. These parts are now used 100% only as replacement parts or spare parts for the end products still in use. Not only are the volumes extremely low but also intermittent and sporadic. The fixed and maintenance costs shoot up, since the volumes do not support these costs and are now a significant part of the total cost. The customers anticipating this, have regulations in the contracts that disable the OEM to raise prices and also enforce to keep the part in production for the next foreseeable future. This phase depending on when both the parties agree as the start of the service period, will last between 10-15 years at the least.

A small table summarizing all the phases and the various components of a product lifecycle is shown below.

	Order of Phases	Duration (in Years)	Volumes (Million units)	Cost ($)	Price($)	% used in New End-product	% used in Used End-Product
NPD	1	0-3	LOW	HIGH	HIGH	100	0
Production	2	3-8	HIGH	LOW	MED	90	10
EOL	3	2-4	MED	MED	MED	30	70
Service	4	10-15	VERY LOW	VERY HIGH	MED	0	100

Figure 2.2 Table summarizing values of variables during different lifecycle stages

2.2 How big is the scale of the issue - a systems dynamics model approach?

There are several implications of handling these EOL and Service parts. But, we need to understand the scale of the issue for an OEM. A simple system dynamics model that shows the flow of a given part in each of these different lifecycle stages described above illustrates how a large proportion of the total portfolio is comprised of these EOL/Service parts. The model is analogous to the following example of buckets (lifecycle stages) that have inlet and outlet valves with a different flow rate. These rates are defined by how long a part stays in a given bucket, i.e. if the time a part stays in the bucket is small, it means that the outflow rate is high and vice versa.

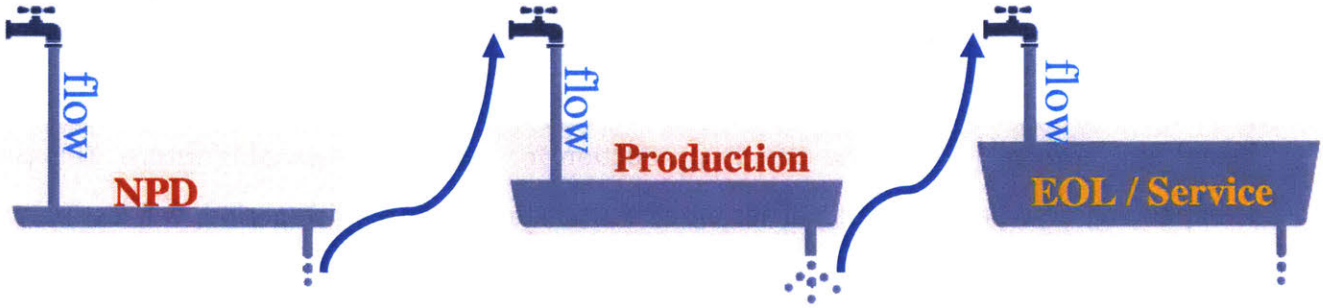

Figure 2.3 Illustration to help understand the stock and flow concept

A simple illustration to help understand the concept of stock(level) and flow as the part goes through different lifecycles. If the incoming flow is fast and outgoing flow is slow, the stock(level) of that stage goes up, as seen in the final EOL/Service bucket

The corresponding System Dynamics model looks as below.

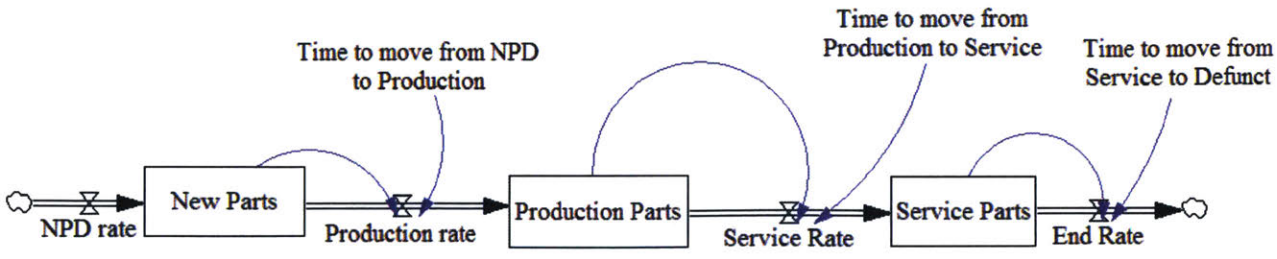

Figure 2.4 Simple System Dynamics Model to understand impact of this problem

Where the Time to move from NPD->Production and Time to move from Production->Service are determined from the figure 2.2 above and can be varied within the given ranges.

The rates, i.e. *Production Rate* means the rate at the which parts are moving from the lifecycle stage of new parts to the production part. It is simply the *Number of New Parts* divided by the *Time to move from NPD to Production.*

Applying all the above assumptions for a company that started 20 years ago, will have the following growth in the stock of Service (& EOL) parts. Presently, (20 years on) they have ~50% of their entire portfolio as service parts and in the next 20 years, that ratio is going to go as high as ~75% of the entire portfolio.

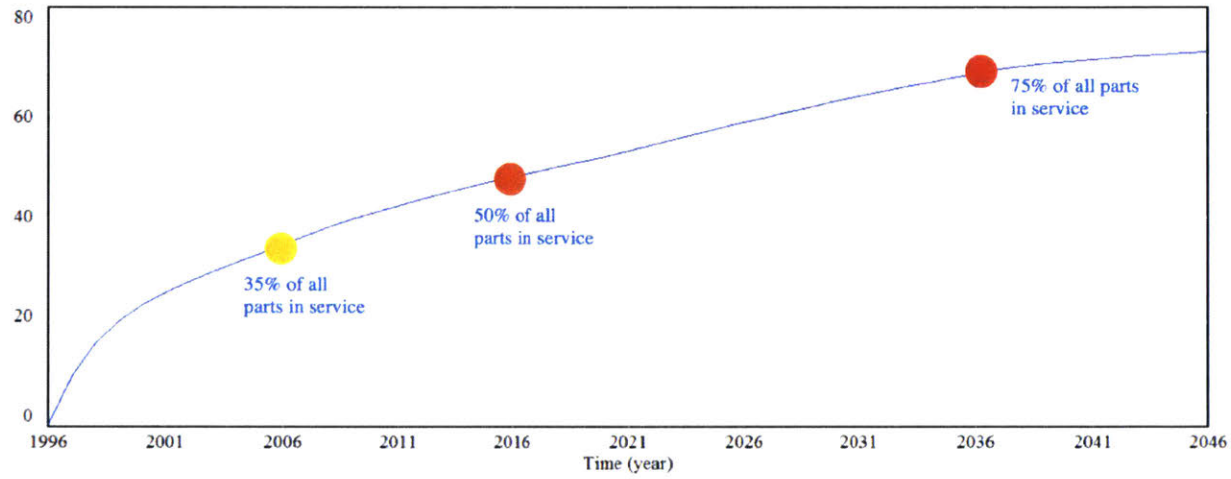

Figure 2.5 Graph showing the need to better manage EOL/Service Parts

With the stocks and flows values and the very long tail of service life we discussed earlier, the graph above shows that these parts become a very large section of the portfolio and managing them well, becomes imperative for the OEMs

This is a big chunk of the portfolio that is difficult to manage and is growing all the time. It warrants dedicated attention from the managers.

2.3 What is the Issue in managing EOL and Service parts?

This section details the potential problems if the OEMs do not do a good job of managing the EOL/Service parts.

2.3.1 Financial Implications

There are several financial implications starting with reducing Gross Profit margins, which sometimes could be in negative, i.e., the OEM makes a loss in every part it actually sells.

- ✓ Suppliers stop giving volume based discounts, resulting in increased raw material costs. Supplier uncertainty results in local or expedited sourcing which in turn results in extremely high costs and delays in procurement. Thus, higher expedited shipping costs on both the sourcing and the delivery side.
- ✓ Machineries need to be maintained, calibrated and periodically serviced.
- ✓ Cost increase in raw materials – MOQ issues
    - When contracts with sub-suppliers were signed initially, a lower price was negotiated based on the higher volume, typically called the MOQ (Minimum Order Quantity). The raw material could only be bought in these discrete volumes.
    - When production is in millions, a MOQ of 10,000 makes total sense, but when the same part is in the service phase and is being produced only in hundreds or tens of units a year, the company will have to buy and hold raw material inventory that could last a decade or may never even be used.
    - Aggregate this problem to more than one sub-parts per spare part produced, the scale of financial impact could be huge

2.3.2 Manufacturing Implications

Machines occupy floor space – there is a finite amount of floor space available in the manufacturing plants and it would be ideal to have the highest volume/revenue producing tools occupy the space. Moreover, the computers on the tools for spare parts are decades' old and are

typically outdated. The technicians who were skilled in the old system may not be with the company anymore.

Each product has several sub-parts which are sourced from sub-suppliers. Because the demand is lumpy and unpredictable, the production planning and make planning have to always plan these tactically. This usually demands a lot of their time, in comparison to the high volume production, since the later is a steady flow. The $/hr spent does not make economical sense.

The lead time for sub-components is an issue. While the lead time to the customer is fixed by contract, the lead times of raw materials could be extremely long in comparison and may not match that of the customer. For example, the lead time could be as high as 16 weeks for a raw material if it is a metal, while the customer lead times promised as per contracts could be only 2 weeks. So, if the OEM has not planned ahead and stocked the raw material in advance, and an order drops in from the customer, there is no way the 2 week lead time can be met without paying extremely high prices for expediting the raw material or in some cases simply not fulfilling the order long after it was due.

2.3.3 Customer Dissatisfaction and Perception of the company

The issues in manufacturing and production results in delayed deliveries or deliveries with quality issues. The customer is unhappy with this and since the volumes are low, penalizing financially may not be an option. So, the customers express their unhappiness in the scores given on scorecards to the OEM as a supplier, that in future, affects when the OEM is bidding for new business. Managing EOL/Service parts poorly hurts the perception of the OEM in the long run.

2.3.4 Constant resource re-allocation

Although, this is a soft issue, it can have significant impacts on the long-term prospective. There are frequently occurring issues related to the EOL/Service parts and resources are constantly being pulled away from planned activities to firefight them. The frequent fire-fighting makes the manager and employees weary and such unscheduled distractions make the planned projects

delayed ultimately hurting the existing projects and the cycle continues. Sourcing for spare parts can thus be very distracting to materials manager.

As is explained in the previous section, from the System Dynamics models, the portfolio of a product manager contains a lot of EOL/Service parts. However, these parts(SKUs) do not bring in significant revenues as the volumes are so low, so the product manager, due to obvious incentives, has higher focus on the production parts. So, the larger the proportion, the lesser the time to evaluate individual part or SKUs, the more the risk of an upcoming issue getting neglected till it blows up into a big issue requiring even more time and money. This is a negatively re-enforcing loop.

To circumvent the above issues, the most common method is to do a Last Time Build. Managers typically make a forecast of the expected demand of the spare-part, for the number of years promised in the contract and add a safety buffer on top of it. Then these parts are manufactured and stored in the warehouse, while the tooling is dismantled and floor space cleared. Although, this alleviates some of the problems, it is an expensive and risky option if the demand does not materialize as forecasted. In the next section, we will discuss the specific problem statement and how the thesis helps provide a framework to aid decision making by product managers.

3 Problem Definition and Existing Options

In summary, Service and EOL parts currently cause many issues with component supply and production, hurt the perception of the OEM with their customers and get very little attention from the organization. There is a need to define a systemic way to more effectively and efficiently manage service parts. The goals of an efficient and sustainable solution are the following.

- ✓ Low cost of production
- ✓ On Time Delivery improvement
- ✓ Improved Customer Sentiment and Scorecards
- ✓ Reduced Complexity at Production/Manufacturing Sites
- ✓ Supplier Consolidation
- ✓ Proactive versus Reactive Approach
- ✓ Profit Enhancement

There are several approaches and combinations of such, that have been tried by different companies to approach this problem at present. A few of these, with pros and cons have been detailed below.

3.1 Build Ahead and Store – Last Time Build

This is the most common solution that companies resort to and will form the base of the research, model build and analysis. In this solution, the OEM estimates expected demand to the best of their ability and builds the parts ahead of time and stores in their own warehouses and satisfies demand as it materializes.

Pros

- ✓ Easier to manage demand, since abrupt demand can be met immediately resulting in higher customer satisfaction
- ✓ Economies of scale are still relevant for the one last build since we will build in larger quantities

- ✓ Do not have to worry about maintaining the supply chain for very long periods of time
- ✓ Machines can be sold/disposed off, to obtain some salvage value, when these machines are still relatively new
- ✓ More floor space feed up for newer high volume SKUs

Cons

- ✓ Cost of holding inventory – locked capital
- ✓ Since, demand is very unpredictable, the OEM might be left with a lot of unsold inventory which they will have to write off
- ✓ On the other spectrum, the OEM could run also out of all the parts they had produced with no capability to build more since they have already closed down the supply chains and disposed off the machineries
- ✓ Perishability of the parts – finite shelf life
- ✓ Finally, if the discount factor is high, the revenues earned in later years will be discounted, whereas, the cost was upfront and non-discounted thereby reducing the profit margins significantly.

3.2 Transfer production to a third party vendor at the start of EOL/Service life

In this alternative solution, the OEM decides to move the entire production lines including the tools and machineries to a third company. The third party then supports the part through the remaining life time.

How can it help the three players involved?

- ✓ The ***OEM*** has extracted most of the value from the part and moving forward, the low volumes are no longer lucrative for this large high volume player and they see it easier and more efficient in the long run, to offload it to a smaller company. They can thus focus on the innovation and design of the next generation parts which is their core expertise.

- ✓ The third party smaller company, sometimes called as ***machine shops*** specialize in optimization of manufacturing process. Because of their smaller scale and higher efficiency, they can extract the value that the large OEM cannot. The can also re-use these machines inherited from the OEM at extremely discounted prices, for building other parts in the future. They also get to start building a relationship with these bigger original clients of the OEMs and stand to win business of their own
- ✓ The ***Customer Company*** does not really have a big advantage/disadvantage, since they typically do not care who makes the part, as long as it meets specs and is delivered on time with minimal cost. However, dealing with a machine shop would provide them the advantage of nimbleness and options for any further customization.

However, for this option to be successful and ensure a win-win-win situation for all the key players involved, some critical decisions have to be made.

Some examples of such critical decisions are:

- ✓ At what point in the lifecycle of the part, should the transfer be done to the machine shop.
- ✓ Who owns the IPs?
- ✓ How is quality ensured?
- ✓ How long of an overlap period required to ensure smooth transitioning etc.?

Some other methods that could be employed by an OEM are:

- ✓ Initial Pricing of the device to include the entire lifetime of the product
- ✓ Last Time Buy by the customer and they hold the inventory
- ✓ Open own spare part stores and franchises that sell at costs high enough to make the sale of each part profitable

3.3 Leveraging Additive manufacturing (3D printing) technology

Of late, significant advances have been been made in the field of 3D printing technology. 3D printing, alternatively known as additive manufacturing, can be defined as the processes to

create a 3-Dimensional object, in which layers of materials are formed on top of each other by heat and pressure by controlling from a computer. Objects can be almost any shape or geometry and are created using digital model data from a 3D model or additive manufacturing electronic file.

The system starts by applying a thin layer of the powder material to the building platform. A powerful laser beam then fuses the powder at exactly the points defined by the computer-generated component design data. The platform is then lowered and another layer of powder is applied. Once again the material is fused so as to bond with the layer below at the predefined points. Depending on the material used, components can be manufactured using stereolithography, laser sintering or 3D printing.

Presently, there are several vendors who own 3D printing machines and help create industrial grade, high quality metal parts, provided the CAD design files. OEMs can choose to leverage the unique opportunity provided by the advent of 3D printing and avail of the services of such vendors to provide the required flexibility in demand planning to help tackle the problem of EOL/Service lifecycle management for spare parts.

The thesis via suitable financial, non-linear programming and Monte-Carlo simulation models explores this possibility and compares it with the traditional and frequently used Last-Time-Build strategy. Depending on conditions of demand and several other variables, the model aims to provide a decision making framework for the manager. The proposed model would help analyze several conditions of demand variations and suggest the best approach on whether to leverage this technology and how best to do so, as compared to the base scenario, where the OEM decides to build all the spare parts ahead of time and satisfying demand as it occurs.

4 Literature Survey

A lot of work has been done in general on modeling demand and plan for a corresponding inventory management. All of these methods have relied on the fact that the parts can only be created via the traditional manufacturing method and improvisations in the forecasting, understanding part characteristics and production planning can help managers better manage spare part inventory.

The life cycle of spare parts is associated with the life cycle of the final products which use them[1]. Their demand is affected by several factors: size and age of the "population" of final products (sales, running fleet, installed base, etc.); maintenance characteristics of these products (preventive, corrective, etc.); and characteristics of the parts and their defects (wear, accident, aging, etc.). Throughout these phases, different decisions have to be taken:

- ✓ *To hold inventory or not:* demands which are very low in the beginning of the life cycle (as well as in the end) lead the manager to question whether parts should be stored or not. For many items, the demand is so low that the decision of not storing, meeting the demand circumstantially after its occurrence may be the best decision;
- ✓ *Initial orders:* uncertainty about the demand growth hampers the planning of the initial orders;
- ✓ *Inventory control:* upon deciding that the part needs to be stored, an inventory replenishment routine is necessary, considering different goals (costs and/or service level) and demand behavior (trends and seasonality) and;
- ✓ *Final orders:* high production and maintenance costs of the productive processes associated with low demands and expected lifespan of products lead companies to interrupt the production of parts at a given time. In some cases, the last production batch is increased to provide additional spare parts final inventory.

Most spare parts present intermittent demand, that is, occur at given moments followed by long and variable periods without demand. Intermittent demands are particularly difficult to predict

and shortage may result in extremely high costs. Demand forecasts are absolutely necessary for the inventory levels planning. Although forecasts are subject to errors, the knowledge of these errors enables the definition of the necessary safety stocks. Ghobbar and Friend in 2003 [2] compared 13 forecasting techniques to aircraft parts demand and proved the superiority of the techniques: weighted moving average, double exponential smoothing (Holt), and Croston's method. Rego and Mesquita [3] in their paper have diligently recorded a complete literature review of spare part inventory control techniques of various authors and have done a simulation study of 136 scenarios for more than 6 years with over 10000 parts to record their findings. Their results were tuned to the best policies within each SKU category.

One alternative for the reduction of spare parts inventory levels is the critical revision of the need to maintain or not each one of the items active. Models developed under the premise that all items must be stored should be reconsidered. Is it worth bearing the costs of storage, even for only one unit, or would it be better to acquire the item under demand? Olthof and Dekker [4] in 1994 presented a storage decision rule for spare parts where at least one unit should be kept in inventory if its unit annual holding cost is greater than the expected annual shortage cost (emergency purchase and penalties for downtime).

The shutdown of the production of a certain product causes the life cycle of the spare parts exclusive of this product to enter a decreasing phase and brings up important questions to managers: for how long should the spare parts inventory be replaced? How much should be ordered in a last batch? After the last order (or even before), given a certain excessive amount of stored parts, how much should be scrapped in face of decreasing demands?
At the limit, not to stock may be the most economical alternative to the manager. Yet, some legal aspects can superimpose the economic criteria in this decision-making.

Silver, Pyke and Petterson in their 1998 book [5] discussed how large the final order should be in face of the decreasing uncertain demands and argued that the costs involved (excess inventory vs. shortage cost) are difficult to balance. Alternatively, they set a minimum desired service level

to be reached by the final order. Their model is based on the estimates of demand during the remaining life cycle and its standard deviation.

Teunter and Fortuin in 1998/99 [1] reported a theoretical improvement after the application of the inventory model for spare parts at Philips, in its service headquarters located in Eindhoven, the Netherlands. This center supplies parts during the service period. The service period, in general, largely exceeds the production period and a final order must be made for the last replacement, which occurs simultaneously to the closing of the production period. The final order should (with high probability) be enough for all the remaining service period. The developed formulation balances the costs of parts shortage (leading to the substitution of the complete product by a new one or to the offer of discounts to the costumers) and the costs for producing/purchasing and storing these parts. The authors apply stochastic dynamic programming to achieve the optimal solution and also present a simplified version that provides near optimal solutions.

Of late however, some companies have actually started using 3D printing technology selectively to avoid having to store vast stocks of spare parts and rather print them as and when they need it. For instance, 3D printing has allowed Audi to disrupt its own internal supply chain.[6] It cannot implement 3D printing across the whole parts catalogue, 3D printing just isn't at that stage. However, with strategic placement of 3D printers around the globe, Audi has managed to eliminate over production of certain parts and can now print them on demand. This saves a vast amount of money sitting in idle stock. The German manufacturer is working with both Direct Metal Laser Sintering and Electronic Beam Additive manufacturing to perfect the process and it won't be long before additive manufacturing is totally ingrained in the manufacturing process.

Daimler, the world's largest truck manufacturer, plans to use three-dimensional printing (3D) to produce spare parts, the latest example of how digital technologies are radically reshaping automotive manufacturing and its supply chain.[7] It will use 3D printing processes for plastic spare parts including spring caps, air and cable ducts, clamps, mountings and control elements.

The truck maker's "printed" spare parts are created with 3D printers based on what is known as a selective laser sintering (SLS) printing process, and ordered using a special spare part number, even for parts on models that are several decades old or even out of production.

Cavalieri, Garetti, Macchi & Pinto have in their paper in 2008 [8] outlined a 5 step process as part of a decision making framework for managing spare parts. The five phases are: Part Coding -> Part Classification -> Part Demand Forecasting -> Stock Management Policy -> Policy test and Validation. By evaluating a spare part and following these step-by-step process, the authors claim that an effective spare part management policy can be built for a company.

In this thesis, however, we discuss specifically about a decision making methodology for Last-Build with the presence of an option to leverage 3D printing (or additive manufacturing) technology and a strategy for securing the lowest costs.

5 Model and Method

To help guide the managers, a model was built as a decision making tool. Several factors were considered in the model that act as variables. Together with a clear set of assumptions, the model evaluates both the options –

1. Last Time Build from the factory
2. Last Time Build with the option to 3D print.

The LTB from factory method from now on will be termed as the **'Traditional'** method, while the LTB method via traditional manufacturing with the option to supplement by 3D printing will be termed as the **'Hybrid'** method.

5.1 Overview

The model is a financial model, that evaluates the Net Present Value for a spare part management strategy over a period of 20 years. We use both deterministic as well as stochastic demand with Non-Linear Programming and Monte Carlo simulations to evaluate and compare different scenarios and create a decision making strategy.

To set the model up, we take an example of a mechanical part (for example a lay gear) that can be 3D printed using the SLS (Selective Laser Sintering) additive manufacturing method. A picture of a lay gear is shown below to help the reader visualize the type of spare part that is being discussed.

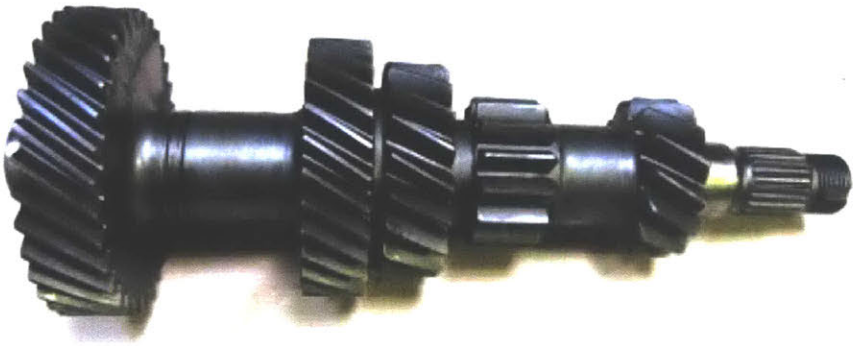

Figure 5.1 A Typical Lay Shaft

Image Credit:
http://www.lrseries.com/resources/user/5/0/a/0/50a008f6cc1750ba525dda4e731a7629f6946d5b/FRC8141-LAYSHAFT-CLUSTER-LT77.jpg

Knowing the cost to produce it via the traditional method, the cost to produce it via the 3D printing method, along with other variables such as expected demand, an inventory management cost, discount rate and a one-time cost of setting up the 3D printer, we can analyze the two strategies and understand which is a prudent option to follow.

5.2 Assumptions

The model has been built based on certain key assumptions. All of these assumptions are listed here to set the stage for understanding the model and methodology better.

- ✓ There is a per-unit-cost to manufacture the part via traditional manufacturing method. This cost is a variable cost, since the fixed cost has long been recovered as the machinery has been in operation for a significant number of years.
- ✓ There is a different and higher cost of producing the same part via a 3D printer.
- ✓ Price of each part sold is constant, since it is bound by the contract. Hence, price has been omitted from the calculations and only costs are being calculated and compared across the various cases and scenarios. The lower cost, the better.
- ✓ The OEM is committed to provide the spare part for all of the 20 years. This is non-negotiable, since it is bound by contract, which is typically the case.

- ✓ A service level of at least 99% is expected to be met
- ✓ The demand is exponentially decreasing with a long tail and is smooth (there are no fluctuations in demand within a given year)
- ✓ The OEM does not buy and own the 3D printer, rather, uses a vendor that owns the printer and helps the OEM set it up. There is a one time cost of setting it up.
- ✓ The speed at which the parts are 3D printed is sufficient to cater to the demand – there is not a need to do multiple installations of the 3D printer.
- ✓ There is no salvage value for any of the traditionally manufactured parts if they are not sold at the end of the 20 years
- ✓ Economy of Scale is not being considered either in the traditional manufacturing method or in the 3D printing method.

5.3 Variables included in the model

Several variables have been considered while building the model. To understand the effect of each of these critical variables, sensitivity analysis has been done and these will be discussed in the results and summary section. A description of each of the variables is discussed below.

5.3.1 Demand

Since the product is in the end of its life, the demand is assumed to be exponentially decreasing over a period of 20 years. The demand falls sharply initially and has a long tail. There is a known demand at year 0 and there is an expected demand at year 20. The area under this curve is the total cumulative demand of the part over the entire period. For, instance, in the deterministic case, for a demand of 150 units at year 0 and a demand of 5 units at year 20, the total cumulative demand is 957 units over 20 years.

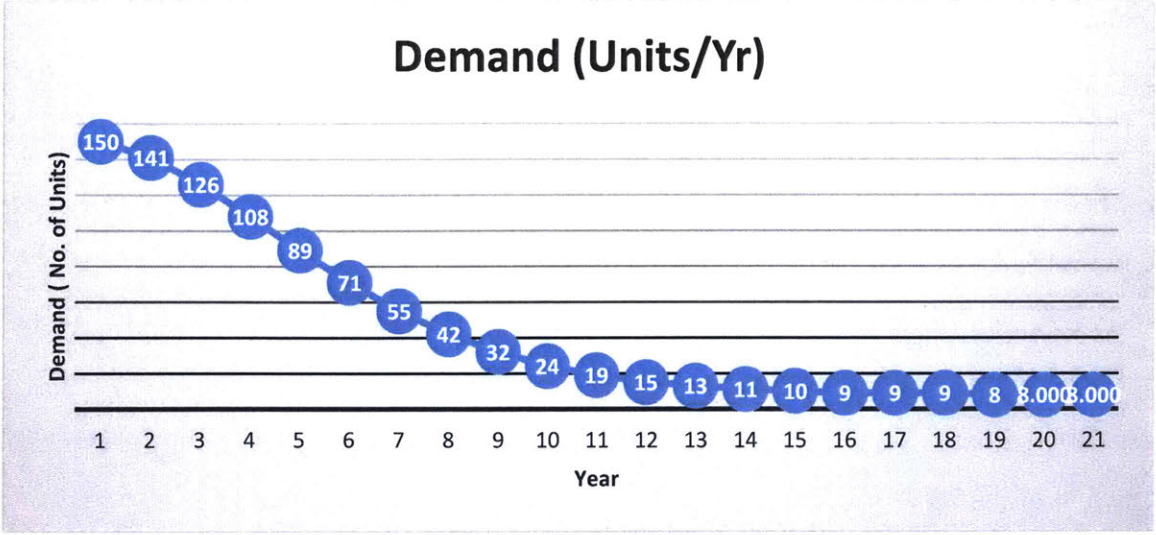

Figure 5.2 Example of an exponentially decreasing demand curve used in model

However, when we introduce uncertainty in demand, we keep the demand at year 0 constant at 150, since we will always have a very good estimate of what the demand is at the beginning of the period. But, the demand in year 20 could vary and we are modeling it such that it is between 0 and 10. A different value at the end of the demand changes the shape of the entire curve, thereby changing the resulting area underneath, which is the total demand. We assume the distribution or probability of each of the different demands to follow a normal distribution centered around the total demand curve of 957. The table below shows the different cumulative demands and their probability distribution.

Demand at year 20	Total demand over 20 years	Normalized distribution centered around 5
0	734	0%
1	778	1%
2	827	4%
3	874	11%
4	917	21%
5	957	25%
6	1003	21%
7	1047	11%
8	1101	5%
9	1147	1%
10	1190	0%

Figure 5.3 Demand Variation and probability of each demand occurrence

As the final year demand changes, the total demand changes. The distribution of these different demands follows a normal distribution centered around the demand of 957 units over 20 years.

A pictorial representation of the various demand curves based on the table, is shown below. Each of the lines represent a different demand and the probability of a certain demand happening is based on the normally distributed.

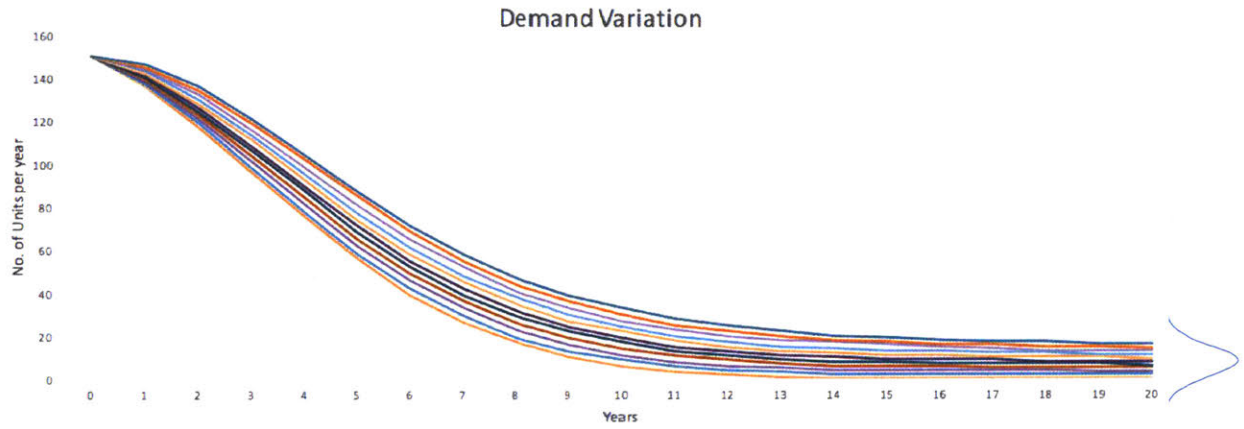

Figure 5.4 Fluctuation in demand resulting in different demand curves

Although all the curves have the same starting point of 150 parts, the demand at the end of the time period, determines the shape of the demand curve and hence the total demand. Please note that the probability of occurrence of each of the curve is also normally distributed as per the curve on the right

5.3.2 Setup Cost of a 3D printer

There is a one-time setup cost assumed for the 3D printer. The OEM does not buy or lease the printer, rather uses it as a service from a vendor who owns the machine. The setup cost includes working with the vendor in setting up the tooling using the digital CAD models of the parts and doing initial testing and quality checks so that the machinery is up to the mark. This cost occurs in the year when the demand outstrips all the inventory remaining in the warehouse. Once installed, all the future demand is then serviced via the 3D printer.

5.3.3 Per Unit Cost of Production

The cost per unit, of the part, via traditional manufacturing, is assumed to be $1500, whereas the cost of production of the same part via 3D printing will cost $2500. The difference in price is because the factory manufacturing process has been thoroughly optimized over its entire life period and can produce in larger batches. However, the 3D printer can produce only one at a time and there is some wastage in material involved. The process is also far slower. Finally, the

3D printed part will need some polishing/cleaning as well as additional quality checks before being shipped out. All these factors result in a higher variable cost of producing the part via 3D printer.

5.3.4 Inventory Management Cost

Parts that are produced via factory will need to be built ahead of time and stored. There are costs associated with each of the different function/elements such as warehousing, material handling, insurance, inventory control, obsolescence, damage and taxes. There is also a cost of locked capital, since we assume that the money to build all these extra parts ahead of time requires a capital investment and hence a borrowing rate.

All the above factors have been combined and assumed at 10% p.a. of the variable cost of production of each part. For example, if we have a 100 hundred parts in the warehouse each costing $1500, it means a capital investment of $150,000 and hence a holding cost of $15,000 for the first year. If, however, we manage to sell 50 of these 100 parts in the first year, the holding cost for the second year would be 10% of the remaining 50 parts i.e. 50*$1500 = $7500. We stop paying holding costs once all the parts in the warehouse have been used. There is no holding cost for a 3D printed device, since the parts are made only when demand materializes and are immediately used to satisfy demand.

5.3.5 Discount Rate

Discount rate is basically the time value of money – the idea that a dollar today, is more valuable than a dollar tomorrow, given that the dollar today has the capacity to earn interest. This concept is very useful when calculating NPV, i.e. bringing the future money into the present, to be able to do an apple-apple comparison between competing strategies. Alternatively, it can be thought of what best use of the capital could the OEM do today, if it were not invested in the given project.

5.3.6 Final Discounted NPV

This is the final output variable that is monitored to compare between the traditional and hybrid strategies. It is the sum of all the costs every individual year over 20 years that is then discounted

at per the discount rate. It is a single number represented in dollars. Since, it is a single number with a known unit, it is very easy to compare it across the two scenarios. Moreover, since the NPV calculations involve only costs, a strategy is considered superior if this value is lower.

A summary of all the variables, their units and initial(base) assumed values are presented below.

Base Values & Units

Holding costs	10	per cent
Discount rate	5	per cent
One-time Setup cost of a 3D printer	100,000	dollars
Cost of a part via traditional manufacturing	1500	dollars
Cost of a part via 3D printing	2500	dollars
Initial demand	150	units per year
Final year demand	5	units per year
Total demand	957	units per year
Final Discounted NPV	As calculated	dollars

Figure 5.5 Variables, units and assumed base values

6 Case Setups, Results and Discussion

To understand the two different strategies and understand how each of the variables described above affects the choice of strategy, the following cases were considered. Each of the cases is described below, with their corresponding findings.

6.1 Case 1 – Deterministic Demand – No 3D printing option – Base Case

In this base case, demand is deterministic, i.e. the exact demand over the 20 years is known, hence parts are built to exactly cater to this demand. Starting with an initial demand of 150 units in year 0 and ending with a demand of 5 units in year 20, for a total of 957 units, keeping the holding costs at 10% and discount rate at 5%, a NPV of $1,964,138 is achieved. This is the base case and we compare other cases with this to understand the effects and hence the strategy.

6.2 Case 2 - Deterministic Demand – Option to 3D print

Again, the demand is deterministic with all variables at the preset levels as in case 1 above. However, in this case there is the option to introduce a 3D printer.

There are tradeoffs involved when introducing a 3D printer:

- Demand can be met as and when it arises and hence there is no need to build ahead parts thereby avoiding locking in capital and paying holding costs
- However, it costs to setup a 3D printer and each part build via the 3D printer costs higher

Because, of these tradeoffs, there is an optimal solution which balances these tradeoffs such that we build the right amount of parts ahead of time and introduce the 3D printer at a future point in time, so that overall NPV is lower. The excel optimization tool – Solver – was used to help find the most optimum solution. Internal to solver, the evolutionary method was used, which is employs genetic and evolutionary algorithms to find solutions.

The optimum solution in this given case turned out to be when:

- ✓ 614 units were built ahead via traditional manufacturing and stored

- ✓ The remaining 343 units, set to be built via the 3D printer &
- ✓ The 3D printer was introduced in year 5

Comparing the NPV of this case with the base case (Case1) we see that there is a net savings of 12.75% with this strategy. Details of comparison below.

Case No.	Description	Analysis Type	Other Variables	No. of parts to Build Ahead	No. of parts via 3D printer	Discounted NPV - Traditional Approach	Discounted NPV - Hybrid Approach	Year - 3D printer was introduced	Net savings versus Case 1
Case 1	No 3D printer Available	Deterministic	Total Units = 957; Discount rate =5%; Holding Cost = 10%;	957	0	$1,964,138		NA	
Case 2	Option for 3D printing available	Deterministic + Non-linear programming	3D Setup cost = $100K; Factory var cost = $1500; 3D printing var cost = $2500;	614	343		$1,713,660	5	12.75%

Figure 6.1 NPV comparison between Case 1 and Case 2

By Introducing the option to 3D print, the net savings over the base case is 12.75%

The demand in case of the hybrid option is fulfilled first by pulling parts from inventory. There is a switchover point in future, when the parts in the inventory run out and future demand is serviced by 3D printing. The figure below illustrates this switchover.

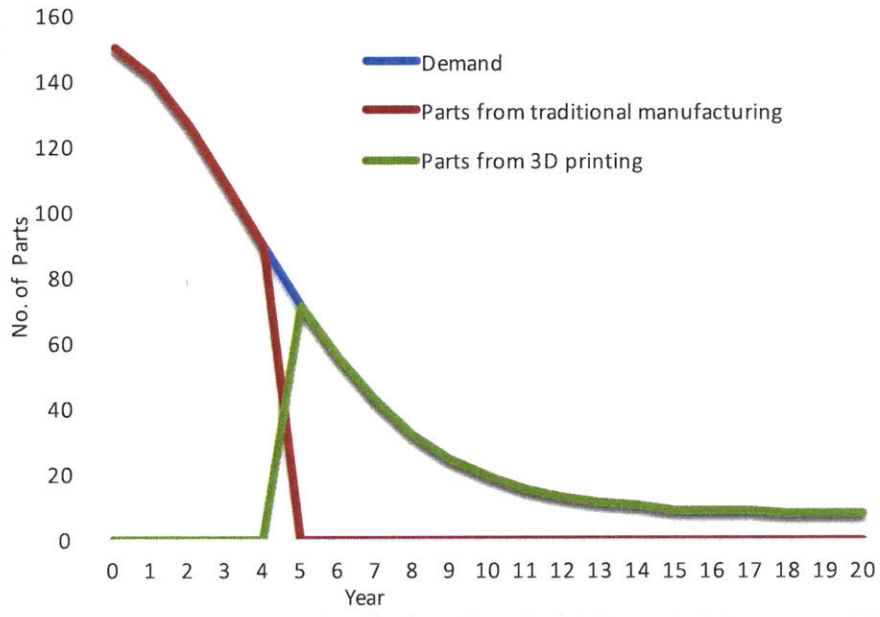

Figure 6.2 Graph illustrating demand fulfillment in hybrid strategy

Starts off with demand being served by parts from the built ahead inventory in the warehouse. Once demand outstrips the existing parts, all future demand is serviced by 3D printed parts. In this case, the switchover happens at the 5 year mark.

6.3 Case 2A - Deterministic Demand – Option to 3D print – Per unit 3D printed cost varies

In this sensitivity analysis case, which builds on case 2 above, a deterministic demand is assumed, there is the option to introduce a 3D printer and the cost of printing each unit via a 3D printer is varied to understand the effect on the strategy of last time build. The original cost of a 3D printed part was assumed at $2500. Keeping the cost of the factory produced part at $1500, the cost of 3D printed part was varied between $1600(which is almost similar to the cost of producing it via traditional method) to a high of $5500. It was observed that, as the cost difference reduces, 3D printing option becomes more and more lucrative. The number of parts that need to be built ahead and stored also reduced, since a 3D printer could be introduced earlier and money saved on the holding costs and upfront capital investment costs. But if the cost of a 3D printed part is as high as $5500 compared to the cost of $1500 via traditional manufacturing, it diminishes all the gains and it would just be better to stick to the original plan as in Case1 and build everything ahead.

Case No.	Description	Analysis Type	Unit price produce by traditional manufacturing	Unit price of 3D printed part	Price Difference ($$)	No. of parts to Build Ahead	No. of part via 3D printer	Discounted NPV Traditional Approach	Discounted NPV Hybrid Approac	Year - 3D printer introduced	Net saving by hybrid approach
Case 2A	Understand effect of per unit cost difference between 3D printed and factory manufactured part. All other variables held constant	Deterministic Demand	$1,500	$1,600	$100	150	807	$1,964,138	$1,342,923	1	31.63%
			$1,500	$1,750	$250	291	666	$1,964,138	$1,431,915	2	27.10%
			$1,500	$2,000	$500	417	540	$1,964,138	$1,551,148	3	21.03%
			$1,500	$2,250	$750	525	432	$1,964,138	$1,643,096	4	16.35%
			$1,500	$2,500	$1,000	614	343	$1,964,138	$1,713,660	5	12.75%
			$1,500	$2,750	$1,250	685	272	$1,964,138	$1,767,883	6	9.99%
			$1,500	$3,000	$1,500	740	217	$1,964,138	$1,809,788	7	7.86%
			$1,500	$3,250	$1,750	740	217	$1,964,138	$1,841,643	7	6.24%
			$1,500	$3,500	$2,000	782	175	$1,964,138	$1,866,920	8	4.95%
			$1,500	$3,750	$2,250	814	143	$1,964,138	$1,887,444	9	3.90%
			$1,500	$4,000	$2,500	838	119	$1,964,138	$1,904,337	10	3.04%
			$1,500	$4,250	$2,750	857	100	$1,964,138	$1,918,558	11	2.32%
			$1,500	$4,500	$3,000	872	85	$1,964,138	$1,930,626	12	1.71%
			$1,500	$4,750	$3,250	872	85	$1,964,138	$1,940,628	12	1.20%
			$1,500	$5,000	$3,500	885	72	$1,964,138	$1,949,431	13	0.75%
			$1,500	$5,250	$3,750	896	61	$1,964,138	$1,957,246	14	0.35%
			$1,500	$5,500	$4,000	896	61	$1,964,138	$1,963,980	14	0.01%

Figure 6.3 Effect of variation of per unit cost of a 3D printed part on the Net savings

A chart of the savings versus rising cost of 3D printed part is shown below. As the cost of a 3D printed part increases the savings also reduce significantly.

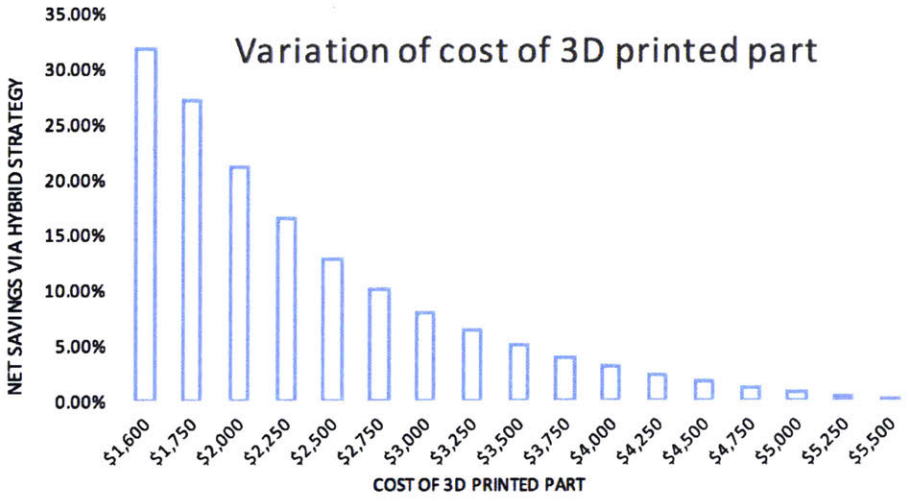

Figure 6.4 Variation in Net savings with variation in the per unit cost of 3D printed parts

A second chart below shows that, as the cost increases, there is a delay in the introduction of the 3D printer. The optimal strategy then shifts, such that more parts are built ahead to avoid paying for a higher cost per part. Also, because of the discount rate, a cost incurred later in time is better as the value reduces when we bring it to the present.

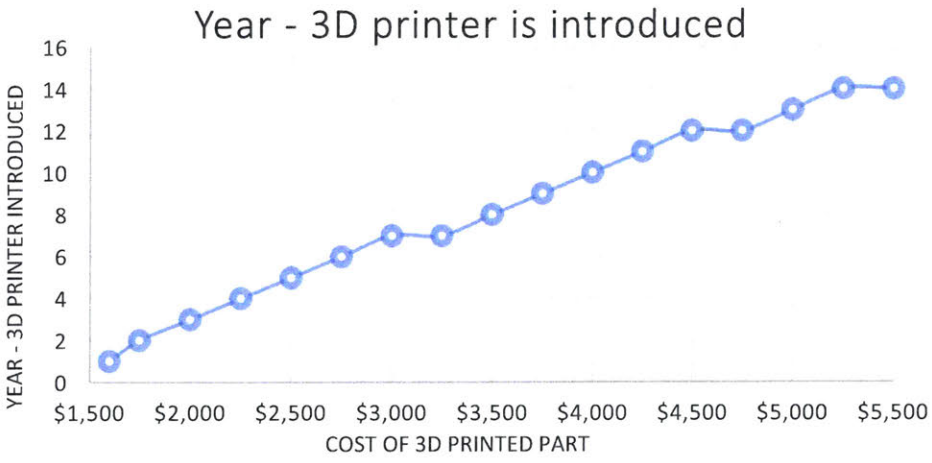

Figure 6.5 3D printer introduction delayed with increase in cost per unit of 3D printed part

6.4 Case 2B - Deterministic Demand – Option to 3D print – Printer setup cost varies

In this case, a deterministic demand is assumed with the option to introduce a 3D printer. The one-time-cost of setting up a 3D printer is varied to get an understanding of the effect on the strategy of last time build. For the base case, the cost of setting up a 3D printer was assumed to be $100,000. This value was then varied in several steps between $10,000 and $500,000. The results show that this cost does not affect the optimal strategy profoundly. For any cost between $10,000 to $400,000, it would still be advisable to build 614 parts ahead out of the 957 required parts. However, if the cost to setup increases to $500,000 or beyond, there is simply no gain in exercising the option of 3D printing and the OEM is better off just building all the parts ahead of time.

Case No.	Description	Analysis Type	Unit price produced by traditional manufacturing	Unit price of 3D printed part	One time price of setting up a 3D printer	No. of parts to Build Ahead	No. of parts via 3D printer	Discounted NPV - Traditional Approach (Case 1)	Discounted NPV - Hybrid Approach	Year - 3D printer was introduced	Net savings by hybrid approach
Case 2B	Understand effect of variation in the one time setup cost of the 3D printing facility at the vendor location.	Deterministic	$1,500	$2,500	$0	525	432	$1,964,138	$1,635,154	4	16.75%
			$1,500	$2,500	$10,000	614	343	$1,964,138	$1,643,143	5	16.34%
			$1,500	$2,500	$25,000	614	343	$1,964,138	$1,654,896	5	15.74%
			$1,500	$2,500	$50,000	614	343	$1,964,138	$1,674,484	5	14.75%
			$1,500	$2,500	$100,000	614	343	$1,964,138	$1,713,660	5	12.75%
			$1,500	$2,500	$200,000	614	343	$1,964,138	$1,792,013	5	8.76%
			$1,500	$2,500	$300,000	614	343	$1,964,138	$1,870,365	5	4.77%
			$1,500	$2,500	$400,000	614	343	$1,964,138	$1,948,718	5	0.79%
			$1,500	$2,500	$500,000	957	0	$1,964,138	$1,964,138	NA	0.00%

Figure 6.6 Effect of variation in one-time setup cost of 3D printer

Although the results seem a bit counter-intuitive, a deeper investigation shows that there are several reasons why the setup cost does not vary the optimal solution, by much, in this setup. The final NPV value is dependent on several factors, namely, the initial capital investment for building the parts, the holding costs, the difference in cost for building the part via 3D versus traditional manufacturing etc. The majority of the cost depends on the initial number of parts built and that cost does not change with the cost in the one-time 3D printing setup. Additionally, since this expenditure happens in year 0, the discount rate does not affect them either. Secondly, because the demand is exponentially decreasing, by year 5 itself, 2/3rd of the total demand has been covered (614/957). Thus, the optimal strategy is to always building 614 units ahead of time and build the rest via 3D printer. Do observe that although reducing/increasing cost does not

change the optimal strategy by much, it does change the final net savings. Reducing cost of setup increases savings. A two-way data table was created to illustrate the effect of setup cost versus optimal build strategy. The lighter color means lower costs (desirable) and darker red color indicates higher costs (undesirable). The lowest cost strategy for a given setup cost is highlighted in green.

The optimal number of parts to build ahe	Variation in one-time setup cost of a 3D printer								
	$0	$10,000	$25,000	$50,000	$100,000	$200,000	$300,000	$400,000	$500,000
150	$1,822,946	$1,832,470	$1,846,755	$1,870,565	$1,918,184	$2,013,422	$2,108,660	$2,203,898	$2,299,136
291	$1,719,882	$1,728,952	$1,742,557	$1,765,233	$1,810,584	$1,901,287	$1,991,990	$2,082,693	$2,173,396
417	$1,660,067	$1,668,706	$1,681,663	$1,703,259	$1,746,451	$1,832,835	$1,919,219	$2,005,602	$2,091,986
525	$1,635,154	$1,643,381	$1,655,721	$1,676,289	$1,717,424	$1,799,694	$1,881,964	$1,964,235	$2,046,505
614	$1,635,308	$1,643,143	$1,654,896	$1,674,484	$1,713,660	$1,792,013	$1,870,365	$1,948,718	$2,027,071
685	$1,651,146	$1,658,608	$1,669,801	$1,688,457	$1,725,768	$1,800,389	$1,875,011	$1,949,632	$2,024,254
740	$1,675,010	$1,682,116	$1,692,777	$1,710,544	$1,746,078	$1,817,146	$1,888,214	$1,959,282	$2,030,350
782	$1,701,665	$1,708,433	$1,718,586	$1,735,507	$1,769,349	$1,837,033	$1,904,717	$1,972,401	$2,040,085
814	$1,728,092	$1,734,538	$1,744,208	$1,760,323	$1,792,553	$1,857,014	$1,921,475	$1,985,936	$2,050,397
838	$1,752,283	$1,758,423	$1,767,631	$1,782,979	$1,813,675	$1,875,066	$1,936,457	$1,997,849	$2,059,240
857	$1,774,730	$1,780,577	$1,789,347	$1,803,964	$1,833,198	$1,891,666	$1,950,134	$2,008,602	$2,067,069
872	$1,794,928	$1,800,497	$1,808,849	$1,822,770	$1,850,612	$1,906,296	$1,961,980	$2,017,663	$2,073,347
885	$1,814,479	$1,819,782	$1,827,737	$1,840,995	$1,867,511	$1,920,543	$1,973,575	$2,026,607	$2,079,639
896	$1,832,669	$1,837,720	$1,845,296	$1,857,922	$1,883,176	$1,933,683	$1,984,189	$2,034,696	$2,085,203
906	$1,850,633	$1,855,443	$1,862,658	$1,874,684	$1,898,734	$1,946,836	$1,994,938	$2,043,040	$2,091,141
915	$1,868,023	$1,872,604	$1,879,476	$1,890,929	$1,913,834	$1,959,645	$2,005,457	$2,051,268	$2,097,079
924	$1,886,578	$1,890,941	$1,897,485	$1,908,393	$1,930,208	$1,973,837	$2,017,467	$2,061,097	$2,104,726
933	$1,906,242	$1,910,398	$1,916,630	$1,927,018	$1,947,794	$1,989,347	$2,030,899	$2,072,451	$2,114,003
941	$1,924,661	$1,928,618	$1,934,554	$1,944,448	$1,964,234	$2,003,808	$2,043,381	$2,082,954	$2,122,528
949	$1,943,974	$1,947,743	$1,953,396	$1,962,818	$1,981,663	$2,019,352	$2,057,041	$2,094,729	$2,132,418
957	$1,964,138	$1,964,138	$1,964,138	$1,964,138	$1,964,138	$1,964,138	$1,964,138	$1,964,138	$1,964,138

Figure 6.7 Deep Dive into understanding results of effect of setup cost variation

6.5 Case 2C - Deterministic Demand – Option to 3D print – Discount Rate varies

In this sensitivity analysis case, the effect of discount rate variation on the optimal strategy is assessed. All other variables are kept constant and only the discount rate is varied. It is observed that the NPV of the base case also varies with varying discount rates, since discount rate affects NPV equally. It is also observed that the optimal savings for the hybrid case changes in line with the discount rate. An increasing discount rate increases the savings of the hybrid strategy and encourages the installation of the 3D printer sooner than later.

The table below illustrates the above observations.

Case No.	Description	Analysis Type	Discount Rate (%	No. of parts to Build Ahead	No. of parts vi 3D printer	Discounted NPV - Traditional Appro (Case 1)	Discounted NPV Hybrid Approach	Year - 3D printer was introduced	Net savings hybrid approach
Case 2C	Understand the effect of variation in discount rate on optimal strategy. All variables held constant except the discount rate.	Deterministic	0%	740	217	$2,066,400	$2,016,200	7	2.43%
			1%	685	272	$2,042,273	$1,948,213	6	4.61%
			2%	685	272	$2,020,201	$1,882,897	6	6.80%
			3%	614	343	$1,999,952	$1,823,537	5	8.82%
			4%	614	343	$1,981,323	$1,765,781	5	10.88%
			5%	614	343	$1,964,138	$1,713,660	5	12.75%
			6%	525	432	$1,948,246	$1,664,674	4	14.56%
			7%	525	432	$1,933,513	$1,616,515	4	16.39%
			8%	525	432	$1,919,823	$1,572,427	4	18.10%
			9%	525	432	$1,907,074	$1,531,962	4	19.67%
			10%	525	432	$1,895,175	$1,494,732	4	21.13%
			15%	417	540	$1,845,954	$1,328,239	3	28.05%
			20%	417	540	$1,809,201	$1,206,112	3	33.33%

Figure 6.8 Effect of variation of Discount Rate on optimal hybrid strategy

It is observed that as the discount rate increases, hybrid strategy becomes more lucrative. Introducing a 3D printer earlier also becomes a better idea as discount rate increases.

A higher discount rate encourages the introduction of the 3D printer sooner, in the hybrid method as an optimal strategy.

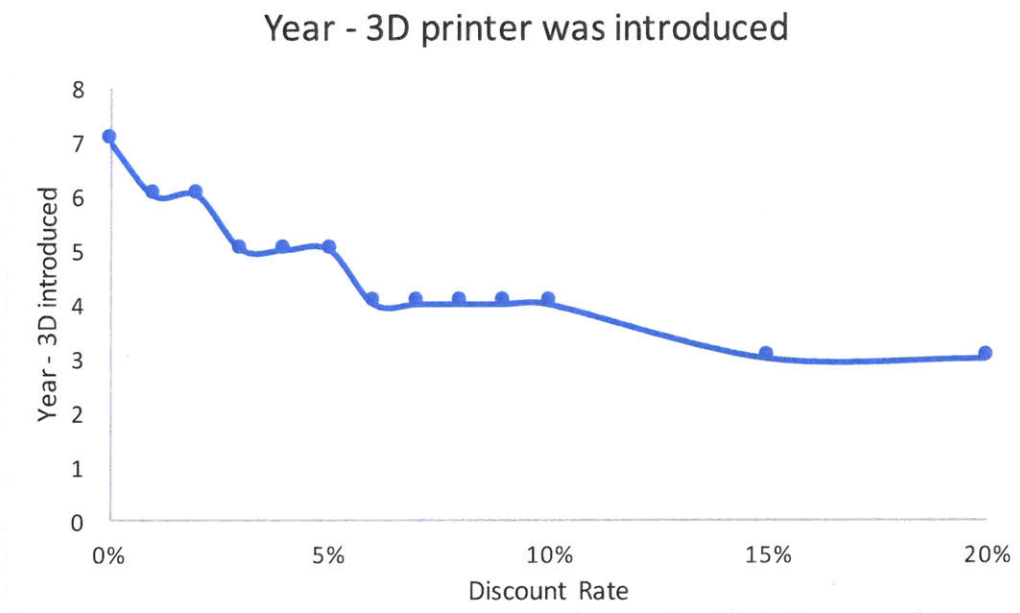

Figure 6.9 Increasing discount rate quickening the process of 3D printer introduction

6.6 Case 3 – Uncertain Demand – No 3D printing option

In this new case, it is assumed that 3D printing option is not available, however demand is stochastic as opposed to deterministic. The variation in demand is enabled by changing the demand at the end of year 20 between 0 and 10 units using a normal distribution centered around 5. 2000 Monte Carlo simulations were done to determine the normal distribution. Now, if were required to meet a service level of 99%, then as per the figure below, it can be seen that the cumulative distribution function meets a 99% or above service level, for a total demand of 1101 parts (as compared to 957 parts in the deterministic case). This results in the fact that, if there is uncertainty and there is a need to meet a high service level of 99%, more parts will have to be built to cover for the variability. The figure below shows the cumulative distributive function as well as the corresponding total demand.

Final Year Demand	Total Demand over 20 years for a given Final Year Demand	Distribution	Cumulative distribution function - service level
0	734	0%	0.0%
1	778	1%	0.9%
2	827	4%	5.3%
3	874	10%	15.0%
4	917	22%	37.1%
5	957	26%	63.4%
6	1003	20%	83.6%
7	1047	12%	95.5%
8	**1101**	**4%**	**99.1%**
9	1147	1%	99.9%
10	1190	0%	100.0%

Figure 6.10 Number of parts to build ahead to support 99% service level

The above chart clearly indicates that in the presence of demand fluctuation (normal distribution around 957) and absence of 3D printing option, a higher number of parts (1101) have to be built ahead to cover for a service level of 99%.

The NPV corresponding to building 1101 parts ahead of time is $2,037,894 – an increase of 3.76% over the base value as seen in Case 1. In summary, it becomes expensive to cover for 99% demand under uncertainty and the OEM will have to build and store more thereby increasing cost.

Case No.	Description	Analysis Type	Other Variables	No. of parts to Build Ahead	No. of parts via 3D printer	Discounted NPV - Traditional Approach	Net savings versus Case 1
Case 1	No 3D printer Available	Deterministic	Total Units = 957; Discount rate =5%; Holding Cost = 10%; 3D Setup cost = $100K; Factory var cost = $1500;	957	0	$1,964,138	
Case 3	No 3D printer Available	With Uncertainity in demand - The tail value varies between 1 unit to 10 units. 2000 Monte Carlo sims and final NPV values such that 99% of the time, demand will not exceed parts built ahead		1101	0	$2,037,894	-3.76%

Figure 6.11 Higher cost to cover uncertainty in demand

If there is uncertainty in demand and absence of any option to 3D print, meeting a service level of 99% requires a ~4% higher cost compared to deterministic case.

6.7 Case 4 – Uncertain Demand – Option to 3D print

In this final case, demand is considered to be uncertain, but there is the option to introduce 3D printing if required. As described in Case 3 above, the total demand can range from 734 units to 1190 units in 11 discrete steps. There is a normal distribution for this demand centered around the demand of 957 units. Different runs of the optimizer show that for each of these possible demand curves, there exists an optimal solution, where the hybrid solution provides the maximum saving. For a 99% service level, the total number of parts to be built is 1101 and the optimal hybrid solution suggests that only 640 of these parts be built in advance with the remaining parts via 3D printing. The details of the optimal solutions for each demand are provided in the figure below.

Case No.	Description	Analysis Type	Normal distribution of the tail value	Cumulative Distribution	Total Cumulative Demand	No. of parts to Build Ahead	No. of parts via 3D printer	Discounted NPV - Traditional Approach	Discounted NPV - Hybrid Approach	Year - 3D printer was introduced	Net savings by hybrid approach
Case 4	3D printer is Available	With Uncertainity in demand there are 11 discrete demand scenarios based on the demand in the final year. For each of these demand, there exists an optimal solution in the hybrid strategy.	0.3%	0.3%	734	574	160	$1,375,778	$1,368,308	5	0.54%
			0.8%	1.0%	778	581	197	$1,494,471	$1,434,350	5	4.02%
			4.1%	5.1%	827	591	236	$1,620,929	$1,512,454	5	6.69%
			10.0%	15.1%	874	600	274	$1,744,589	$1,585,397	5	9.12%
			22.4%	37.4%	917	607	310	$1,858,769	$1,651,806	5	11.13%
			24.9%	62.3%	957	614	343	$1,964,138	$1,713,660	5	12.75%
			21.6%	83.8%	1003	623	380	$2,084,780	$1,785,308	5	14.36%
			10.9%	94.7%	1047	631	416	$2,201,303	$1,853,073	5	15.82%
			4.3%	99.0%	1101	640	461	$2,344,304	$1,936,499	5	17.40%
			0.9%	99.8%	1147	650	497	$2,462,552	$2,010,048	5	18.38%
			0.2%	100.0%	1190	657	533	$2,577,680	$2,075,228	5	19.49%

Figure 6.12 Savings in hybrid strategy in spite of uncertainty

The above numbers clearly suggest that despite uncertainty in demand, the option of introducing a 3D printer increases the net savings. The more the uncertainty, the more the savings in a hybrid approach compared to traditional approach, where extra units were built to cover for uncertainty.

It was observed that, as demand increases, the hybrid method starts showing better savings, indicating the fact that if there is uncertainty in demand, the hybrid method will provide greater benefits. In fact, comparing Case3 and Case4 to the base deterministic Case1, it was observed that, under uncertainty and under obligation to maintain a 99% service level, while the traditional method (Case 3) costs 3.7% higher, the hybrid method (Case 4) in turn gives a saving of 17.4%! The higher the uncertainty, the higher the need to build extra upfront to cover for uncertainty in the traditional case. In the hybrid case, however, higher the uncertainty, higher is the number of parts to be built via 3D printing. This is beneficial, because if demand does not materialize, there is no locked capital in parts that would go unused. A graphical representation of Case 4 is below.

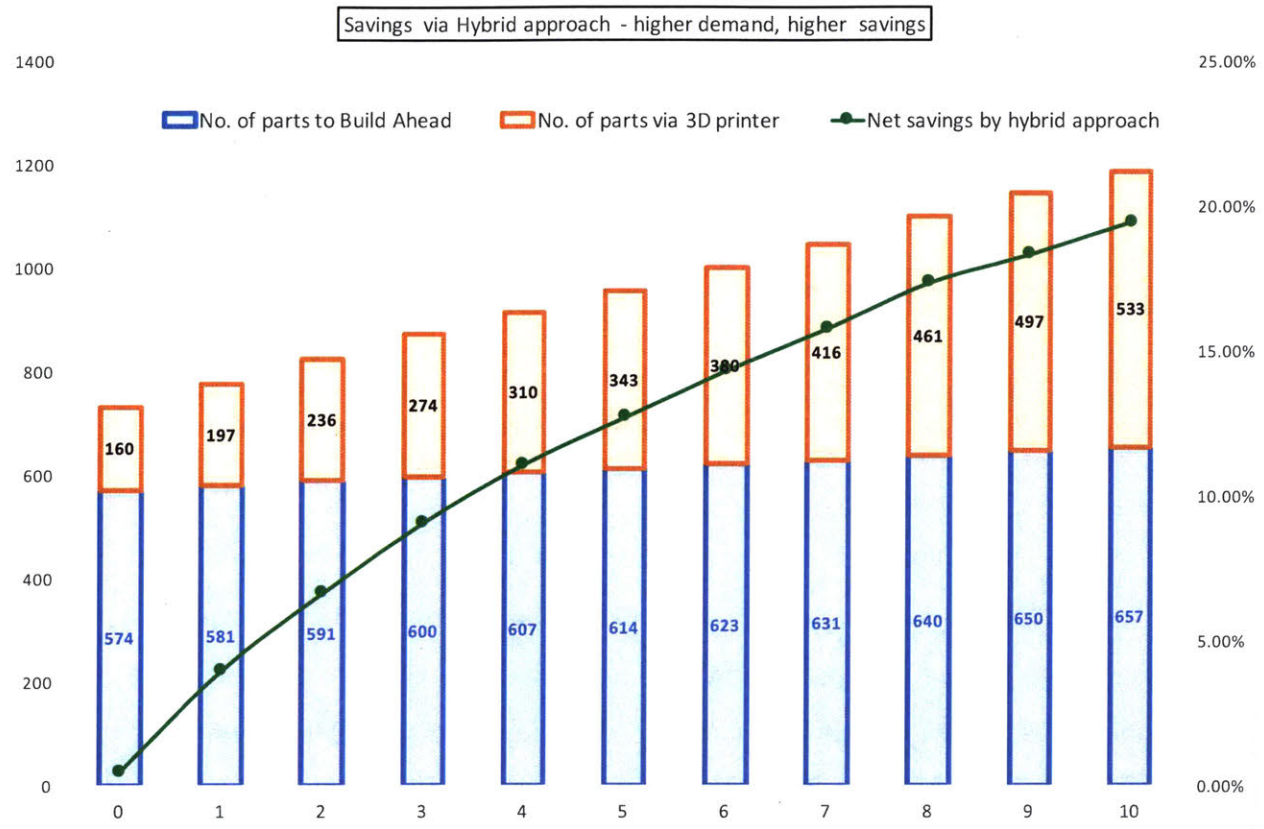

Figure 6.13 Higher savings in hybrid method as uncertainty increases

The chart illustrates that as uncertainty increases, there is a higher cost to satisfy a higher service level, because more number of parts have to be built ahead to cover for the uncertainty. However, with a 3D printer, the number of parts to be built ahead is smaller(compared to demand) and hence a higher net savings

6.8 Summary of Insights Gained

A lot of interesting insights and learnings were gained from the model, using the various cases where one or more conditions were modified. A consolidated summary of the findings and insights is listed below:

- ✓ With deterministic demand and having an option to 3D print, there is a saving of 12.75% of total costs with optimal hybrid strategy. (Case 1 vs Case 2)
- ✓ With deterministic demand, as the cost difference between a 3D printed part and traditionally manufactured part reduces, the hybrid option provides much higher benefits.

Alternatively, the higher the cost per part of 3D printing, the more delayed is the introduction of the 3D printer. (Case 2A)

- ✓ Varying the one-time setup cost of a 3D printer does not affect the original optimal strategy vastly. The optimal solution recommends that the 3D printer be introduced at the 5-year mark. However, if the 3D printer setup cost is prohibitively high, then the optimal solution is not to introduce a 3D printer at all. (Case 2B)
- ✓ Higher is the discount rate, higher is the benefit from the Hybrid strategy. Higher discount rates encourage earlier introduction of a 3D printer, since a higher cost in later years translates to a lower value when brought back into the present. (Case 2C)
- ✓ With uncertainty in demand, absence of the option of a 3D printer and the need to meet a 99% service level, higher number of units have to be build upfront. This results in a higher cost of 3.8% over the base case where the demand is deterministic and the required parts are built upfront. (Case 1 vs Case 3)
- ✓ With uncertainty in demand and the presence of an option to 3D print, the benefits of the hybrid strategy are very high. To account for uncertainty and to maintain a service level of 99%, in the absence of 3D printer, the only option was to build a higher number of units as seen in Case 3, increasing cost by 3.8%. This is cost prohibitive. However, it is observed that with a 3D printer option the cost can, in fact, be reduced by 17.4%, for a total cost advantage of 21.2%! The higher is the target service level and higher is the uncertainty, the higher are the benefits of adopting a hybrid strategy. (Case 4)

7 Conclusion and Future Work

The model and all the various experiments done, provide a good decision making framework for managers when they are making a Last-Time-Build decision. More often than not, the data above suggest that companies are better off employing a 3D printer at some point of time in future. If there is demand uncertainty, which very likely, is the case with such kind of parts, hybrid strategy is a clear winner. With the advances in 3D technology, both the one-time setup cost and per unit production cost are more likely to go down in the near future. If that turns out to be true, hybrid strategy is again the strategy of choice. In future, it would be prudent to believe that OEMs are going to employ the Hybrid strategy and introduce 3D printers to provide better service to their customers as well as make profits even at the end of life and service phases of a product lifecycle.

There are some aspects of the analysis that can be explored further in future work, by expanding on some of the assumptions made in this analysis. The demand pattern can be changed to include yearly variations on either side of the deterministic demand (non-smooth curve). Instead of assuming a single discount rate that is valid over the entire period, evaluations can be done for scenarios when discount rates are based on a yearly changing curve. The demand is assumed to be for 20 years, but in reality the demand could be over 15 or 25 years and this number is not known at the time of evaluation and simulations can to be done to cover for a flexible total duration. Economies of scale aspect can be introduced in the model which would make the comparison complex and results interesting. Finally, the price which is assumed to be constant and hence not considered in the model, could be introduced in the model, with scope to modify it at certain points of time during the life of 20 years.

This thesis has been an attempt to understand the tradeoffs involved in employong this amazing technology of additive manufacturing (3D printing) to a problem that is both relevant and important. It has given us good insights into the problem and helped us understand how leveraging 3D printing technology appropriately could aid in decision making and thus be beneficial to both the OEMs and their end customers.

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