ISCTE Business School
Instituto Universitário de Lisboa

The benefits of additive manufacturing on spare parts supply chain

Mariana Areosa Santos

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Orientador:
Prof. Doutor Marco Alexandre de Oliveira Leite, Prof. Auxiliar, ISCTE Business School, Departamento de Marketing, Operações e Gestão Geral

Co-orientador:
Prof. Doutor Giuseppe Aiello, UniPa

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Resumo

A produção aditiva é uma tecnologia que está em constante desenvolvimento e está sendo adotada por cada vez mais empresas. Este novo método pode ser uma solução para vários problemas dentro da empresa, sendo um deles a gestão de peças sobresselentes que devido às peculiaridades de sua função de procura se torna uma atividade de alto custo. Portanto, o objetivo desta tese é encontrar uma solução possível para reduzir esse custo. Para atingir esse objetivo, os custos relacionados com as políticas ótimas de gestão de inventário que deveriam ser adotadas foram comparados nas tecnologias tradicionais e de produção aditiva. Primeiramente, foi realizada uma revisão preliminar da literatura, com o objetivo de identificar modelos de custo referenciados para a realização da análise comparativa. Em seguida, um modelo matemático foi formulado para comparar o custo de uma política tradicional de inventário e uma política otimizada para a tecnologia de produção aditiva. O modelo desenvolvido foi aplicado a um estudo de caso da Irritec, onde três procuras diferentes foram escolhidas para analisar a diferença entre ter um maior ou menor número de peças em stock por ano.

Os resultados obtidos mostram que os custos de produção são altos para essas peças, representando uma alta percentagem no custo final. No entanto, o custo de manutenção de inventário pode ajudar a decidir entre usar um método ou outro devido à grande divergência entre os valores do stock e porque este custo influenciará o funcionamento da cadeia de abastecimento. Também é possível ver que com um menor número de peças é mais conveniente utilizar a nova tecnologia, enquanto com o aumento de peças o processo tradicional torna-se mais económico.

Palavras Chave: Produção Aditiva, Partes Sobresselentes, Custos, Inventário

JEL ClassificationSystem: O14; O33.

Abstract

Additive Manufacturing is a technology that has been in constant development and is being adopted for more and more companies. This new method can be a solution to various problems within the company, being one the spare parts management that due to the peculiarities of their demand function becomes a high cost activity. Therefore, the objective of this thesis is finding a possible solution for reducing that cost. In order to meet such objective, the costs related to the optimal inventory management policies that should be adopted were comparedto traditional technologies and with additive manufacturing. First, a preliminary literature review has been done, with the objective of identifying referenced cost models for performing the comparative analysis. Then, a mathematical model was formulated to compare the cost of a traditional inventory policy and a policy optimized for additive manufacturing technology. The model developed has been applied to a case study from Irritec where 3 different demands were chosen to analyze the difference between having a higher or lower number of parts per year in stock.

The results obtained show that the manufacturing costs are high for these parts representing a high percentage in the final cost. Although, the cost of inventory holding cost can help deciding on using one method or the other due to the large divergence between the values of inventory and this cost will influence the way the supply chain works. It is also possible to see that at lower number of pieces is more convenient to use the new technology while with the increase of pieces the traditional becomes more economical.

Key Words: Additive manufacturing, Spare Parts, Costs, Inventory.

JEL ClassificationSystem:O14; O33.

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Chapter I –Introduction

Additive Manufacturing is a technology that has been in constant development and is being adopted for more companies, mainly in just in time strategy due to more demanding clients that want their customizedproducts at the right time and at the right place. And spare parts are considered those kind of products that costumers want to receive exactly when they request them and besides that are parts with peculiar characteristics.

I.1.Problem Definition and Research Questions

Irritec is a company that uses injection molding to produce all their products, a traditional manufacturing method and is looking for an alternate approach to be applied to the spare parts that they are producing, therefore is planning to adopt the JIT production strategy incorporating AM whereproduction can be started right after anorder is received from the customer. This production strategy would helpreducing the risk of bearing the obsolescence cost and stock outs.
The objective of this study is to minimize the supply chain cost of meeting demand of spare parts.

So, the questions they want to address are as follows:

- Q1. Which part specifications affect the cost of manufacturing in-house using additive manufacturing significantly?
- Q2. Which supply chain strategy is cheaper for given part specifications?

I.2. Research Methodology

To answer the proposed question and achieve the objectives, there are going to be two approaches.
On the first one a literature review will be presented, where the main topic will be discussed to have a better understanding of the specific topics and what other authors have already discovered about it, those topics are the additive manufacturing characteristics and why is better or not than using a traditional method and also, what are spare parts and why they

usually are considered a problem for the companies. Then a methodology based on reference cost model, discussed in the first part, will be created and applied to a case study from Irritec to analyze the impact of the different cost in both additive manufacturing and injection molding.

ChapterII - Additive Manufacturing

This chapter will analyze the different features of this new technology called additive manufacturing. First, to enter the subject a background about additive manufacturing will be presented, then different processes will be identified with a brief description and the final two sectionswill be a comparison between additive manufacturing and the traditional manufacturing process about the advantages and drawbacks of each one and the costs.

II.1. Background on Additive Manufacturing

Additive manufacturing (AM) is a technology that has been developed for more than 25 years, and it is useful to manufacture 3D parts straight from computer aided design (CAD) models by joining materials layer by layer.

It was first developed by a Massachusetts Institute of Technology team led by Emanuel Sachs (patent 5204055 filed in 1989, awarded in 1993). It was also known as binder jetting because it involved laying down a layer of a powder and then squirting a liquid binder on the areas to be solidified and it was a 3-D printer because it is possible to build additional layers on top of previous ones to build 3-D objects from the most simpler to the most complex.

In 1972, Ciraud produced one of the first successful AM processes using a powder deposition method with energy beam. Although, most of the techniques used today were invented, developed and patented in the 1980s.

Nowadays, with Rapid Prototyping (RP) we can go straight from layers (CAD models) to finished to components (example of an additive manufacturing technology) making it easier and faster for producing complex parts. (Prakash, Nancharaih, & Rao, 2018)

The layers are virtual and computed (3D CAD data, CT, MRI scan and 3D digitizing systems) by a software and each of them represents a cross-section of the desired part and is sent to the RP machine where the part will be built. And using this technology liquid, powder or sheet material can be joined to form physical objects. The materials that can be processed by RP machines are plastic, paper, ceramic, metal and composite materials from thin, horizontal cross sections of computer models. (Prakash, Nancharaih, & Rao, 2018) Additive Manufacturing is being studied and appliedby various companies and institutes, like National Science Foundation (NSF), that are researching and developing to mature it.

II.2. Different Processes of Additive Manufacturing

There are different AM processes to build and consolidate layers, such as: Fused deposition modelling (FDM); Laminated object manufacturing (LOM); Laser engineered net shaping (LENS); Stereo lithography (SLA); Selective laser sintering (SLS). Each one of them as different featureswhich makes them more appropriate for a certain type of materials and complexity.

Stereo lithography (SLA)

Stereo Lithography (SLA), was the first and the most used process of rapid prototyping. It is a liquid-base method that resides in their curing or solidification of a photosensitive polymer when ultraviolet laser makes contact with the resin. Being an AM technologies, it starts with a CAD software that is interpreted to a STL file where the parts are cut in layers each one of them containing its own information. Depending on what type of equipment is being used the thickness and resolution of each layer will vary. The basis of this process are the photo polymerization where a liquid monomer or polymer passes to a solidified polymer by using ultraviolet light as a catalyst for the reactions. It is possible to use other materials if those are covered with the resin. (Wong & Hernadez,2012)

3DP

It is a MIT-licensed process in which water-based liquid binder is provided in a jet onto a starch-based power to print the data from a CAD drawing. The powder particles lie in a powder bed and they are glued together when the binder is jetted. This process can handle a high variety of polymers. (Cooper,2001)

Selective Laser Sintering (LSL)

It is a three-dimensions printing process in which a powder is sintered or fused by the application of carbon dioxide laser beam. This process can be used by a variety ofplastic products, metals, combination of metals, combination of metals and polymers, and combination of metal and ceramics. Being that one of its biggestadvantages. It also can be used by material to reinforce others already in use and unused powder can be recycled,

although is necessary to be careful with the gases that are being send to the atmosphere. (Wong & Hernadez,2012)

Electro Beam Melting

It is similar to the SLS process and is new in the market but with a high growth rate. However, the melting mechanism of the powder it through an electron laser beam powered by a high voltage (30 to 60 KV) and it is projected fto build metal parts. But, it can also process a high variety of metal combinatios. (Wong & Hernadez,2012)

Laminated Object Manufacturing (LOM)

LOM is a process that associates additive and subtractive techniques to build a part layer by layer. The materials arrive in sheet form and are bonded together by pressure and heat applications and using thermal adhesive coating. The sheets are cut with a carbon dioxide laser into the shape of the layers.Using this method is possible to build large parts and it is a low- cost method. Nevertheless, there is more waste and it is difficult to have a clean part. It can be used with papers, composites and metals. (Negi, Dhiman& Kumar Sharma, 2014)

Laser Engineered Net Shaping

This process consists in building a part through melting metal powder injected into a specific location. It becomes molten by employing a high-powered laser beam and then to solidify the material is cooled down. With this process is possible to use a broad variety of metals and is possible to repair parts that would be impossible to with other processes. (Wong & Hernadez,2012)

Fused deposition modelling (FDM)

It is an extrusion-based process that works with a layer-by-layer principle. So, the equipment is composed by an extrusion head that is the main part of this technology, which is compact and removable (ideal for different materials and maintenance). It is possible to use a variety of build materials in a support relationship. The equipment has a compact construction and a good geometric accuracy, it is mostly used is the area of Medicine. (Cooper,2001)

II.3. Additive Manufacturing vs Traditional Production: advantages and drawbacks

Mellor et al., 2014, identified some of the advantages of using additive manufacturing: no tooling is needed; small production batches are feasible and economical and also customization; possibility to faster change design; products can be optimized for function; possibility to reduce waste; potential for simpler supply chains, shorter lead times and lower inventories.

However, like every other process it also has its drawbacks when competing with traditional manufacturing, such as: size limitations (the lack in strength of the material used does not allow to produce a large-size product and also the time can be a constraint in this case); imperfections (products usually have a rough and ribbed finish due to the layer process); cost (the machine is considered an expensive investment as its accessories and other material). (Prakash, Nancharaih& Rao, 2018)

Furthermore, this is a process in constant evolution and has advanced highly during the last years consequently yielding more space in the industries, offering low volume products specifically with complex geometries and with a potential for customization. Some of those industries are the Aerospace (since they use complex geometries made usually from advanced materials which are difficult, costly and time-consuming small); Automotive (in the area of new product development, design and development of new pieces, that is constitutes a costly and time-consuming process and is also applied to make small quantities of structural and functional parts); Bio-medical (produce implants, tissues scaffolds, artificial organs, among others) and Energy (portable power supply, automotive systems and distributed power system).

The aerospace industry is often driven by the possibility of improving the buy-to-fly ratios (because AM processes have high material utilization, mostly metal-based) and reducing weight of parts through the design optimization.

But, the decision to invest in AM technologies must be connected to the market and product characteristics. And there several external and internal factors that affect this decision such as:

strategic factors; organizational factors; Operational factors and supply chain factorsMellor, Hao & Zhang, 2014)

The aforementioned factors conclude that not all products should be considered for the application of an AM technology. So, for a product to be produced by AM should have the following characteristics: degree of customization; increased functionality through design optimization and low volume. Furthermore, they added that also the company strategy must be in accordance and prepared to the adoption of this process, technologically (have the machines needed and skilled personnel) and culturally (the company culture). Moreover, all the supply chain and their intervenient needs to be ready to this change that will affect everyone involved, particularly the relationship between the suppliers and the customers. Since, this technology will directly affect the level of intensity of the user-supplier interaction process.

Hassan & Rennie, discovered that the use of additive manufacturing could be an advantage in the spare part industry, because the traditional manufacturing process always has the same problem related to stock. Since, there are big variety of parts and their demand arrives in small and intermittent batches and they are programmed to produce big quantities as they depend on economies of scale for profit so if they produce too much they need to stock the parts that they do not need causing elevated inventory holding cost. Then a problem is generated and companies do not know what and how much they should stock.

The supply chain strategy used the most by the companies is the “make to stock”, where they produce high quantities of the product (to have lower production costs) and stock them in a central warehouse and distribute when the demand arrives. Although it leads to a high service level from the delivery company it also leads to high transportation and inventory holding costs having always the risk of stock out or parts going obsolete if the demand is equal to zero, being an accurate forecast one of the secrets for this method fine results.

But, the objective is to have the possibility of having a high service level and at the same time lower inventory holding costs. In this case is discussed a part that have an intermittent demand which more easily will cause obsolescence costs consequently, the additive manufacturing method is a an alternative that must be taken into account in these cases. Even though the material cost is high, the extremely lower cost of inventory and risk of stock out

will make it even and possible with a lower demand will make it cheaper than a traditional method.

Additive manufacturing when compared to traditional methods would demonstrate economical and doable when there is a low demand forecast mainly because of the lower inventory costs, where there would only be needed a minimal safety stock if the part was not produce at the point of use.

Manufacturing Method	**Advantages**	**Drawbacks**
Additive Manufacturing	No tooling needed JIT Production (it is a possibility) Faster change Design Customization Products can be optimized for function; Possibility to reduce waste; Potential for simpler supply chains, shorter lead times and lower inventories.	Size limitations Imperfections High material cost
Traditional Manufacturing (Injection Molding)	Low material cost Large Batches No size limitation	High tool cost Complex supply chain with higher inventories costs Waste of material

Table 1: Advantages and Drawbacks of Additive Manufacturing and Injection Molding

II.3. Cost estimation of additive manufacturing vs. traditional

The manufacturing costs, according to Young (1991) can be divided in "well-structured" such as labor, material and machine costs and in "ill-structured" which are associated to failure, machine setup and inventory.

Ill-structured (Thomas & Gilbert, 2014)

Inventory: a high number of resources spent to manufacture and store products could be lowered if the inventories numbers were diminished and by using additive manufacturing. Because, with that technology would be possible to produce the parts on demand. This is even more important when the discussion is about spare parts, since those have an intermittent demand and are needed at the moment because waiting for a long time for themand beingvery costly that in case of traditional manufacturing is necessary to order a high quantity of inventory that will not be used and will be deteriorated and become obsolete, while the use of additive manufacturing will reduce those unnecessary costs by producing on demand.

Transportation: with additive manufacturing is possible to produce multiple parts at the same time in the equivalent build, being conceivable to manufacture a whole product. While with the traditional process is usually necessary to have the production of parts at different sites where inventory is often needed and where is then required to send them to the location where they are going to be assembled, requiring high inventories of every part involved and also high transportation costs being harder to have a just-in-time service.

Supply chain management: the use of additive manufacturing will reduce the costs implied in the management of the producing supply chain bringing the manufactures closer to consumers, reducing the intervenient in the supply chain. It will also help to reduce the number of problems along the supply chain because it will have fewer places to have it as well, meaning less points for potential disruption. Moreover, it will consequence in more decentralized production having more facilities producing less products than otherwise. In this supply chain, there are manufacturers who transfer parts between them or to a build to assembly the product and after being assemble the product is send to a retailer or distributer who delivers the product to his customer. However, with additive manufacturing there are the

material providers and then they are send to localized productions where the parts are produced and the product assembly and after that it goes through the normal process of retailer and clients, reducing he disruptions.

Well-Structured Costs

Material costs: with additive manufacturing is possible to manufacture products using less material while having the same objectives. However, the price of the raw material used with is technology is often higher than the one used with traditional manufacturing. One way to reduce these costs is to use complementary machines or services where possible, to use the same resources and materials and other is the increase of using AM will lead the companies the companies to buy more of these materials and by that decreasing their price through the economies of scale.

Machine costs: it has among others a high impact in the implementation of an AM process. Being that this kind of machines isreally expensive to acquire and that their prices have been varying over the years and according to what type of process and material it uses.

Size: the size of machine can impact the manufacturing process in two ways, being one the fact that is too small for some products because only the products of the size of that space can fit in that printer. Other is the related to the use of the total volume of build capacity that will affect the amount of energy used by the machine, the more space is occupied the less energy is utilized.

Building rate: It is an important part when talking about the costs of AM. There are two main ways to estimate the building time through a detailed analysis (data about how system works) or a parametric analysis (information on how long the process takes and its characteristics).

Energy consumption: It is an indispensable resource for the machine to work but for many studies is not even considered because its contributionto the ultimate cost is very insignificant and it does not impact or make any difference on it.

Labor: one of the advantages of using AM is the fact that it does not need many employees to work in the machine and for that reason the cost of it will be only a small part in the overall costs, in this case labor only includes take the finish product, put the raw material and mostly

finish something that is not possible to do with the mechanism. Also installing the machine can be count as part of this cost. (Costabile, Fera, Fruggiero, Lambiase &Pham, 2017)

There are five studies about the costs of additive manufacturing and among them there are two that are evidenced. The Hopkinson and Dickens one where a comparison is made between traditional manufacturing model of injection modelling (IM) and a layer manufacturing process (AM), according to unit cost for parts in different quantities. The results obtained by this study was that, for some geometrics forms at a relative high production volume it is better to use the AM. In this analysis, the costs were divided into machine costs, labor costs and material costs.

$$Total\ Cost = Machine\ cost\ per\ part + Labor\ cost\ per\ part + Material\ cost\ per\ part \quad (1)$$

The assumptions made to make this formula are the machine produces one part constantly during a year and the material used is polyamide.

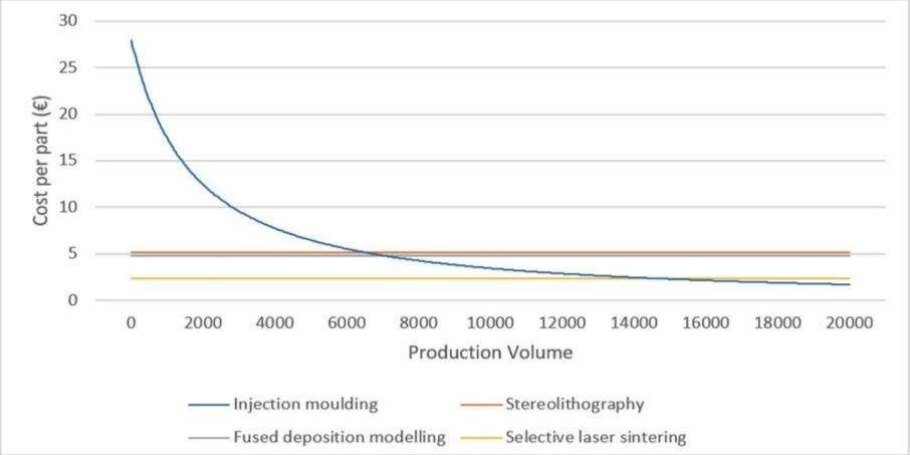


Figure 1: Study Analysis by Hopkinson and Dickens

Just by analyzing the study made by this authors was possible to see the differences between using and additive manufacturing method or a traditional one, in this case injection molding, although this was one of the first studies made and for that reason the technology was not matured, so other researchers started to develop new improved methods.

Ruffos et al., 2016,was one of the researchers that analyzed and improved the Hopkinson and Dickens model. He used the same product but using laser sintering to make a comparison between his model and the one mentioned before. According to this new researcher, the costs of the mold and the cost of the machine is amortized in the initial production phase. In this case it is an activity based costing, having a breakdown cost structured in different activities. Therefore, to each activity involved a definition and cost are associatedandthen the total cost is the sum of those different activity costs. Each singular cost is divided into direct and indirect cost and are connected to an single part with a full costing system, being the only direct cost the material cost and the other are all indirectly allocated. So, the sum of the direct costs (depends on the quantity of material used) and the indirect costs (depends on the time of construction) are equal to the cost of producing one part (cost of build).

$$Cost\ of\ a\ build = Direct\ costs + Indirect\ costs \quad (2)$$

One of the main differences found between this new model and the HD was the machine utilization set that changed from 90% to 57% (100hours/week for 50 weeks) which is a more realistic value.

With this new approach was possible to consider producing different parts taking into account that if it what is needed a new “bed” must be built to start a new part when all the layers, of the previous one, are finished and full. These will cause changesin the production and cost curve depending on what type of situation is needed, related to the layers position, sizing and the need to start a new bed.

The trend noticed in the aforementioned curve is caused by the impact of a fixed time for every full production (warm-up and cool-down) and every layer (powder deposition). The increase of parts produced in both steps will make that time and cost drop, while the opposite will have a negative impact on the costs. Image 2 shows exactly that difference between those two models and what would be impact if they were applied to a part.

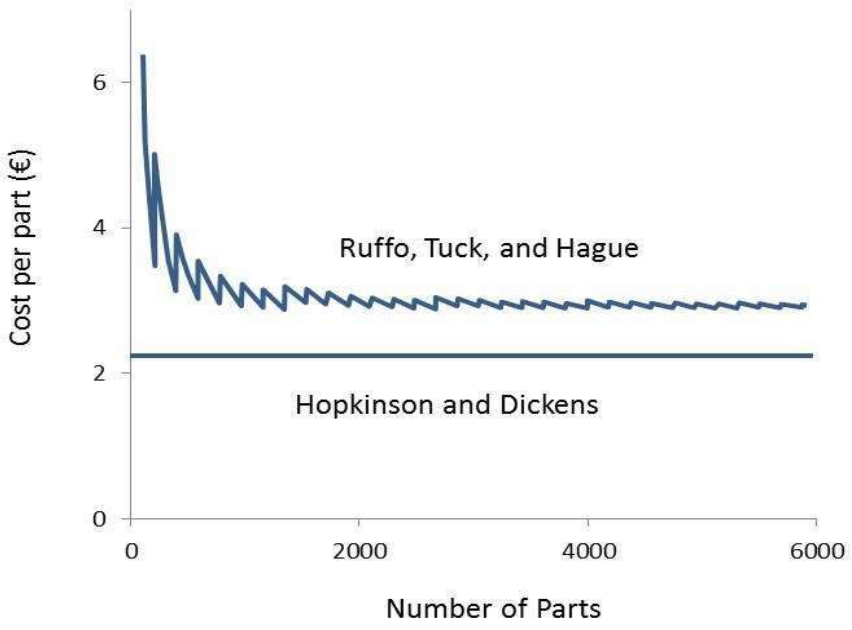


Figure 2 : Relation between cost and number of parts by Ruffo and Hopkinson and Dickens

Ruffo's model has a significantly higher cost for a single piece than the calculated by HD, proving that the first has some cost defaults. Also, is possible to conclude that when the discussion is about producing high volumes, the curve will start to stabilize because of the indirect costs diving into a bigger number of parts.

It is important to remember that those methods only consider the production of one part but one of the advantages of using additive manufacturing is the possibility of producing different components simultaneously. So, having a "smart mix" of parts would help to reduce the costs. (Douglas S. Thomas and Stanley W. Gilbert)

Ruffo and Hague (2007),had different methods to apply that idea because it would be more complex than just dividing the total cost for the produced parts because each part as different characteristics. One was based on parts volume, other on the cost of building a single part and a third one of cost built in high-volume. After applying all the methods to a case study, they concluded that only the third would provide a fair solution to this problem because for the other the reduction was too drastic.

And those studies only mention the manufacturing costs but the reality is that other benefits of using this type of process are hidden in inventory and supply chain costs. Because with this method is possible to assembly a product in only built contrary to a traditional process where the part would need to go through a series of steps to be complete. Therefore, in the first case this advantage can reduce the need for part of the transportation and inventory, causing effects throughout the supply chain, especially if we are talking about intermittent products that are very costly to companies due to this kind of cost mentioned.

ChapterIII - Spare Parts Management

Spare parts management is one of the topics most discussed among authors. So, in this chapter there is a resume of what are spare parts and their relation between maintenance. The biggest problem related to these parts is their demand and some of their features are described in this chapter as well as how to choose the appropriate forecasting approach when instead of constant demand we need to meet intermittent demand. Finally, it is a section that joins this parts and the supply chain strategies that should be applied when producing these parts.

III.1. Life cycle of product and spare parts

The life cycle of a product has three phases: the introduction stage, the maturation and the declination. At the first stage, we have a new product so, with some parts never used before. Therefore, there is no need to stock spare parts for the new ones since at the beginning they have low failure rates and likewise the knowledge is low because the producers do not know how the product will behave, the exception is if they find a defect in that product that will need a part replacement. At the second phase is possible to identify a demand pattern and so is easier to analyze the need for spare parts. In the last phase, the demand for spare parts will continue even in the case of a discontinuation of a product because the product is stillon the market, but that will generate a more uncertain pattern because the company producing them does not have any idea of how much they should produce. (Fortuin & Martin, 1999)

Every type of machinery or technical installations needs to use a maintenance policy and sometimes be replaced due to failures or because it has passed a certain period. Those parts that will serve as replacement are the spare parts. It includes all parts that replace others during the operating life of the equipment.(Gopalakrishnan &Benerji, 2004)

III.2. Maintenance and Spare Parts

Maintenance is a combination of all technical and associated administrative actions intended to retain an item or system in, or restore it to, a state in which it can perform its required function and its objectives are to ensure that the system works correctly, to ensure the system

life, ensure safety and human well-being, and in the case of production the first one should be the most important. There is a mathematical modelcalled Maintenance optimization where both costs and benefits of maintenance are quantified and in which an optimum balance between both is achieved. (Dekker, n.d.)

It is also another important point related to these parts, and the most important for this study, since is directly related to the failures of a system and how it can cause a lot of costs and problems for the company where it happens. A system failure not only impliessafety issues but also critical performances declines, which generate downtimes and significantlosses. And, if we are talking about high-value products the spare part´s management will play a critical role to avoid the problems mentioned before that will be higher in this case.

The maintenance in a service is bound by several constrains such as time, resources, desired reliability before the start of the next service and the supply lead times and a need of a service spare part arises when a component fails or requires replacement.

There are two fundamental maintenance policies: preventive maintenance and corrective maintenance. In the first case, the demand is scheduled and is stochastic with regards the demand size but deterministic as far as the demand arrival is concerned. In the second case, the demand arises, after a failure has occurred, is stochastic with regards to the time arrival but deterministic in quantity (being just one in most cases). Therefore, we are preventing a failure or correcting one. But, both require forecasting on the part of the stockist who is holding the relevant part.

For corrective maintenance, since is carried out after failure detection there is no wayofknowing in advance the parts that are going to be needed because it is just known when the company that suffer the failure communicate that need that part. So, this can be considered one of the biggest problems of this kind of parts and maintenance.

For preventive maintenance, we know the time in advance, but the demand for spare parts is stochastic. In these kind of operations, we may know part of the demand for spare parts due to past monitoring or inspection that revealed potentially defective items or if something must be replaced based on some maintenance policy or due to an inspection that can lead to a replacement. As such, demand related to preventive maintenance is still stochastic and consequently needs to be estimated. (Wang &Syntentos, 2011)

For both planned and unplanned maintenance, it is necessary to have some kind of safety policy, that should include implicitly and explicitly costs, to avoid stockouts and their consequences. The replenishment decisions are then computed according to a probability distribution of the demand, the parameters of which are estimated through an adequate forecasting method.(Wang&Syntentos, 2011)

To choose the right forecasting method is necessary to taking into account that this type of demands is intermittent and happens infrequently within many times periods. And when it arrives, usually is with very low demand size (slow demand) or with high demand turning this demand a lumpy demand (time and size).

III.3.Features of Spare parts demand

The process of managing spare parts is a very specific one because of their specific demand features and of the high value they have in the maintenance, repair and operations area. Since, there is the need to satisfy the needs of the customers and reduce at the same time the costs of doing it. However, the ability to provide those parts with high fulfillment rates at low costs is the major challenge to overcome because this is an area where firms need to make large investments to achieve the right fulfillment rates and reliability. Usually, there is the need to hold relatively high inventories of those parts close to the consumptions places which leads to problems such as high warehousing, inventory and capital costs related to slow-moving parts.
In conclusion, there are several features that make spare parts demand and inventory management a challenging job such as: elevate number of managed parts; intermittent or lumpy demand patterns; high responsiveness due to downtime cost for customers and to efficiently convert inputs into outputs; improve asset utilization; and risk of stock obsolescence. (Mobarakeh, Shahzad, Baboli&Tonadre, 2017)

III.3.1. Different Forecast Methodologies for Spare Parts Demand

A crucial feature of spare parts is their atypical demand pattern characterized by a high number of zero values intercalated by random non-zero demands, so finding the right way to prevent failures, increase customer service levels and reduce inventory is a challenging job due to this particular demand.(Hasni, Babai, Aguir&Jemai, 2018)

Part stocking is the most used and usually if done correctly the most efficient wayto allow a rapid reaction in case of failure solving first the issue and only after find how to repair the problem in a more definitively way, minimizing the effects of failure, regarding the downtimes. But, for that to be efficient is necessary to have a method to delimit the stock quantity able to cover the demand within the re-supply time minimizing the inventory costs.

More than one method should be used to forecast "lumpy" demand because demand peaks will evoke distortion and preventable elevated inventory levels generating big orders that reduce the product availability and the service level. (Zotteri&Kalchsmidt, 2007)

During the decade's most studies have been done to find the best method to forecast low and intermittent demands (spare parts).

One of those methods is the **Croston**methodology which is the most commonly employed for the forecast of spare parts or any parts with those specific characteristics. This is a method proposed in 1972 that captures the nature of the relevant demand patterns (demand arrivals and sizes). (Wallström&Segerstedt, 2011)

t was suggested the use of **Single Exponential Smoothing (SES)** for separately forecasting the interval between demand incidences and sizes, when it occurs. And the ratio of the latter over the previous may then be used in order to estimate the mean demand per time period. (Wang &Syntentos, 2011)

Croston's method is connected with a positive bias and that results in over-forecasting mean demand. So, a new modified method was proposed **Syntetos-Boylan approximation (SBA)**. This method applied a deflating factor to the original Croston's method that is linear in the smoothing constant used for updating the demand intervals. Several studies proved that this

new approach was better than the Croston's in the forecasting and inventory performance area. However, this is not an optimal solution because it still has negative bias leading in some cases for losses compared to the Croston. Furthermore, these methods are not prepared to analyze periods with non-zero demand so in the periods with negative demand, forecasts are not adjusted downwards pondering inventory obsolescence. (Babai, Dallery, Boubaker, &Kalai, 2018)

Trying to solve this situation, a new method was developed **Teunter-Syntetos-Babai (TSB)** where demand probability is updated instead of where there is a demand interval is in every period. So, it can help to deal with the obsolescence problem providing an up-to-date forecast, including intervals with zero demand.

However, due to the update in every period of the demand probability it affects the mean squared error (MSE) performance of the estimator being in these cases overtook by the SBA method. **SES** is another method that can be better than the Croston´s method and SBA when real data is analyzed with a decreasing demand pattern and this good performance is related to the updated forecast in every period. (Babai et al., 2018)

Hyperbolic-exponential-smoothing by Prestwich, is an Croston-type method that try to deal with "lumpy" demand and stock obsolescence and it associates exponential smoothing with an application of Bayesian inference when there is no demand. This is a method that shows a high level of accuracy and that could outperform TSB has not been evaluated yet in the inventory performance. (Babai et al., 2018)

Other methods are the **bootstrapping approach (non-parametric)** and the **parametric approach**. The second one, according to Zhou and Viswanathan, relies on the statement that the demand history follows a particular probability distribution and then point forecasts of the most important parameters such as the distribution instants estimated by using historical data, but this one is considered worse than the Croston method mentioned before.

The bootstrapping approach relies upon the plug-in principle.It was studied because researchers believed it was important to have an accurate forecast of all the distribution of each possible lead-time demand values than just point values. The way it works is by taking samples from the original data, and continually resamples them to form an estimation of the

aggregate demand distribution over the lead time. Few bootstrapping methods were studied for this kind of demand but there were two with particularly importance: **the WWS** and **VZ** bootstrapping methods; where the second is an improvement of the first and it samples separately the demand history from the demand intervals and sizes. And in 2011, Zhou and Viswanathan, compared with the Croston and with an empirical and numerical study and concluded that VZ was better to generate data with long demand histories. (Hasni et al., 2018)

III.4.Spare parts andSupply chain

This section is focused on how a certain supply chain strategy can be more appropriate to a specific type of demand.

III.4.1.Supply chain strategies to meet uncertain demand

Fisher (1997)began the studies about corresponding supply chain strategies to the right level of demand ambiguity. According to this author, the critical decisions in a company should also be made taking into account the positioning of inventory and the availability of production capacity to meet uncertain demand. Besides that the suppliers should be chosen on their flexibility and speed to deliver the raw materials.

Christopher (2000) suggested that an agile supply chain is required to have the capability to answer this kind of uncertainty, meaning that the definition of waste is different from that appropriate for lean supply. The author made a description of the evolution from the traditional supply chain to the his idea of a customized “leagile” process.

In some markets delivering the right product at the right price and at the right is critical to have success when compared to other companies. Cristopher and Towill (2001) discovered that depending on the criteria used, cost or costumer service, respectively the strategy should be lean philosophy or agility. They also studied the possibility of combining both strategies into one hybrid where both the criteria’s had the same level of importance, which for many companies could be the best option.

Chapter IV - Methodology

The methodology applied in this project was an application of reference cost models. Which means that from the two most studied cost models for additive manufacturing were taken some parts and put together to create a new improved method. Moreover this new method evolves other calculations because it has a different objective by using also the inventory holding costs, therefore other formulas were needed to complete this new model.

The methods chosen were the Ruffos method and the Hopkinson and Dickens method.

This new method, that combines the Ruffos and the Hopkinson and Dickens in just one optimized methodology, is divided in two parts the manufacturing costs and the inventory holding costs. In both groups different costs are calculated are those that will use a formula based on the methods aforementioned.

The Manufacturing costs are the sum of the material costs, labor cost and the machine cost. While the inventory cost are the sum of the energy cost and the storage cost.

IV.1. Manufacturing Cost

Material Cost

Material cost is the cost of the raw material needed to build the product and according to both methods is considered a direct cost. It varies according to the different characteristics of the raw material used. In this case since we have a unique type of raw material the formula will be only composed by the price of the material (Pmaterial), measured in euros per kilogram, multiplied by the mass in kg (M).

$$Material\ Cost = Pmaterial \times M \ (3)$$

Labor Cost

Labor cost is a function of the number of employees and the cost to have them working to build all the demand necessary. In order to simplify this part some assumptions were made that all workers that work with the machine receive the same salary and work the same amount of time per year. Then, the calculation will be as simpler as the multiplication of number of workers (N) by the their annual salary (Salary).

$$Labor\ Cost = N \times Salary\ (4)$$

Machine Cost

The machine cost is equivalent to the machine usage cost that is a function of the mechanism working time. That can be divided according to the different processes used on the machine from the deposition of the raw material to the scanning the part and removing it from the equipment. For this method we are discussing about the same process over and over to produce only one product. Therefore, what is taken into account to make this calculation is the initial investment and the maintenance of the machine over the years. To calculate the initial investment an Excel formula is usedcalled PMT (which will calculate financial how much the machine will cost per year) and the variables will be the cost of the machine (Cmachine), the accounting life of the machine (AccountingLife) and the interest rate ($\propto$).

$$Investment\ Cost = PMT\ (Cmachine; AccountingLife; \propto)\ (5)$$

To calculate the maintenance cost of the machine the investment cost is multiplied by the maintenance rate (Rmaintenance) and this value is what is need to pay to keep the machine operating normally over the time.

$$Maintenace\ Cost = InvestementCost \times Rmaintenance\ (6)$$

The total cost of the machine will be the sum of the investment cost and the maintenance cost.

$$Machine\ Cost = InvestmentCost + MaintenaceCost\ (7)$$

IV.2. Inventory Holding Cost

Energy Cost

The energy consumption cost is related to machine working time and how much energy it costs to use that machine. Since, we are discussing a singular product using a specific machine which is already known it's power consumption (Pconsumption) per year, there is only the need to multiply it by the energy cost (Ecost) that varies according to the address where the machine is being used.

$$Energy\ Cost = Pconsumption \times Ecost \quad (8)$$

Storage Cost

The storage cost is the cost of keeping stock of finish products. The method used to make this calculation is the economic order quantity, the safety stock and using those values the average inventory.

The economic order quantity is a method used when the demand is steady and predictable, even though we are talking about low values of demand. (Bacel Maddah*, Nazim Noueihed). This method will indicate the optimal quantity to replenish the inventory providing the quantity that minimizes the inventory holding cost and ordering costs. (Ms. S.M.Samak-Kulkarni[a]*, Dr.Mrs.N.R.Rajhans) To apply this method there is the need of the following variables demand, set up cost and manufacturing cost and interest rate. Being the set up cost the cost of placing an order and the manufacturing the cost of actual producing that product. So the Economic order quantity is two multiplied by the demand and the set up cost (S) and that value is divided by the multiplication of the manufacturing cost and interest rate and finally there is a square root of that final value that came from the division.

$$EOQ = \sqrt{\frac{2 \times \lambda \times S}{ManufacturingCost \times \propto}} \quad (9)$$

The safety stock is the stock needed to make sure that there are always products to answer an order at the requested time, to mitigate the risk of stockout caused by the uncertainty of the demand. It is used as buffer to prevent the chaos and problems in a company inventory and planning system. The safety stock is computed using the standard deviation of the forecasted demand, the lead time and the service level. This value can be calculated based on a cost perspective or based on a service level perspective. The desire service level is usually a percentage but to use in the formula for the safety stock it is used the its z-score that is a tabulated value and it is discriminated in table 2.

Desire Service Level (SL)	Z-Score
84%	1
85%	1,04
90%	1,28
95%	1,65
97&	1,88
98%	2,05
99%	2,33
99,9%	3,09

Table 2: Z-score according to the desire service level

The formula used to calculate the safety stock when there is a constant demand is the z-score (Z) multiplied by the standard deviation of the demand (and by the square root of the lead time (LD).

$$SS = Z \times \partial\lambda \times \sqrt{LD} \ (10)$$

Like the names says the average inventory is the EOQ ,which in this case is the optimal order quantity, divide by two. However, when holding safety stock it passes to be the sum of the economic order quantity divided by two and the value of the safety stock (SS). This value will correspond to the number of parts in stock.

$$AverageInventory = \frac{EOQ}{2} + SS \ (11)$$

Finally, the storage cost is calculated as the product of the average inventory to the rate of storage (Rstorage).

$$StorageCost = AverageInventory \times Rstorage \ (11)$$

Inventory Holding Costs

The inventory holding costs will be the sum of all the costs calculated before multiplied by the number of parts in stock, which is the average inventory, and by the rate of return on investment or cost of opportunity ().

$$InventoryHoldingCost = (ManufacturingCost + EnergyCost + StorageCost) \times AverageInventoy \times \propto (12)$$

IV.3. Total Annual Cost

The total annual cost will be the sum of the manufacturing costs, the energy costs and the inventory holding costs.

$$TotalAnnualCost = ManufacturingCost + EnergyCost + InventoryHoldingCost \ (13)$$

This same model is applied to both methods that are being compared the additive manufacturing and the injection molding. Although, there are some small differences when applyied to the injection molding. The material cost is the same for both models. On the other hand in the machine cost there is a change in the investment cost because when injection molding is used there is also the need to have tooling therefore this cost is added to the investment cost. Instead of having just the machine cost in the PMT function it is included the tooling costs, besides the previous variables there are also the tooling cost multiplied by beta , this values is the difference between the accounting life of the machine and the accounting life of the tooling, and the accounting life of the tooling.

$$InventoryHoldingCost = PMT\ ((Cmachine + Ctooling \times \beta);(\ AccountingLife; \propto)\ (14)$$

This is the only change in terms of equation the rest depends on the data that is available to apply this model.

Chapter V -Case Study

A case study analysis was made, in order to apply this new model and to prove that if the inventory holding cost are taking into account the use of additive manufacturing is better than the injection molding. First, a description of the case study is reported, and then according to the data available, the method is applied and conclusions are taken.

V.1. Case Study – IRRITEC

IRRITEC is an organization that receives demand for a variety of parts in different quantities. At present, it has been fulfilling its customer's demand by delivering parts stocked in their central warehouse and those were manufactured by injection molding (IM). The demand for the parts produced by these organizations , which are replacement parts, are generally low and intermittent so stocking and therefore having inventory to meet this demand is expensive and it has a high possibility of stock-outs or parts of going obsolete causing an obsolescence cost.
Mr. RosaiosGiuffrè, son Carmelo and brother Cono, who founded Siplast in 1974 in the delightful town of Capo d'Orlando, between the mountains and the sea in the province of Messina. At that time the firm had 18 employees and the main activity consisted in the production of PVC blinds. The young Carmelo Giuffre begins to hatch the idea that the future was in irrigation and water conservation. And that intuition, now allows the Irritec to distribute its products in more than 140 countries in the world, counting more than 700 employees and production facilities in Italy, Spain, United States, Mexico and Brazil. In addition, the recent openings of warehouses in Ulm, Germany, Bologna and Algiers complete our global inventory.
In our over 40 years, Irritec has grown steadily while maintaining a solid foundation and important innovations in the field of irrigation. In four decades there have been numerous Italian and global companies that have chosen Irritec's products for their crops knowing that they could count on theirreputation, quality products and professional assistance.
As is possible to see in table 3, Irritec has a fifth per cent market share in market where there are two main leaders, that together have seventy five per cent of market share and only there is only one more with eleven per cent that exceeds the five per cent of Irritec.

Company	Sales 2011 – 2012 (Millions of dollars)	Market Share (%)
Netafim	800	35
Jain Irrigation System	690	30
John Deer Water Technologies	260	11
Irritec	**95**	**5**
Euro drip	86	5
Toro Micro Irrigation	75	4
Others	290	12
Total	2292	100

Table 3: Irrigation Market

Irritec produces more than seven thousand products with different types of demands. By using an ADI-CV (average inter demand interval and coefficient of variation) matrix, shown in figure 3, it is possible to see the representations of the products and how it's their behavior according to the respective demand.

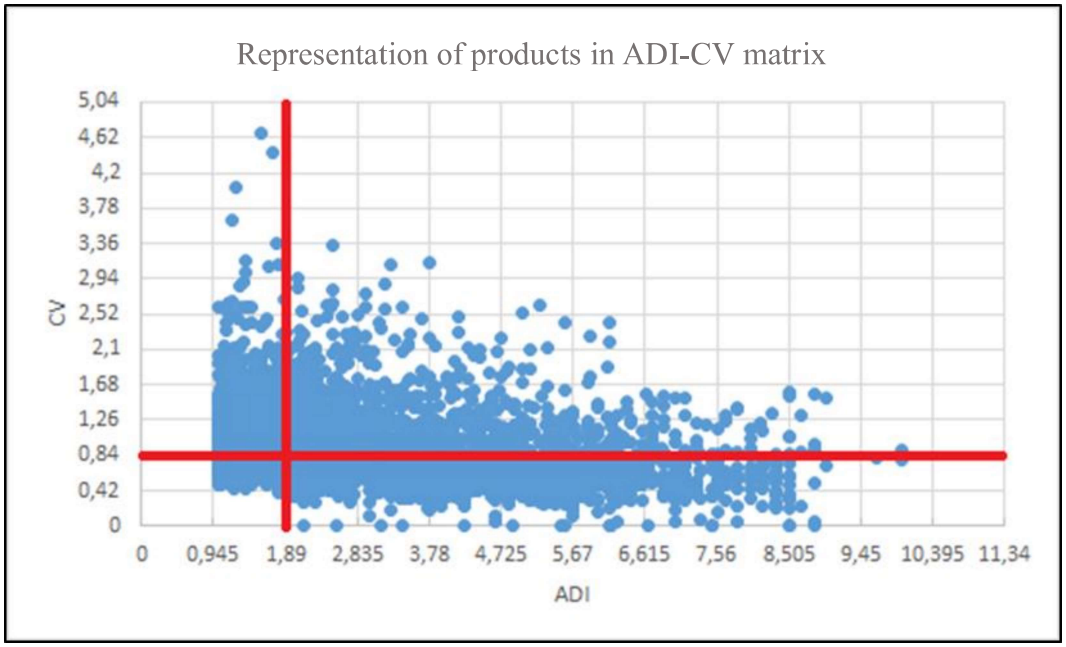


Figure 3: Representation of the products

Like mentioned before all type of demands are identified in this company so next thereis figure 4, that helps understand which demands types are important in this case study and which one is the more used.

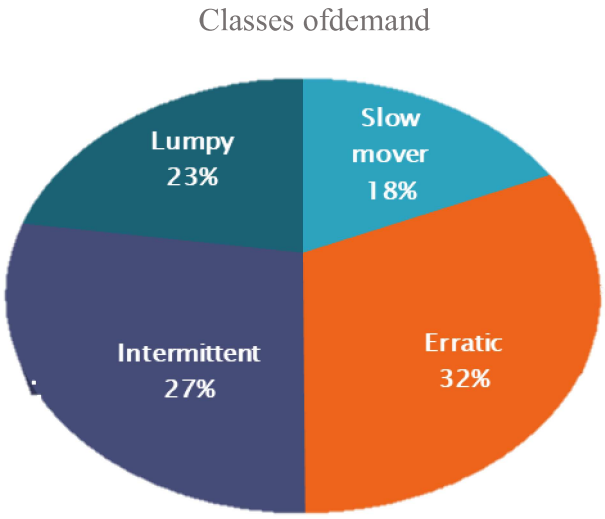


Figure 4: Classes of Demand

V.2. Data Collection - IRR2071

V.2.1 Product Specifications

This case study specifically studies the item IRR2071 or the body clamp of the YHG.

This product being a spare part is just one of the pieces that together with others make a complete product sold by Irritec. It is important to take into account that the same product is going to be used to compare both the injection moulding method and the additive manufacturing, remembering that the use of one or other method has its own advantages.

It is a plastic product with a moderate level of complexity therefore this is not a characteristic that will influence the way of working of the method. The YHG is used in a secondary filtration in systems for irrigation, conducting to a safe filtration. The disk filter allows high efficiency and filtration precision. And the part studied is the body for clamp closing that is made of polypropylene, a type of plastic.

The product characteristics are represented in table 4.

Product	(inches)	L (mm)	A (mm)	H (mm)	Weight (kg)
YHG	2''	446	223	370	5,30
Body	1''	446	223	185	2,65

Table 4: Product Specifications

V.2.2. Demand Specifications

This product has a demand considered intermittent and lumpy. The employment of an appropriate forecasting method (being Croston the one applied and like seen before the best option for this type of demand) lead to a reduction of the safety stock (MAD 0.62-> MAD 0.53).

To this case study was considered three types of demand for this product. A lower demand of 500 pieces, a demand of 5000 pieces and a demand 15000 pieces, to better understand how the costs will vary when there are different demands.

V.2.3. Machine specifications

The machine considered for this study was the Stratasys Fortus Series 250. This machine can be used to create a variety of plastic products with different degrees of complexity. It has the choice of a three layer building resulting on products with high resistance and thickness, with 178, 254 or 330 microns. It can create items up to10 x 10 x 12 inches and the printer can handle things as big as about 20 liters in volume. It is really easy to use making it a very good option to this case study where we are trying to implement a new method in a company that has been using other for a long time now. It is important to understand that the cost of 3D printer in 1998 is over 4000% lower the cost of buying one today and that happens because the market for them is becoming wider and more are appearing with more diversifies functions and utilities.

V.2.4 Costs

Material Costs

The material used to produce this item varies according to the method that is being used therefore its costs will also vary with it, it is known that the cost of raw materials for additive manufacturing is very high due to its specific characteristics and it can also vary according to the machine that is going to be used. Those costs are represented in table 5.

Method	Cost per kilogram (€)
Injection Molding	2,1
Additive Manufacturing	50

Table 5: Cost per Kilogram

Machine Costs

For the machine costs, shown in table 6, is necessary to consider the initial cost of the machine and since there are two methods in this comparison there are two different costs depending on the method used. Both machines are considered to have a depreciation of 8 years.

Method	Investment Cost (€)
Injection Molding (Irritec)	500.000
Additive Manufacturing (Stratasys Fortus Series 250)	40.000

Table 6: Investment Cost

Tooling Cost

One of the advantages of the additive manufacturing is that they do not need to use tooling in their process but on the other side for the injection molding there is the need to consider the cost of tooling which in this study is fifty thousand euros and like the machine has an accounting life of eight years.

Labor Costs

In terms of labor is important to know how much cost to have an employee and for this study there is the need to know the wage of the employee or employee that works with the machine and keep them working. To make it the simple Irritec gave the value of the employee annual salary, so in total how much they will spend with one employee. Which in this study is forty-five thousand euros per year.

Energy Costs

The power consumption of the Stratasys Fortus series 250 is about one thousand and two hundred kwh per year. And is taken into consideration that the cost of energy is around twelve cents per kwh. On the other hand, the cost of the machine of injection used by Irritec consumes three thousand kwh per year, and since both of the methods are applied in the same local the cost of energy is the same for both of them.

V.3. Application of the method

In order to achieve the objectives of this study and answer the questions made at the beginning, a set of calculation were made representing the application of the methodology studied in this paper. This will be organized first on a cost by cost analysis comparing and discussing the results obtained for both methods arriving to the total cost where the main differences will be seen and analyzed. It is also divided in two parts being on the manufacturing cost and the other the inventory holding cost.

The data that is going to be applied is already known and was given by Irritec like said previously.

V.3.1 Manufacturing Costs

Material Cost

This is the first cost, which is represented in table 7, and after applying the formula from the methodology with the respective data which is the material cost, the weight of the product and the waste caused by each one of methods, it is possible to conclude that even though there is a

higher percentage of waste in the injection molding the material cost will overcome that. This proves that in relation to material, using additive manufacturing is more costly than other types of machine, in this specific case there is an increase of eighteen per cent in the cost.

Material Cost			
Demand	Method	Additive Manufacturing	Injection Molding
500 PARTS	Per Part	€10,50	€1,89
	Annual	€5 250	€945
5000 PARTS	Per Part	€10,50	€1,89
	Annual	€52 500	€9 450
15000 PARTS	Per Part	€10,50	€1,89
	Annual	€157 500	€28 350

Table 7: Material Cost

Labor Cost

The labor cost has the same data and weight for both of the machines, so the values are the same and are represented in table 8.

Labor Cost	Additive Manufacturing	Injection Molding
Per part	€450	€450
Annual	€45 000	€45 000

Table 8: Labor Cost

Machine Cost

In table 9, is possible to observe the impact that the investment cost had since the cost difference between the machines is really high, not forgetting that adding to this cost, in the case of the injection molding, there is the tooling part that will make it be an even bigger

difference between both of the cost making an annual difference of almost seventy thousand euros. The value of the investment, which is €4 000 for the AM process and €45 000 for the IM is the same for all the different demands. The same happens with the maintenance that is €200 for the AM and €2 250 for the IM.

Machine Cost			
Demand	Method	Additive Manufacturing	Injection Molding
500 PARTS	Per Part	€8,40	€94,50
	Annual	€4 200	€47 250
5000 PARTS	Per Part	€0,84	€9,45
	Annual	€4 200	€47 250
15000 PARTS	Per Part	€0,28	€3,15
	Annual	€4 200	€47 250

Table 9: Machine Cost

Manufacturing Costs

With all the cost from this part discriminated previously is achievable to analyze what will be the impact of manufacturing cost in this study with this type of characteristics. The total cost of additive manufacturing, exemplified in table 10, is more or less half the cost of injection molding, therefore only by analyzing this part the changing of method from the company to additive manufacturing has already some advantage even though may not be enough to justify the alteration, since we are before a lumpy demand that can change at any time and with that change the need of the company causing a higher cost especially in the case of the material cost.

Manufacturing Cost			
Demand	Method	Additive Manufacturing	Injection Molding
500 PARTS	Per Part	€108,90	€186,39
	Annual	€54 540	€93 195
5000 PARTS	Per Part	€20,34	€20,34
	Annual	€101 700	€101 700
15000 PARTS	Per Part	€13,78	€8,04
	Annual	€206 700	€120 600

Table 10: Manufacturing Cost

V.3.2. Inventory Holding Costs

Energy Costs

For this cost the only part that will make a difference in the decision between choosing one machine or other would be the power consumption, and like is seen in table 11 the consumption of the injection molding is higher mainly because in the case of the additive manufacturing we are mentioning a printing machine so the use of it is more control and is used only when is needed while the other is always producing products.

Energy Cost			
Demand	Method	Additive Manufacturing	Injection Molding
500 PARTS	Per Part	€0,29	€0,72
	Annual	€144	€360
5000 PARTS	Per Part	€0,03	€0,07
	Annual	€144	€360
15000 PARTS	Per Part	€0,01	€0,02
	Annual	€144	€360

Table 11: Energy Cost

Storage

The first difference observed between the methods is the inexistence of an economic order quantity for the additive manufacturing this value is also considered the operation stock and is for that reason that is not considered for this method. That happens because it is a process that function on a just in time (JIT) mode so the products are made when the request is made therefore there is no need to have a stock of this product to give to the client, so for this case the production lead time is also considered as the procurement lead time. On the other hand for the injection molding, it is not a JIT process so the product that is given to the client is already in stock because it was produced previously to the request and according to the forecast made by the company, which in this case is Irritec. For the safety stock the difference is also notable, being one almost half of the other. There is the need to consider safety stock for both of the methods firstly because it is discussed a lumpy demand so it can have various times of unpredictability and also because at any time a problem can happen with the machine or process and to keep a high level of service there is the need to even in those moments to respond the clients requests and only way to do it is by having some kind of safety stock even if it is a really low value. And since there is a different lead time which is justified by one being a JIT process and the other a normal one it causes a difference of around 8 products between the two safety stocks. The final values that are part of this cost are a conjunction of

the previous values so it is clarified the big difference of values between both of the methods. All that is observable in table 12.

Storage			
Demand	Method	Additive Manufacturing	Injection Molding
500 PARTS	EOQ	-	231,63
	Safety Stock	6,09	36,53
5000 PARTS	EOQ	-	2217,30
	Safety Stock	19,25	115,52
15000 PARTS	EOQ	-	6108,47
	Safety Stock	33,35	200,08

Table 12: Storage

Inventory Holding Cost

This final cost, represented in table 13, evolves all the cost from the manufacturing cost to the energy and those costs are now related to the stock and in this case to the average inventory because it is the one that has the operation and the safety stock together. By analyzing only these values is easier to say that the use of additive manufacturing is better that injection molding because one is more costly than the other, so is possible to say that this cost is going to affect the decision between the two models and will probably be tie breaker between choosing one or other.

Inventory Holding Cost			
Demand \ Method		Additive Manufacturing	Injection Molding
500 PARTS	Per Part	€0,13	€5,70
	Annual	€66,48	€2 850
5000 PARTS	Per Part	€0,01	€0,50
	Annual	€39,22	€2 498,77
15000 PARTS	Per Part	€0,003	€0,17
	Annual	€45,98	€2 624,28

Table 13: Inventory Holding Cost

V.3.3. Total Annual Costs

To conclude it is presented the total annual cost of this product for the company, which is shown in table 14. Where is easy to analyze that the use of additive manufacturing is more economic for the lower demand,that demonstratesin a more accurate way the comportment of spare parts, therefore it is a better choice for products in this conditions, with an intermittent demand, and with this specific data from IRRITEC. When a higher number of parts is achieved injection molding becomes more economic.

Total Annual Cost			
Demand	Method	Additive Manufacturing	Injection Molding
500 PARTS	Per Part	€109,03	€192,09
	Annual	€54 516,48	€96 045,50
5000 PARTS	Per Part	€20,35	€20,84
	Annual	€101 739,22	€104 198,77
15000 PARTS	Per Part	€13,78	€8,21
	Annual	€206 745,98	€123 224,

Table 14: Total Annual Cost

V.4. Analysis of the results

Infigure5 is represented the percentage that the additive manufacturing cost and the inventory holding cost have in the final cost per part. In both of the methods the manufacturing cost represents over 96% of the total cost, therefore this is the cost with the most impactregarding the general cost of the part. While in image 6,there is the value of the different costs in the final cost of each method. It is simple to analyze that both the machine, the material and the labor cost, which are the manufacturing cost, represent the highest value of the final cost while the inventory holding cost has lower impact, but in the case represented is the inventory holding cost that makes the difference between choosing one method or other, so this can also be a cost that can make the difference in the final value.

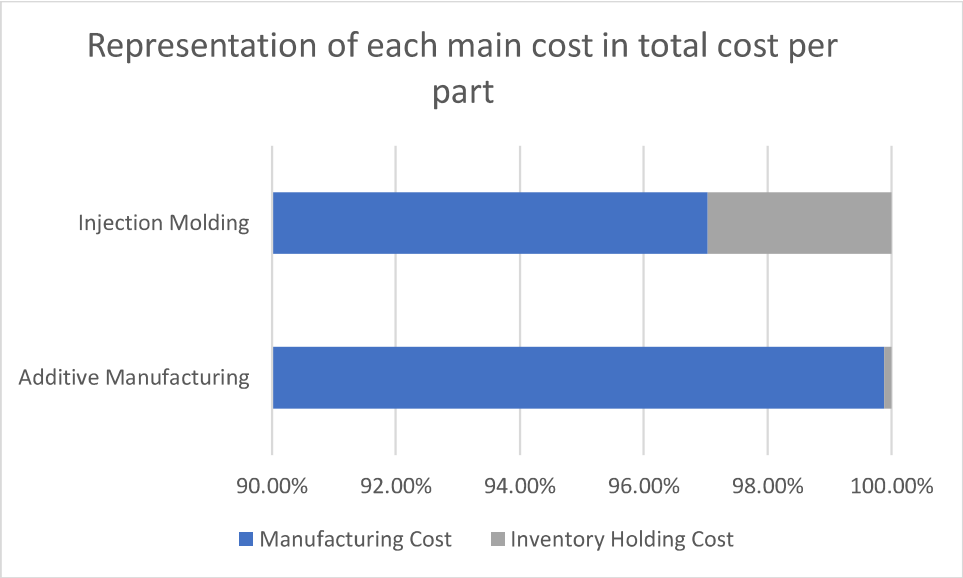


Figure 5: Representation of MC and IHC in the total cost per part

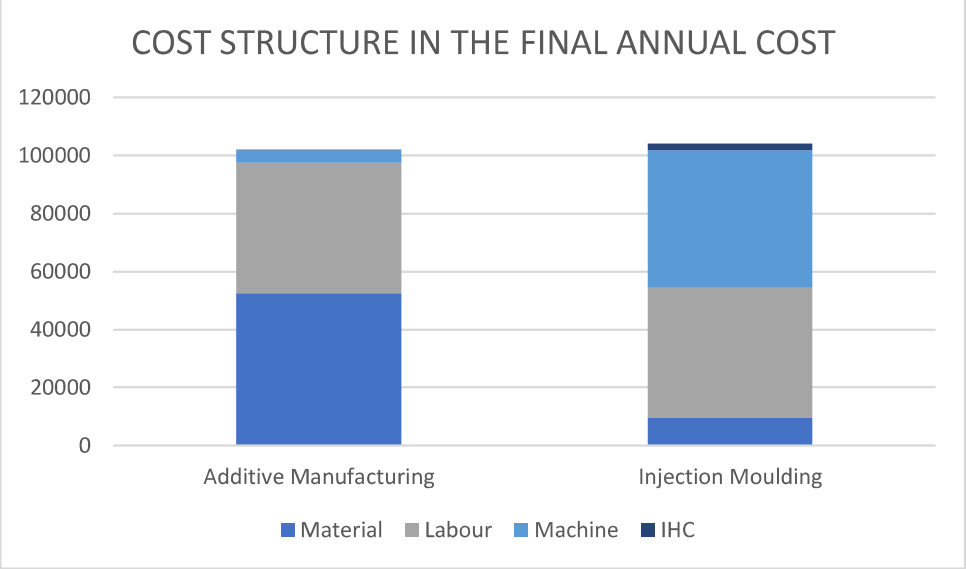


Figure 6: Cost structure in the final annual cost

Figure 7 represents the difference of values between the methods for the manufacturing, inventory holdings and total costs per part being that the first conclusion is the same and the most costly part is the manufacturing and also that all this costs are higher for injection molding when compared to additive manufacturing. But, with the blue line represented in the graph is possible to determine that when comparing the two methods costs where there is the biggestdifference of costis the inventory holding cost where the injection molding is over 4284%, while for additive manufacturing the increase is 171% and for the total cost per part is

176%. Even though,the inventory holding cost is not a variable with a high impact in the final one it can also be considered important because of the difference between both processes, being that a change in this cost could make an impact on what process to choose.

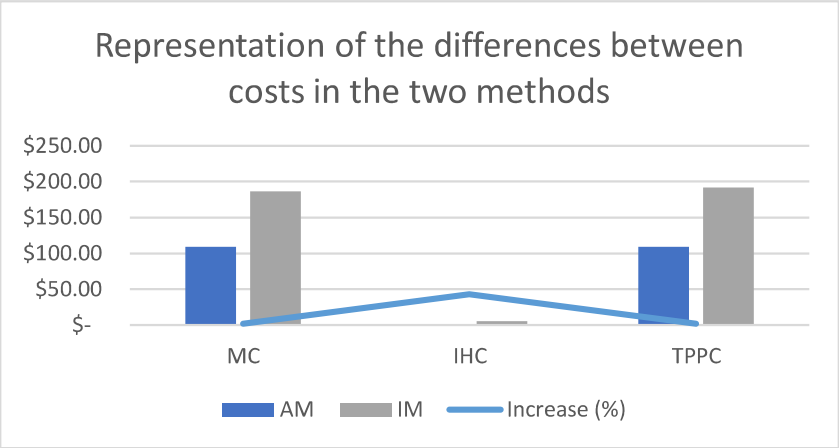


Figure 7: Differences between costs in the two methods

With figure 8,is possible to observe the breakeven point , in this case the value of the demand and the respective cost, where the cost of producing with additive manufacturing is and injection molding is the closes because the number is too complex to be found. But, finding that demand the company will know when they should use one method or another. In this case the point is around the 5300 parts, which is very close to one of demands studied before, where the total cost per part is around 19 euros (19,79 for AM and 19,77 for IM). And it is accurate to say that from thisvalue forward injection will become more economic in a faster way, while for additive manufacturing the difference will become slower and more constant, getting to a demand where using injection molding is 5 euro cheaper than using additive manufacturing.

In annex 1 is possible to see how this variance of demand (from 500 units to 14900 units) will affect all the different main cost, such as manufacturing costs, inventory holding cost and total costs.Those values were obtained using a macro, represented in annex 2, on the Excel that resulted on the table mentioned previously.

If we compare this figure to figure 1 mentioned in the literature review, it is clear that the values of additive manufacturing are not constant as in figure 1, but theinjection moldingseen in the graph below is decreasing,however this happens manly due to the changes on the constants of manufacturing costs, this occurs not only because of values that those authors

maintained constant,but also because in this new case besides the manufacturing cost we added the inventory holding costs which will cause part of this variation. Unlike figure 2, also mentioned in the literature review, that is closer to the real case situation becoming a clearer example of the this new graph.

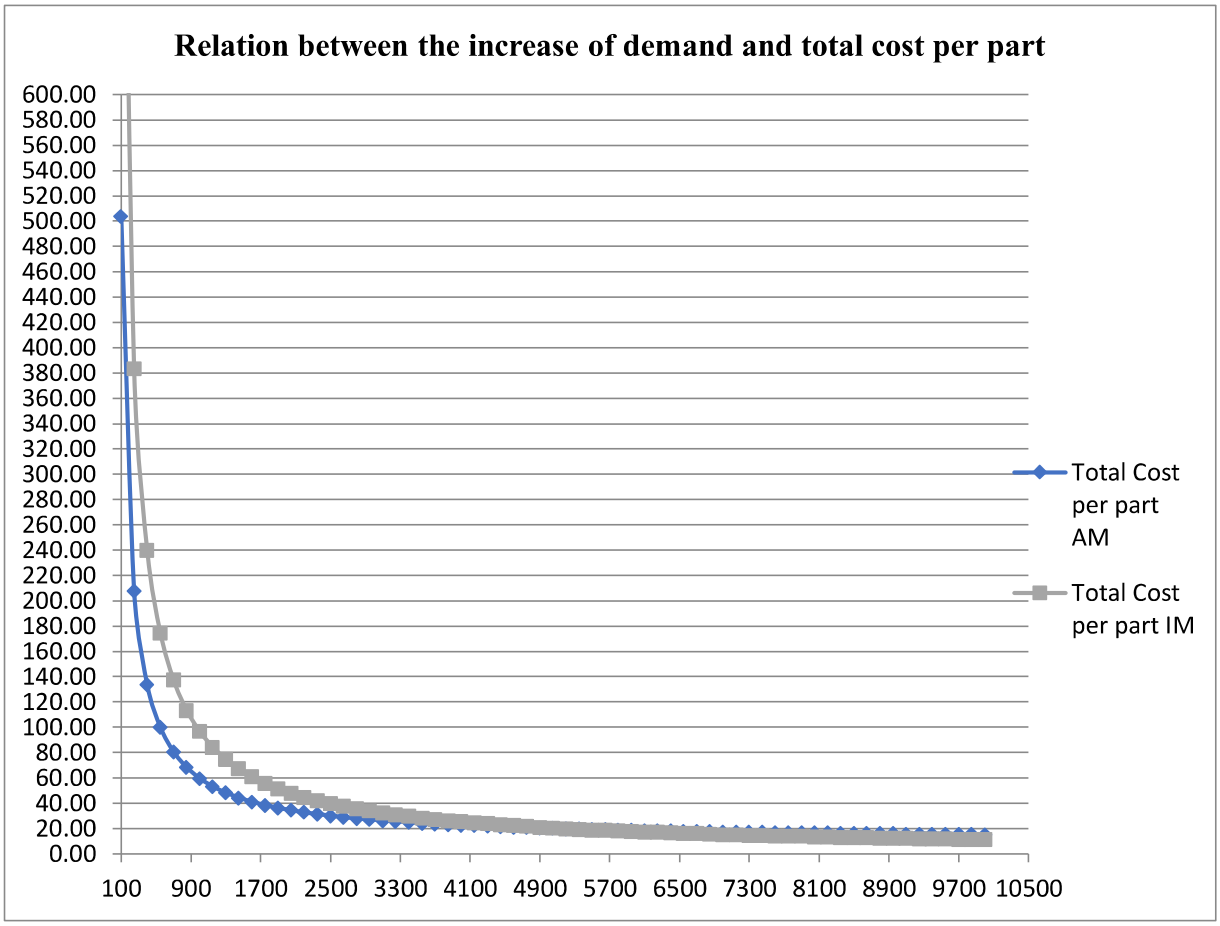


Figure 8: Relation between the increase of demand and total cost per part

V.5.Scenario

The made were if the lead time of the additive manufacturingwas the same of the injection molding, though in normal conditions this would not happen it was important to analyze how much the impact was of this factor in the final cost and other variablesrelated in this case to

the storage, shown in table 15. In the three cases is easy to observe that there are no big differences in both the inventory costs or the total cost, where only a small increase in cost justified by the 30 days of lead time. The major difference as it was expected occurred on the value of the average inventory, which since it shown only the additive manufacturing part is equal to the safety stock due to the inexistent of EOQ, where there is a significant difference growth of parts with the increase of the lead time.

Scenario Summary : Increase of the lead time for additive manufacturing			
		Current Values:	New Values:
Changes Cells:			
Lead Time		5	30
ResultCells:			
15000 PARTS	**Average Inventory**	33,35	200,08
	Total per part IHC	45,98	275,91
	Total Annual IHC	€0,003	€0,018
	Total Annual Cost	€206 745,98	€ 206 975,91
	Total Cost per Part	€ 13,78	€ 13,80
5000 PARTS	**Average Inventory**	19,25	115,52
	Total per part IHC	39,22	235,30
	Total Annual IHC	€0,01	€ 0,05
	Total Annual Cost	€101 739,22	€ 101 935,30
	Total Cost per Part	€20,35	€ 20,39
500 PARTS	**Average Inventory**	6,09	36,53
	Total per part IHC	66,48	398,86
	Total Annual IHC	€ 0,13	€ 0,80
	Total Annual Cost	€ 54 516,48	€ 54 848,86
	Total Cost per Part	€ 109,03	€ 109,70

Table 15: Scenario Summary

Chapter VI -Conclusion

At the beginning of this thesis some questions were made by the company with the objective ofbeing answered through this study. For the first question, the cost that represent the biggest part of the total cost is the manufacturing with all his different cost representing over 96% in both additive manufacturing and injection molding.

Although, when both of the methods are compared the main difference among costs are the inventory holding cost, even though they represent a small part in the final cost they are the ones that can make the difference. The increase can be over 4000% when comparing additive manufacturing to the injection molding, while for the manufacturing is around 170%. In the case of additive manufacturing, even though the most costly is the manufacturing the one that can make the difference is the inventory cost, also because is in this case that there is one of the advantages of using this method instead of other because it works on just in time strategy causing an almost inexistent stock. In the second question the decision depends on the demand of the part, since it is a spare part it has anintermittent demand and can have periods of 0, so it will be a lower demand and in this case as it can be seen in the case the best method to use is the additive manufacturing, being that the injection molding will become more economic only when there is a demand of over 5300 pieces.

For future researches should be considered analyze how this model or an improved one would vary if other scenarios were made and which are the main specifications that affect this model not in terms of costs but product specifications or other type of data to find why choosing additive manufacturing is the better option for this parts that usually have a demand on time and need to be produced when requested or otherwise would cause great problems to the companies. Also, it would be possible to considerer the application of this method to a case where the values of inventories are low, taking that into account the main difference between the two methodologies are easier to analyze and to make more conclusions regarding the best choice of method.

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Annex

Annex 1 - Macro Analysis

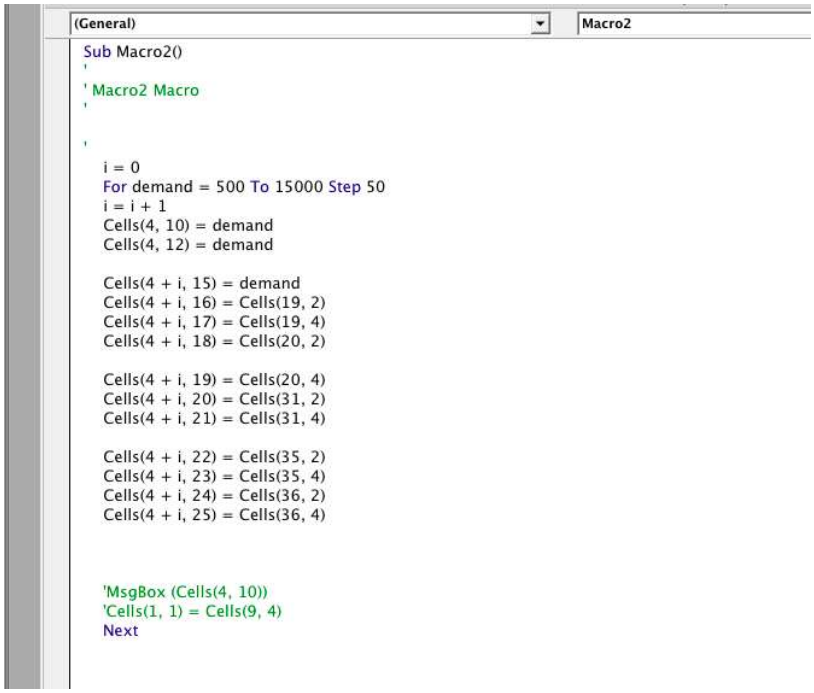


Figure 9 : Macro Analysis

Annex 2 – Variance of costs having different demands

	AM	IM	AM	IM	AM	IM	AM	IM	AM	IM
DEMAND	MC - TA	MC - TA	MC-TP	MC-TP	IHC-TA	IHC-TA	TC	TC	TP	TP
500	54450,00	93195,00	108,90	186,39	66,48	2850,50	54516,48	96045,50	109,03	192,09
550	54975,00	93289,50	99,95	169,62	63,99	2820,44	55038,99	96109,94	100,07	174,75
600	55500,00	93384,00	92,50	155,64	61,85	2794,38	55561,85	96178,38	92,60	160,30
650	56025,00	93478,50	86,19	143,81	59,99	2771,55	56084,99	96250,05	86,28	148,08
700	56550,00	93573,00	80,79	133,68	58,34	2751,35	56608,34	96324,35	80,87	137,61
750	57075,00	93667,50	76,10	124,89	56,89	2733,33	57131,89	96400,83	76,18	128,53
800	57600,00	93762,00	72,00	117,20	55,59	2717,15	57655,59	96479,15	72,07	120,60
850	58125,00	93856,50	68,38	110,42	54,42	2702,54	58179,42	96559,04	68,45	113,60
900	58650,00	93951,00	65,17	104,39	53,36	2689,27	58703,36	96640,27	65,23	107,38
950	59175,00	94045,50	62,29	99,00	52,40	2677,15	59227,40	96722,65	62,34	101,81
1000	59700,00	94140,00	59,70	94,14	51,53	2666,06	59751,53	96806,06	59,75	96,81
1050	60225,00	94234,50	57,36	89,75	50,73	2655,85	60275,73	96890,35	57,41	92,28
1100	60750,00	94329,00	55,23	85,75	49,99	2646,44	60799,99	96975,44	55,27	88,16
1150	61275,00	94423,50	53,28	82,11	49,31	2637,72	61324,31	97061,22	53,33	84,40
1200	61800,00	94518,00	51,50	78,77	48,69	2629,64	61848,69	97147,64	51,54	80,96
1250	62325,00	94612,50	49,86	75,69	48,11	2622,12	62373,11	97234,62	49,90	77,79
1300	62850,00	94707,00	48,35	72,85	47,57	2615,11	62897,57	97322,11	48,38	74,86
1350	63375,00	94801,50	46,94	70,22	47,07	2608,55	63422,07	97410,05	46,98	72,16
1400	63900,00	94896,00	45,64	67,78	46,60	2602,42	63946,60	97498,42	45,68	69,64
1450	64425,00	94990,50	44,43	65,51	46,17	2596,68	64471,17	97587,18	44,46	67,30
1500	64950,00	95085,00	43,30	63,39	45,76	2591,28	64995,76	97676,28	43,33	65,12
1550	65475,00	95179,50	42,24	61,41	45,38	2586,20	65520,38	97765,70	42,27	63,07
1600	66000,00	95274,00	41,25	59,55	45,02	2581,42	66045,02	97855,42	41,28	61,16
1650	66525,00	95368,50	40,32	57,80	44,69	2576,92	66569,69	97945,42	40,35	59,36
1700	67050,00	95463,00	39,44	56,15	44,37	2572,67	67094,37	98035,67	39,47	57,67
1750	67575,00	95557,50	38,61	54,60	44,08	2568,65	67619,08	98126,15	38,64	56,07
1800	68100,00	95652,00	37,83	53,14	43,80	2564,85	68143,80	98216,85	37,86	54,56
1850	68625,00	95746,50	37,09	51,75	43,53	2561,25	68668,53	98307,75	37,12	53,14

1900	69150,00	95841,00	36,39	50,44	43,28	2557,85	69193,28	98398,85	36,42	51,79
1950	69675,00	95935,50	35,73	49,20	43,05	2554,62	69718,05	98490,12	35,75	50,51
2000	70200,00	96030,00	35,10	48,02	42,83	2551,56	70242,83	98581,56	35,12	49,29
2050	70725,00	96124,50	34,50	46,89	42,62	2548,65	70767,62	98673,15	34,52	48,13
2100	71250,00	96219,00	33,93	45,82	42,42	2545,89	71292,42	98764,89	33,95	47,03
2150	71775,00	96313,50	33,38	44,80	42,23	2543,27	71817,23	98856,77	33,40	45,98
2200	72300,00	96408,00	32,86	43,82	42,05	2540,78	72342,05	98948,78	32,88	44,98
2250	72825,00	96502,50	32,37	42,89	41,89	2538,41	72866,89	99040,91	32,39	44,02
2300	73350,00	96597,00	31,89	42,00	41,73	2536,16	73391,73	99133,16	31,91	43,10
2350	73875,00	96691,50	31,44	41,15	41,57	2534,02	73916,57	99225,52	31,45	42,22
2400	74400,00	96786,00	31,00	40,33	41,43	2531,98	74441,43	99317,98	31,02	41,38
2450	74925,00	96880,50	30,58	39,54	41,29	2530,04	74966,29	99410,54	30,60	40,58
2500	75450,00	96975,00	30,18	38,79	41,17	2528,19	75491,17	99503,19	30,20	39,80
2550	75975,00	97069,50	29,79	38,07	41,04	2526,43	76016,04	99595,93	29,81	39,06
2600	76500,00	97164,00	29,42	37,37	40,93	2524,76	76540,93	99688,76	29,44	38,34
2650	77025,00	97258,50	29,07	36,70	40,82	2523,16	77065,82	99781,66	29,08	37,65
2700	77550,00	97353,00	28,72	36,06	40,71	2521,64	77590,71	99874,64	28,74	36,99
2750	78075,00	97447,50	28,39	35,44	40,61	2520,20	78115,61	99967,70	28,41	36,35
2800	78600,00	97542,00	28,07	34,84	40,52	2518,82	78640,52	100060,82	28,09	35,74
2850	79125,00	97636,50	27,76	34,26	40,43	2517,52	79165,43	100154,02	27,78	35,14
2900	79650,00	97731,00	27,47	33,70	40,34	2516,27	79690,34	100247,27	27,48	34,57
2950	80175,00	97825,50	27,18	33,16	40,26	2515,09	80215,26	100340,59	27,19	34,01
3000	80700,00	97920,00	26,90	32,64	40,19	2513,96	80740,19	100433,96	26,91	33,48
3050	81225,00	98014,50	26,63	32,14	40,12	2512,89	81265,12	100527,39	26,64	32,96
3100	81750,00	98109,00	26,37	31,65	40,05	2511,88	81790,05	100620,88	26,38	32,46
3150	82275,00	98203,50	26,12	31,18	39,98	2510,91	82314,98	100714,41	26,13	31,97
3200	82800,00	98298,00	25,88	30,72	39,92	2510,00	82839,92	100808,00	25,89	31,50
3250	83325,00	98392,50	25,64	30,27	39,87	2509,13	83364,87	100901,63	25,65	31,05
3300	83850,00	98487,00	25,41	29,84	39,81	2508,31	83889,81	100995,31	25,42	30,60
3350	84375,00	98581,50	25,19	29,43	39,76	2507,53	84414,76	101089,03	25,20	30,18
3400	84900,00	98676,00	24,97	29,02	39,71	2506,79	84939,71	101182,79	24,98	29,76
3450	85425,00	98770,50	24,76	28,63	39,67	2506,10	85464,67	101276,60	24,77	29,36
3500	85950,00	98865,00	24,56	28,25	39,62	2505,44	85989,62	101370,44	24,57	28,96
3550	86475,00	98959,50	24,36	27,88	39,58	2504,82	86514,58	101464,32	24,37	28,58
3600	87000,00	99054,00	24,17	27,52	39,55	2504,24	87039,55	101558,24	24,18	28,21
3650	87525,00	99148,50	23,98	27,16	39,51	2503,69	87564,51	101652,19	23,99	27,85

3700	88050,00	99243,00	23,80	26,82	39,48	2503,18	88089,48	101746,18	23,81	27,50
3750	88575,00	99337,50	23,62	26,49	39,45	2502,70	88614,45	101840,20	23,63	27,16
3800	89100,00	99432,00	23,45	26,17	39,42	2502,25	89139,42	101934,25	23,46	26,82
3850	89625,00	99526,50	23,28	25,85	39,39	2501,83	89664,39	102028,33	23,29	26,50
3900	90150,00	99621,00	23,12	25,54	39,37	2501,44	90189,37	102122,44	23,13	26,19
3950	90675,00	99715,50	22,96	25,24	39,35	2501,08	90714,35	102216,58	22,97	25,88
4000	91200,00	99810,00	22,80	24,95	39,32	2500,75	91239,32	102310,75	22,81	25,58
4050	91725,00	99904,50	22,65	24,67	39,31	2500,44	91764,31	102404,94	22,66	25,29
4100	92250,00	99999,00	22,50	24,39	39,29	2500,16	92289,29	102499,16	22,51	25,00
4150	92775,00	100093,50	22,36	24,12	39,27	2499,90	92814,27	102593,40	22,36	24,72
4200	93300,00	100188,00	22,21	23,85	39,26	2499,67	93339,26	102687,67	22,22	24,45
4250	93825,00	100282,50	22,08	23,60	39,25	2499,47	93864,25	102781,97	22,09	24,18
4300	94350,00	100377,00	21,94	23,34	39,24	2499,28	94389,24	102876,28	21,95	23,92
4350	94875,00	100471,50	21,81	23,10	39,23	2499,12	94914,23	102970,62	21,82	23,67
4400	95400,00	100566,00	21,68	22,86	39,22	2498,98	95439,22	103064,98	21,69	23,42
4450	95925,00	100660,50	21,56	22,62	39,21	2498,86	95964,21	103159,36	21,57	23,18
4500	96450,00	100755,00	21,43	22,39	39,21	2498,76	96489,21	103253,76	21,44	22,95
4550	96975,00	100849,50	21,31	22,16	39,20	2498,68	97014,20	103348,18	21,32	22,71
4600	97500,00	100944,00	21,20	21,94	39,20	2498,62	97539,20	103442,62	21,20	22,49
4650	98025,00	101038,50	21,08	21,73	39,20	2498,58	98064,20	103537,08	21,09	22,27
4700	98550,00	101133,00	20,97	21,52	39,20	2498,56	98589,20	103631,56	20,98	22,05
4750	99075,00	101227,50	20,86	21,31	39,20	2498,55	99114,20	103726,05	20,87	21,84
4800	99600,00	101322,00	20,75	21,11	39,20	2498,56	99639,20	103820,56	20,76	21,63
4850	100125,00	101416,50	20,64	20,91	39,20	2498,59	100164,20	103915,09	20,65	21,43
4900	100650,00	101511,00	20,54	20,72	39,21	2498,64	100689,21	104009,64	20,55	21,23
4950	101175,00	101605,50	20,44	20,53	39,21	2498,70	101214,21	104104,20	20,45	21,03
5000	101700,00	101700,00	20,34	20,34	39,22	2498,77	101739,22	104198,77	20,35	20,84
5050	102225,00	101794,50	20,24	20,16	39,22	2498,86	102264,22	104293,36	20,25	20,65
5100	102750,00	101889,00	20,15	19,98	39,23	2498,97	102789,23	104387,97	20,15	20,47
5150	103275,00	101983,50	20,05	19,80	39,24	2499,09	103314,24	104482,59	20,06	20,29
5200	103800,00	102078,00	19,96	19,63	39,25	2499,22	103839,25	104577,22	19,97	20,11
5250	104325,00	102172,50	19,87	19,46	39,26	2499,37	104364,26	104671,87	19,88	19,94
5300	104850,00	102267,00	19,78	19,30	39,27	2499,53	104889,27	104766,53	19,79	19,77
5350	105375,00	102361,50	19,70	19,13	39,28	2499,70	105414,28	104861,20	19,70	19,60
5400	105900,00	102456,00	19,61	18,97	39,29	2499,89	105939,29	104955,89	19,62	19,44
5450	106425,00	102550,50	19,53	18,82	39,30	2500,09	106464,30	105050,59	19,53	19,28

5500	106950,00	102645,00	19,45	18,66	39,32	2500,30	106989,32	105145,30	19,45	19,12
5550	107475,00	102739,50	19,36	18,51	39,33	2500,52	107514,33	105240,02	19,37	18,96
5600	108000,00	102834,00	19,29	18,36	39,35	2500,75	108039,35	105334,75	19,29	18,81
5650	108525,00	102928,50	19,21	18,22	39,36	2501,00	108564,36	105429,50	19,21	18,66
5700	109050,00	103023,00	19,13	18,07	39,38	2501,25	109089,38	105524,25	19,14	18,51
5750	109575,00	103117,50	19,06	17,93	39,40	2501,52	109614,40	105619,02	19,06	18,37
5800	110100,00	103212,00	18,98	17,80	39,41	2501,79	110139,41	105713,79	18,99	18,23
5850	110625,00	103306,50	18,91	17,66	39,43	2502,08	110664,43	105808,58	18,92	18,09
5900	111150,00	103401,00	18,84	17,53	39,45	2502,38	111189,45	105903,38	18,85	17,95
5950	111675,00	103495,50	18,77	17,39	39,47	2502,68	111714,47	105998,18	18,78	17,81
6000	112200,00	103590,00	18,70	17,27	39,49	2503,00	112239,49	106093,00	18,71	17,68
6050	112725,00	103684,50	18,63	17,14	39,51	2503,32	112764,51	106187,82	18,64	17,55
6100	113250,00	103779,00	18,57	17,01	39,53	2503,66	113289,53	106282,66	18,57	17,42
6150	113775,00	103873,50	18,50	16,89	39,55	2504,00	113814,55	106377,50	18,51	17,30
6200	114300,00	103968,00	18,44	16,77	39,57	2504,35	114339,57	106472,35	18,44	17,17
6250	114825,00	104062,50	18,37	16,65	39,60	2504,71	114864,60	106567,21	18,38	17,05
6300	115350,00	104157,00	18,31	16,53	39,62	2505,08	115389,62	106662,08	18,32	16,93
6350	115875,00	104251,50	18,25	16,42	39,64	2505,46	115914,64	106756,96	18,25	16,81
6400	116400,00	104346,00	18,19	16,30	39,67	2505,84	116439,67	106851,84	18,19	16,70
6450	116925,00	104440,50	18,13	16,19	39,69	2506,23	116964,69	106946,73	18,13	16,58

Table 16: Variance of costs having different demands