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Alternative business strategies based on the comparison of modern and traditional manufacturing technologies

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Abstract

This dissertation was written as part of the Executive Master in Business Administration (EMBA) at the International Hellenic University.

Additive Manufacturing technology has been evolving for several years. New material options, better processing speeds and greater autonomy are some of the characteristics of this technology that are still under research. However, in its current state, many commercially available 3D printers are competing with traditional manufacturing techniques in the fabrication of end-use products. In the current dissertation, Additive Manufacturing is compared with Injection Molding in terms of fabricating a plastic housing for a real-world company. In the first half of the dissertation, literature is reviewed regarding Additive Manufacturing, the opportunities and barriers that come with it, its application on various industries and its impact on supply chains. In the second half of the dissertation, a case under study is examined. First its existing production strategy based on Injection Molding is presented and afterwards, a number of alternative production strategies based on different Additive Manufacturing technologies are explored. A comparison is made in terms of Lead Time and Total Production Cost and finally, the findings are displayed. Some of the conclusions drawn from this research are that none of the Additive Manufacturing technologies is able yet to replace Injection Molding for medium- and high production volumes. However, as regards low-volume production, both Rapid Tooling and Rapid Manufacturing can offer a shorter Lead Time and a lower Total Production Cost, while offering also increased flexibility, reduced warehousing costs and the potential of adopting a mass customization business strategy.

Keywords: Additive Manufacturing, 3D printing, Injection Molding, mass customization, supply chain

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Preface

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Contents

1. Introduction

Modern times is otherwise known as the Digital Age. The current period in human history is characterized by the wide spread of technological achievements in every part of the planet. The wide use of Internet allows the information to travel very fast anywhere in the world and many gadgets and digital devices have become inseparable tools in everyday life. One of these technological achievements that is going to shape the way things are made is Additive Manufacturing. As stated by its name, Additive Manufacturing is a manufacturing process that uses a digital blueprint in order to fabricate an item. Additive Manufacturing, or else known as 3D printing, has been evolving for several years now. There are many different technologies that belong to this term, however they all perform the same task; they create a 3D object by adding build material to it layer by layer.

This dissertation aims to provide to the reader information about Additive Manufacturing technology and its potential. It presents also a case under study about a company, which produces all plastic parts using a traditional manufacturing method, i.e. Injection Molding, and examines the possibility of adding Additive Manufacturing into its production portfolio. Specifically in the first section of this dissertation, a literature review is presented regarding Additive Manufacturing features, the opportunities it provides and the barriers that it still has to overcome. It refers also to various applications that Additive Manufacturing technology has and reveals its current and future impact on supply chain management. In the second section of the dissertation, the case under study is presented, while in the third section the existing production strategy of the company is analyzed. The existing strategy relies heavily on medium- and high-demand products and has organized the entire structure of the company in such a way, so that these products are manufactured at a low cost. The functions of Lead Time and Total Production Cost of the existing strategy are presented, along with all the variables that a decision-maker should take into account when choosing the appropriate business strategy. In the fourth section of this report, a number of alternative production strategies are presented that are all dependent entirely or in some part in Additive Manufacturing technology. Specifically the use of the PolyJet technology as a Rapid Tooling method is examined and the use of Fused

Deposition Modeling, Stereolithography and Selective Laser Sintering as Rapid Manufacturing methods. In addition, the functions of Lead Time and Total Production Cost for each different strategy are presented. In the sixth section the results derived from the comparison of all aforementioned productions strategies are depicted. The comparative study is performed not only between traditional and modern methods, but also amongst the different modern methods. Furthermore, it refers mainly to the Lead Time and Total Production Cost of each production method, however some quality issues and further features are also discussed. In the last section, a number of conclusions are drawn according to the findings of the research.

2. Literature review

2.1 Additive Manufacturing

Additive Manufacturing (AM) is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Wohlers Associates, Inc., 2010). Other terms that are often used are additive fabrication, additive layer manufacturing, layer manufacturing, and freeform fabrication. There are various manufacturing technologies that belong to the additive manufacturing processes. These technologies can be classified either by the form of the starting material or by the basic mode of operation, also known as channel mode. In reference to the form of the starting material the additive manufacturing technologies can be classified as processes using raw material which is: a) liquid, b) powder, c) molten, and d) solid sheets. In reference to the basic channel mode, there are three alternatives: a) a moving point, b) a moving line consisting of an array of points, which scans across the entire layer and c) a layer mode using a mask projection system in which the layer is created all at once (Groover, 2013).

Additive Manufacturing has more than 20 years of history. At the beginning it was mostly used for the manufacturing of conceptual and functional prototypes, a process known as Rapid Prototyping (RP) (Santos et al., 2006; Mellor et al., 2014). Rapid Prototyping was initially driven by the need of reducing "Time to Market", i.e. by shortening the product life cycle (Levy et al., 2003). These prototypes could be created in just a few hours directly from the computer models and they were used as communication and inspection tools (Santos et al., 2006, Mellor et al., 2014). Nowadays, Additive Manufacturing processes are used not only for Rapid Prototyping, but also for Rapid Manufacturing (RM) and Rapid Tooling (RT). Rapid Manufacturing is defined by Rudgley (2001) as "the manufacture of end-use products using additive manufacturing techniques (solid imaging)”. On the other hand, Rapid Tooling is considered a sub-category of RM and is used to fabricate tools that serve traditional manufacturing processes, such as Injection Molding (Dimov et al., 2001). A definition of Rapid Tooling given by Achillas et al (2014) is that " RT describes a process that is the result of combining RP techniques with conventional tooling practices to produce a mold quickly or parts of a functional model from computer aided design (CAD) data in less time and at a lower cost relative to traditional machining methods". In general, according to Wohlers Associates, Inc. (2013) a steady growth is observed in the percentage of Additive Manufactured parts used for final products. In ten years the percentage grew from 3.9% to 28.3% of the total product and service revenues from global Additive Manufacturing (Wohlers Associates, Inc., 2013).

In the current global economy it is very important for a company to stay competitive. In order to achieve that, a company must organize its entire production having in mind to decrease the time and cost of the design and manufacturing, while at the same time it enhances flexibility and quality (Kerbrat et al., 2011). The Additive Manufacturing technology is able to provide a manufacturer with the above qualities. Investment in Additive Manufacturing can provide the firm with new business opportunities, as it improves existing and creates new manufacturing capabilities. This may lead to a technology-push strategy (Mellor et al., 2014). Firms operating either in the service or product sector may redesign their product and supply chain strategies in order to gain a competitive advantage. It has been emphasized by Mellor et al. (2014) that the success of this investment is based on whether the company will be able to link the technology benefits to the new business strategy. However, as described by Sonntag (2003), it is also important for the company to understand the limitations of the new technology and accept the trade-off. One should also take under account the lack of technical standards, which is caused by the relative immaturity of the new technology (Mellor et al., 2014). In order for the company to succeed in the implementation of the new technology, it is very important to re-structure the organization and the various processes (Dalton et al., 1980; Dean et al., 1992; Belassi and Fadlalla, 1998; Ghani et al., 2002; Sun and Cui, 2007; Saberi et al., 2010). Some necessary changes may be in jobs, tasks and work practices (Mellor et al., 2014). As part of the implementation it is also very important for the firm to recognize the need of adopting a new business strategy. The focused factory concept, which encourages the companies to concentrate their resources on manufacturing specific and finite product lines in order to become competitive, is proven not to be optimal for all cases. Especially in an uncertain and fast-changing business environment, where flexibility and customization start to dominate. In this environment the use of less focused and specialized strategies may be necessary (Ketokivi & Jokinen, 2006). In this light, the adoption of Additive Manufacturing technology practices may be critical. The company can continue using the traditional and low-cost manufacturing methods for producing their high demand products, while at the same time it enables its clients to customize and order one-of-a-kind products. The company actually adds a new focused production line within the focused factory environment (Achillas et al., 2014).

2.2 Opportunities

The Additive Manufacturing technology has several attributes that if used correctly, they can underlie many opportunities. The main attributes that provide most of the advantages are according to Groover (2013): a) the speed of delivery, b) the simplification of the process since the file that is uploaded to the Additive Manufacturing machine is the CAD file that already exists and c) the liberation from the low-complexity designs and the freedom in the new design forms.

Additive Manufacturing is a tool-less process and so the shift from the design to the production can occur within one day. There is no up-front cost such as expense of tool design and tool making. Also the fact that there is no tooling means that changes to the design cost nothing to implement.

In reference to the complexity advantage, it is well known that the lead time and the manufacturing cost of an injection mold is greatly influenced by the complexity of the part design. In contrary, in Additive Manufacturing the part complexity has no significant influence neither on the lead time nor on the manufacturing cost. It takes the same time to 3D print a very intricate part as a simple cube of the same volume (Gibson et al., 2010), while the manufacturing cost of an intricate part may be a little higher than the cube's, however this would be a result of the part orientation and the existence or not of support material and not a result of the geometry complexity itself. In general, it is proved that the Additive Manufacturing advantage increases as the geometry of the part becomes more complex (Groover, 2013).

In relation to the material, when a part is created by a traditional manufacturing method, e.g. Injection Molding, one homogeneous material is usually used. There are some cases where more than one materials can be in one part, however there is a definite boundary between each material. In Additive

Manufacturing it is possible to mix and grade materials in any combination so that the final part benefits from the properties of all the materials involved (Hopkinson et al., 2006).

Another very important attribute of Additive Manufacturing is the fact that it is a labor-free process. Once the CAD files are uploaded, the machine can work for hours, even days, without any manual intervention (Zonder & Sella, 2014). Thereby one can leave the machine work unattended and take advantage of evenings and weekends for long builds in order to reduce the lead time of production.

All the above attributes of Additive Manufacturing make this technology suitable for covering the needs in production that are still not covered by conventional manufacturing methods. According to Stratasys (2013), a major global vendor of Additive Manufacturing machinery, Additive Manufacturing can be used for pilot production, bridge-to-production, full production and bridge-to-end of life.

Pilot production is very useful when the company plans to launch some new products. These products can be created by an Additive Manufacturing machine instead of the traditional method, so that the company can gain from the fast building and the no up-front cost. It can use these products as samples in order to get feedback and avoid making costly mistakes. During pilot production the company can still develop the product, make changes to the design and generally reduce time to market without having to make expenses in tool making.

Bridge-to-production is the time elapsed after a product has been finalized and before the mass production starts. This time may be several months in the case of Injection Molding, since it is actually the time required for the mold to be created so that the mass production can start. Additive Manufacturing machines can cover the need here by building the first batch of the products while waiting for the delivery of the injection mold. This opportunity is significant for first-of-a-kind products or for products that are outmoded quickly.

Although Additive Manufacturing equipment has the ability to work for the full production of products of any demand, the dominant opinion in the literature (Zonder & Sella, 2014; Groover, 2013) is that Additive Manufacturing is more efficient when used for low-volume production, one-off products, highly customized or complex products. The quantity of a low-volume production is dependent on product size. In general, smaller products can be produced in larger quantities, as there is the possibility to stack and nest the products in the build in order to produce more in the same build time. Additionally, one of the greatest advantages of Additive Manufacturing technology is that it doesn't require any tooling, thus making financially feasible the scenario of producing any number of products, with no minimum quantity requirement. Also the fact that complexity doesn't increase the time nor the cost of the production makes it possible to produce highly complex parts that couldn't otherwise be made.

Additionally, Additive Manufacturing technology can be used as a bridge-to-end of life of a product. Often there is a problem when a product is near the end of its life cycle and some tooling needs repairing or there are no spare parts of the product and the production machines are occupied producing another product. This problem can be solved with the use of Additive Manufacturing technology. 3D printers can extend a product's life and build spare parts when needed, thus eliminating the need of maintaining a physical inventory.

All in all, there are many opportunities derived from the Additive Manufacturing technology, such as freedom in the design of a product, reduced time to market, reduced manufacturing and warehousing costs, increased flexibility and the ability to produce customized or highly complex parts (3D Systems, 2015). All these opportunities occur, while at the same time the company can manufacture in-house whatever it needs and keep its intellectual property on site (Stratasys, 2015).

2.3 Barriers

There are many barriers about this technology that are presented in the literature, which stunt its growth. These barriers have to do with the material availability, the material cost, the speed of the process and the quality of the manufactured part that often requires extensive post-processing. In the present work some issues regarding the intellectual property rights and some improper use of this technology are presented.

Additive Manufacturing is a very broad term that includes a wide variety of different manufacturing techniques. Most of these techniques can work only with a limited number of materials, since it is essential for their process to use materials with specific properties, e.g. photosensitive material. Most of the materials used in 3D printing lack the mechanical properties of the materials used in traditional manufacturing methods (Groover, 2013).

Also the price per kilogram of the materials used in 3D printing is significantly higher than the price of other engineering plastics used in traditional manufacturing processes (T.A. Grimm & Associates, Inc., 2010). The real material cost can be even higher if one considers some Additive Manufacturing technologies, where due to the technology limitations there is a lot of wasted material or due to the orientation of the part fabricated there is a lot of support material used. However, there are some Additive Manufacturing technologies, which use for each build the amount that is exactly needed, as well as other processes, where the excess material can be reused (Reeves, 2008; Gebler et al., 2014). Caution is needed also in handling the raw materials. When recycling the excess material it is important not to let any contaminants mix with the material, because it will be ruined. In addition, some raw materials have limited shelf-life and must be in storage conditions that prevent them from chemical reactions. Exposure to moisture, light and other polluting substances should be also prevented (Gibson et al., 2010).

Additive Manufacturing is generally a very slow process. Of course there is range in speed according to the specific technology and the machinery used, however even the fastest process cannot be compared with traditional manufacturing methods, e.g. Injection Molding. Technologies that use an extruder and not a laser are even more slow and one build can take several days in order to complete. Print speed may be defined as "time required for printing a finite distance in the Z-direction" (3D Systems, 2015), since building in the x-y axis is very fast. Part orientation is a significant decision here, as tall builds take longer to build than short ones (Gibson et al., 2010). This is the reason why it is strongly advised to maximize utilization of all the available build volume by stacking and nesting parts so that the manufacturer gains additional throughput (3D Systems, 2015).

One other major barrier for the mass use of Additive Manufacturing machines is the quality of the fabricated part. In Additive Manufacturing every object is created in layers and so it is often observed that the surface of the object is not smooth, but suffers from stair-stepping. The degree of the stair-stepping depends on the layer thickness and varies according to the surface inclination and the part orientation (Levy et al., 2003). There are many ways to fix this problem in Additive Manufactured parts, however the solution includes a lot of post-processing work, which adds time and increases the production cost.

Other issues deriving from the growth of this technology have to do with the intellectual property of the digital blueprints. Especially in the case of 3D scanners, where almost every product can be scanned and digitalized and afterwards recreated with the use of a 3D printer (Simon, 2013; Weinberg, 2013), there will be many issues regarding copyright, patent and trademark systems. Similar issues arose also with the digitalization of music and the mass use of internet (Korkki, 2013). Another field that must be evolved along with the growth of Additive Manufacturing technology is the certification procedure for production and product proving, such as CE, ISO, etc. (Hopkinson et al., 2006).

The digitalization of the blueprints and their wide distribution via the internet, along with the manufacturing capabilities of the Additive Manufacturing technology may provoke also security threats (Gebler et al., 2014). One characteristic example is the Japanese who 3D printed a gun in his home and was sentenced to two years in prison for making illegal firearms (Hornyak, 2014).

2.4 Applications of Additive Manufacturing technology

Additive Manufacturing technology has many applications so far and it can evolve in having many more. Its ability to fabricate one-of-a-kind parts without high initial cost, the design freedom it provides with the freeform fabrication of very complex parts, its relatively high speed compared to other traditional processes and the current trend and need for mass customization derived from the "Maker movement" (Anderson, 2012) make this technology ideal for a number of fields and applications.

A very suitable application for Additive Manufacturing technology is the medical field. There are various applications here such as the production of hearing aids, biocompatible plastic bridges, implants, supports, bones, etc. The main characteristics in these applications is that they are all custom-made for each patient (Levy et al., 2003).

A very interesting application are the 3D printed buildings. A Chinese company has managed to manufacture a 5-floor building by using a 3D printer of 150m length and 6 meter height. The raw material used for the construction of the building was recyclable building material with some contents of fiber glass, steel and cement. The same company has also 3D constructed a villa of 1,100 square meters (B2Green, 2015). In the same field, a Dutch company has announced its plans to 3D build a canal house in Amsterdam, while a few months ago they revealed to the public the first walls of the canal house (Zimmer, 2014).

An unforeseen use of Additive Manufacturing technology is to 3D print tattoos. The new technology provides new potential in designs and it can reach body parts that could not be manually reached (LIFO, 2015). Another equally unexpected use of Additive Manufacturing is to 3D print food. Other than engineering students and high-tech companies that are experimenting with the 3D fabrication of chewing gum, chocolate and pasta, NASA is also considering of using a 3D printer to make food in space (3D Printing Industry, 2015; NASA, 2013).

Other applications of Additive Manufacturing technology are 3D printed clothes, such as textiles, shoes and accessories (3D Printing Industry, 2015), and personalized jewelry fabricated with materials which include Sterling Silver and 14k Gold (Shapeways, 2015). Finally, one should not forget more traditional applications, such as the aerospace and the automotive industry, in which the parts need to have complex geometry and weight effectiveness (Levy et al., 2003).

2.5 Impact of Additive Manufacturing on Supply Chains

Additive Manufacturing is giving all the necessary signs that it can become a disruptive force and change radically the way modern supply chains work (Achillas et al., 2014). 3D printing brings back manufacturing close to the point of sale (Hopkinson et al., 2006) and shifts production into a more resource-efficient process (Gebler et al., 2014). Notions like just-in-time and lean manufacturing play a dominant role.

First of all, Additive Manufacturing gives a company the benefit of keeping a digital inventory instead of a physical one. Blueprints of all kinds of designs, customized for every client become a reality. There is no need of keeping any semi-finished products, the only inventory needed are the raw materials. Bill of materials

(BOM) decreases and so are time and expenses associated with managing and maintaining inventory (Stratasys, 2013). Just-in-time becomes a viable system even with unstable demand of products.

Second of all, manufacturing returns back to the developed countries. The labor-free process of 3D printing makes it ideal for ageing societies and the production shifts from the developing countries back to the consumer countries, as China and other developing countries lose their labor cost-related comparative advantage (Campbell et al., 2011). Supply chains become shorter, as the production becomes more localized (Reeves, 2008) and the physical movement of goods is partially replaced by the digital distribution of blueprints (Campbell et al., 2011). This results in the supply chains being less transport intensive (Birtchnell et al., 2013) and therefore having a reduced carbon footprint (Kaltenbrunner, 2014). In addition, businesses can locate manufacturing centers close to demand locations and therefore reduce even more the lead time (Mellor et al., 2014).

One thought expressed by Kaltenbrunner (2014) regarding the future outlook of third party logistics companies (3PLs) is their need to adapt to the supply chain changes that the growth of Additive Manufacturing brings. Since the physical movement of goods decreases, traditional 3PLs will eventually see their revenues also decreasing. The idea proposed by Kaltenbrunner (2014) is the transformation of traditional 3PLs into third party printing companies. These companies could invest in Additive Manufacturing machinery and instead of just transporting the goods of their clients, they could use the digital blueprints to manufacture the products on their clients' behalf and transport them afterwards. In this way the products will have a smaller carbon footprint and the supply chains will become far more agile.

3. The Case under Study

The case under study is about the production strategy of a medium-sized company located in Northern Greece. The company trades in developing innovative electronic safety and security systems by using state-of-the-art technology. It has been operating since 1979 and its products are exported in 72 countries worldwide.

The company offers a big variety of products that are sold both in Greece and abroad. Almost all of its products consist of a number of plastic parts that serve as a housing for the electronic circuits. Therefore the company decided several years ago to invest in machinery and start producing all required SKUs in-house. Regarding the manufacturing of the plastic parts, the company installed four (4) Injection Molding machines in 2002 and another four (4) in 2005, reaching a total of eight (8) machines installed and working currently.

3.1 Products under examination

In the case under study that is presented in this work, the manufacturing process of four (4) different products of the company are examined. Product A is a security light that consists of three different plastic parts. It is sold worldwide, both in Greece and abroad, and it is the company's product with the highest demand. Its sales in 2014 reached 11,328 units and the company keeps a stock for this product in the range of 3,000 units. Product B is a home light. It consists of two different plastic parts and it is sold mainly in the Greek market. Its sales in 2014 reached 9,334 units, it is considered to be of medium-high demand and the company keeps a stock of 500-600 units. Product C is also a home light and it consists of six different plastic parts. It is sold mainly in Greece and its sales in 2014 reached 1,080 units. It has a stock in the range of 70-80 units and it is considered to be of medium-low demand. Product D is a weather spot light. It consists of two different plastic parts, it is sold mainly abroad and it sold 210 units in 2014. Its demand is considered low and thus, the company doesn't keep any stock at all for it. The products and their characteristics are summarized in Table 1.

Table 1: Products under examination

PRODUCT CODE	NUMBER OF PLASTIC PARTS	SALES IN 2014	DEMAND	SKU	MARKET
Product A	3	11328	very high	3000	Worldwide
Product B	2	9334	medium-high	500-600	Greece
Product C	6	1080	medium-low	70-80	Greece
Product D	2	210	low	0	Abroad

4. Existing Production Strategy

The current production strategy of the company is to produce all plastic parts in-house. For this purpose as mentioned the company has installed eight (8) Injection Molding machines of different size and clamping force (tonnage). In Table 2 the eight different Injection Molding machines as well as their power consumption are depicted. It should be highlighted that the Injection Molding machines require not only power to work but also water. However the water that runs in the system of each machine runs in a close loop and therefore the cost for water is negligible (it is estimated that there is a need of 300ml of extra water every time the machine opens in order to change the mold). However, the close water loop uses power in order to work. There are two (2) motors for this purpose that share the water circuits of the eight machines. In Table 2 the power consumption that relates to the water system of each machine is also illustrated.

Table 2: Injection Molding machinery already installed

INJECTION MOLDING MACHINE	**POWER CONSUMPTION**	**WATER POWER CONSUMPTION**	**TOTAL POWER CONSUMPTION**
Haitian HTF 22x	9 kW	3.5 kW	12.5 kW
Haitian HTF 58x	16.5 kW	3.5 kW	20 kW
Haitian HTF 86x	18.7 kW	5 kW	23.7 kW
Haitian HTF 86x	18.7 kW	3.5 kW	22.2 kW
Haitian HTF 150x	22.5 kW	5 kW	27.5 kW
Haitian HTF 200x	30.9 kW	3.5 kW	34.4 kW
Haitian HTF 360x	56.5 kW	5 kW	61.5 kW
Haitian HTF 380x	56.5 kW	3.5 kW	60 kW

During production there is a need of one employee in almost every Injection Molding machine. This employee gathers and sorts out the items that were just produced and he also performs random quality controls.

The raw material that is used by the company in the Injection Molding machines is Polycarbonate (PC). The company's supplier is based in Italy. Polycarbonate costs 3 Euro/kg and it has a delivery time of two months. Polycarbonate is supplied in granular form and melts inside the machine in order afterwards to be injected into the mold. At the end of every working day the Injection Molding machines are turned off and so the raw material that is inside the extruder and has already been melt down, it cools down and solidifies during the night. This amount of raw material cannot be heated again and so it is considered a waste and it is removed from the machine every morning. It is estimated that for the two largest machines the wasted raw material every morning is approximately 2kg, while for the rest of the machines it is 1kg.

The molds that are used in Injection Molding are made of steel or aluminum. The choice of the material has to do with the expected number of cycles of the specific mold. Steel molds have a very long lifespan. These can last for millions of cycles and their cost can reach as high as hundreds of thousands of Euro. Also the lead time to produce these molds is measured in months rather than weeks or days. On the other side, aluminum molds are less expensive - they have a cost range from 2,000 - 20,000 Euro - and are faster to produce (2 - 6 weeks) but they can only last for tens of thousands of cycles. The company under study uses steel molds. It still uses molds that were constructed 15 years ago. The long lifespan offsets the high initial cost over a high number of parts that can be produced before the mold wears out. Besides the initial cost there is also a cost associated with the maintenance of each mold. After every use, when the mold exits the machine and before it is stored again, it is greased using a special lubricant for the outside and another one for the inside. The cost of these lubricants is 7 Euro/glass container for the interior lubricant and lasts for 2 weeks, while the cost of the exterior lubricant is 60 Euro/glass container and lasts for 2 years.

4.1 Lead Time

The Lead Time (LT) consists of three variables: the pre-processing time ($T_{pre\text{-}processing}$), the processing time ($T_{processing}$) and the post-processing time ($T_{post\text{-}processing}$).

$$LT = T_{pre-processing} + T_{processing} + T_{post-processing} \quad (4.1)$$

The pre-processing time in Injection Molding consists of the warm-up time (WU), the mold setup time (MOS) and the machine setup time (MAS). The warm-up time is different than the machine setup time because the warm-up time occurs only once in the working day, that is in the morning at the start of the day. Afterwards the machine is always on a stand-by mode even if it is not producing. The machine setup time has to do with the setting of the parameters that the machine needs in order to start producing. These parameters may be different from product to product and therefore, every time the mold changes, the new parameters have to be adjusted. The mold setup time is the time needed to remove the mold that was previously used from the machine and insert the appropriate mold for the current production.

Although for a company that has been operating since 1979 most of the molds are already manufactured and stored in the warehouse, it is rather short-sighted to consider that these same molds will also cover its needs in the future. The market moves towards the age of mass customization and the customers are becoming more and more demanding. Other than the fact that the company could offer a highly customized product for every client, a redesign of existing products so that they meet new technical or even aesthetic requirements is something that the company will confront at some time. It should be marked here that the existing customers of the company that are based abroad are already asking for customization in their orders. Of course the company cannot offer this customization right now in regards of the product design, but all they can do is to laser engrave a logo or print and place a different sticker on the product.

Considering the above thoughts, one more variable called mold construction time (MOC) is added to the $T_{pre\text{-}processing}$ equation (4.2) . The mold construction time represents the time required for a new mold to be constructed and delivered to the company. It should be noted here that the company does not have the machinery required in order to construct the molds but it is outsourcing its construction to third-party companies in Greece. The $T_{pre\text{-}processing}$ equation is:

$$T_{pre-processing} = WU + MOS + MAS + MOC \quad (4.2)$$

The processing time is the build time (BT). It is the actual time needed for the production of a plastic part. For the specific four products of the company, which are under examination, the processing time of a part varies from 20 sec to 55 sec.

$$T_{processing} = BT \quad (4.3)$$

The post-processing time is the time needed for the part that has been produced to cool down (CD) and the assembly time (AT) that is required afterwards. In Injection Molding there is no possibility in producing complex parts in one cycle and so it is often that complex parts are split in some simpler - in terms of geometry and complexity - parts. That means that in order for the final product to be considered ready to ship, one must take under consideration also the necessary time after the production for the assembly of all the parts that consist the product. The four specific products of the company that are herein examined consist from 3 to 7 plastic parts (see Table 1). Their assembly time is estimated to be 10 minutes for every product.

$$T_{post-processing} = CD + AT \quad (4.4)$$

Using the equations (4,1), (4.2), (4.3) and (4.4), the Lead Time can be calculated as follows:

$$LT = (WU + MOS + MAS + MOC) + (BT) + (CD + AT) \quad (4.5)$$

4.2 Total Production Cost

The Total Production Cost (TC) consists of five variables: the material cost (MC), the machine cost (MA), the mold cost (MO), the labor cost (LC) and the fixed overhead cost (FC).

$$TC = MC + MA + MO + LC + FC \quad (4.6)$$

The material cost depends on the raw material that the company uses for Injection Molding, as well as the size of the order. In the specific case, Polycarbonate (PC) is used and due to the usual size of the order its price is at 3 Euro/kg. The machine cost consists of four factors; a) the machine depreciation (MAD), b) the machine maintenance expenses (MAM), c) the cost of power (CP) and d) the cost of water (CW). As it was previously stated, the cost of water in Injection Molding is negligible and so the machine cost equation is:

$$MA = MAD + MAM + CP \quad (4.7)$$

The mold cost consists of the mold depreciation (MOD) and the mold maintenance expenses (MOM). The labor cost can be calculated if the hourly wage (HW) of the employees involved in the production is multiplied by the time that they spend for these activities and by an utilization factor (u). The utilization factor has the value "1" for a manual operation and the value "0" for a fully automated operation. For all other operations, i.e. semi-automated, it takes an intermediate value.

$$MO = MOD + MOM \quad (4.8)$$

$$LC = HW * T_{pre-processing} * u_{pre-processing} + HW * T_{processing} * u_{processing} + HW * T_{post-processing} * u_{post-processing} \quad (4.9)$$

The fixed overhead cost consists of the building cost (BC), the warehousing cost (WC) and some general overhead costs (OC), such as utilities, etc.

$$FC = BC + WC + OC \quad (4.10)$$

If the equations (4.6), (4.7), (4.8), (4.9) and (4.10) are used, the total production cost is calculated as follows:

$$\begin{aligned} TC = (MC) + (MAD + MAM + CP) + (MOD + MOM) \\ + \left(HW * T_{pre-processing} * u_{pre-processing} + HW * T_{processing} \right. \\ \left. * u_{processing} + HW * T_{post-processing} * u_{post-processing}\right) \\ + (BC + WC + OC) \end{aligned} \quad (4.11)$$

5. Alternative Production Strategies

Additive Manufacturing has been involved very much from the beginning and it has started to substitute traditional manufacturing processes. Additive Manufacturing is the process of making a product by adding very thin layers of material one on top of the other and hence, creating in the end a product in three dimensions. Of course the technology is still evolving and there is still a lot of room for improvement in terms of characteristics like speed, material selection, surface smoothness, etc. However nowadays the technology has already reached a satisfactory level of efficiency and performance and that is why it is herein examined as an alternative production strategy. Specifically, the use of PolyJet technology is considered as a Rapid Tooling method and the use of Fused Deposition Modeling, Stereolithography and Selective Laser Sintering as Rapid Manufacturing methods.

5.1 Rapid Tooling

During the mid '90s when the phrase "Rapid Tooling" was first used, it described any method that would replicate an injection mold to manufacture a physical plastic or metal part. Today Rapid Tooling is defined as a process that combines Rapid Prototyping processes with conventional tooling practices in order to produce a mold quickly and at a lower cost compared to conventional techniques. Rapid Tooling either uses a Rapid Prototyping model as a pattern or fabricates directly a tool, such as an injection mold, that is used to produce a limited number of pieces.

One additive manufacturing method that is appropriate for Rapid Tooling is the PolyJet technology. PolyJet technology can produce smooth, accurate prototypes, parts and tooling. It has a 16-micron layer resolution and accuracy as high as 0.1 mm and it can produce thin walls and complex geometries using a wide range of materials. Digital Materials expand the possibilities by blending two or three base resins to create nearly 1,000 composite materials with specific, predictable properties.

PolyJet 3D printing works similarly to inkjet printing, but instead of jetting drops of ink onto paper, PolyJet 3D Printers jet layers of curable liquid photopolymer onto a build tray. Then the layers are instantly cured by a UV-light and thus, they are solidified. Where overhangs or complex shapes require support, the 3D printer jets a removable gel-like support material. The support material can be easily removed by hand or with water. There is no need for post-curing and so, the molds created can be immediately placed into an Injection Molding machine and used to create prototypes from the same material that is specified for use in the final product. These realistic, finished-product examples can be used to gather true-to-life, performance data or even meet the demand of a low-volume product.

PolyJet 3D Printers can give the company the ability to build injection molds in-house, quickly and easily. A mold can be built within a few hours as compared to days or weeks to create traditional molds. The production cost of a PolyJet mold is relatively low and it makes no difference in the cost how complex the geometry of the mold is or if it has any fine details or not. In cases where design changes are required, a new iteration of the mold can be created in-house at minimal cost. The material selection for a PolyJet mold is very important, because it has an impact on the number of cycles that the mold can be used for. Digital ABS is known to be the optimal choice since it combines strength and toughness together with high temperature resistance. In general PolyJet molds are used for 100 - 150 cycles.

The literature refers that "PolyJet injection molds are not intended to be replacements for soft or hard tools used in mid- and high volume production. Rather, they are intended to fill the gap between soft tool molds and 3D printed prototypes" (Stratasys, 2014). However, in the case under study the use of PolyJet injection molds is examined for products of low, but also mid- and high demand.

5.2 Rapid Manufacturing

Rapid Manufacturing is the use of Additive Manufacturing technologies for the creation of an end-use product. Rapid Manufacturing, unlike Injection Molding, is a tool-less process, which does not involve any melting and subsequent solidification of materials within a mold so that the part can be produced.

5.2.1 Fused Deposition Modeling (FDM)

One Additive Manufacturing method that is appropriate for Rapid Manufacturing is the Fused Deposition Modeling (FDM) technology. In FDM, a filament of wax and thermoplastic polymer is extruded onto the existing part surface from a work head in order to create each new layer. The work head creates each layer in the x-y axis and then it moves up in the z axis by a distance equal to the layer thickness so that it creates afterwards the new layer on top of the previous one.

FDM technology is widely used among many Additive Manufacturing machines, since it is a clean and office-friendly technology, as there are no powders or liquids that require special handling. However, the most important benefit is that FDM technology can use the same thermoplastics that are also used in traditional manufacturing processes and thus, create objects that are tough, biocompatible or resistant to high temperature. On the other hand, FDM also has certain disadvantages. One disadvantage is the slow speed compared to the other technologies. This comes from the fact that the material is deposited through a work head that cannot move as fast as a laser spot. One additional disadvantage is that the extruder has a circular nozzle orifice that makes it difficult to form sharp corners. Furthermore, FDM engineered parts usually have a rough surface due to the visible layer lines and thus, some post-processing work is required so that the quality of a product produced by a traditional method, e.g. Injection Molding, is reached. This is the reason why mass finishing is widely used for almost all FDM manufactured parts. Mass finishing works by smoothing material from the outside surface of the part, removing 0.04 to 0.08 mm from the surface. There are several available methods such as sanding, melting with solvents, etc.

5.2.2 Stereolithography (SLA)

Stereolithography (SLA) is an Additive Manufacturing process which employs a tub of liquid photosensitive polymer and a UV laser and is used for producing prototypes and end-use parts. The laser beam traces a cross-section of the part pattern on the surface of the liquid polymer and cures and solidifies the part of the polymer that it is exposed to. Then the machine platform lowers by a distance equal to the layer thickness and fresh material is being recoated on the surface. The laser beam traces again the part pattern and so the new layer is solidified on top of the previous one.

In SLA, the typical layer thickness ranges from 0.05 to 0.15 mm. Thinner layers provide better resolution and allow more intricate part shapes but processing times are longer. The choice of available materials is not so wide as in FDM process, however there are several available options that include properties like high impact strengths, tensile strengths and resistance to high temperature. One of the biggest advantages of SLA is its high speed. However, the use of photosensitive polymers require special attention in warehousing and handling.

SLA process requires a lot of post-processing work. The parts created must be UV cured and afterwards cleaned. The post-processing curing provides a tough and durable final finish for the SLA engineered parts. Cleaning is also necessary and it is done with the use of specially formulated long-lasting cleaning solutions. For both post-processing activities there is specific finishing equipment commercially available.

5.2.3 Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) is an Additive Manufacturing technology that uses a high power laser to fuse small particles of plastic, metal, ceramic or glass powders into a 3-dimensional part. The laser selectively fuses powdered material by scanning cross sections generated from a 3D digital description of the part on the surface of a powder bed. After each layer is completed, the powder bed is lowered by one layer thickness, a new layer of loose powders is spread across the surface, and the process is repeated until the part is completed. The powders are preheated to just below their melting point to facilitate bonding and reduce distortion of the finished product. Preheating also serves to reduce power requirements of the laser. In areas not sintered by the laser beam, the powders remain loose so they can be poured out of the completed part. Meanwhile they serve to support the solid regions of the part as fabrication proceeds. The SLS process is usually accomplished in an enclosure that is filled with nitrogen to minimize degradation of powders that might be susceptible to oxidation (e.g. metals).

SLS is generally a high speed process. Layer thickness can vary from 0.075 to 0.50 mm. It offers unlimited geometrical possibilities, since no support is required and part orientation can be selected freely without the need for jigs or fixtures. There are many materials that can be used, like polymers, metals and ceramics, and these materials are usually less expensive than the photosensitive polymers used in processes like PolyJet and Stereolithography. Almost 80% of the material used in a build can be recycled and used again in a different build. The contemporary SLS machines have automated production tools, power handling and recycling functions.

5.3 Lead Time

As previously discussed (equation 4.1), the Lead Time consists of three variables, the time needed for the pre-processing activities, the time needed for the processing activities and the time needed for any post-processing activities that might be necessary.

The pre-processing time in Additive Manufacturing consists of the time needed for the file preparation (FPREP) and the machine preparation (MPREP).

$$T_{pre-processing} = FPREP + MPREP \quad (5.1)$$

The file preparation is the decision about the orientation of the product during the build, if the use of support material is necessary or not and what will the layer thickness be. It also includes the time to create the STL file that will be uploaded in the machine.

The decisions that must be made during the file preparation are very important, because they will have a significant impact on both the production time and the production cost. All the types of Additive Manufacturing machines tend to be very quick in building in the x,y axis, while building in the z axis is more time consuming. However this cannot be the only criteria for the orientation, because one must also take under consideration the shape of the product. It might be due to the shape and the chosen orientation that more support material is needed and therefore the overall production cost will rise. Other equally important considerations for the part orientation are the strength that the final product will have, the surface finish, the airflow - especially for high temperature materials - and the time and ease with the removal of the support material. Furthermore, the layer thickness, or else the number of slices, influences the build time, the surface quality, the feature resolution and the part strength.

The machine preparation has to do with the loading of the necessary files on the machine and its warm-up. Then comes the processing time, which in this case as well as the case of Injection Molding is the actual build time (BT). Of course the build time in Additive Manufacturing is very much longer than the build time in Injection Molding, which usually takes around 30 sec. In any of the Additive Manufacturing methods the build time can be calculated by multiplying the time required to build one layer (BTL) by the total number of layers (NL).

$$T_{processing} = BT = BTL * NL \quad (5.2)$$

The post-processing time varies greatly depending on the Additive Manufacturing technology. It usually includes a wait time for the product to cool down (CD) and some time for the support material to be removed (SMR), while also, depending on the method used, it can include some time for the product to harden (HT) or drain (DT). Again depending on the Additive Manufacturing technology, the product that comes out from the 3D printing machine could be the final product, already assembled and with smooth surfaces, however it could require some additional processes, for example cleaning (CLT), curing (CUT) or sanding (SAT). All in all, the post-processing time equation could be estimated as follows:

$$T_{post-processing} = CD + SMR + HT + DT + CLT + CUT + SAT \quad (5.3)$$

As earlier discussed, not all variables in the above equation are necessary for every Additive Manufacturing method.

Using the equations (5.1), (5.2) and (5.3), the Lead Time can be calculated as follows:

$$LT = (FPREP + MPREP) + (BTL * NL) + (CD + SMR + HT + DT + CLT + CUT + SAT) \quad (5.4)$$

5.4 Total Production Cost

The Total Production Cost in any Rapid Manufacturing method can be estimated using the following equation:

$$TC = MC + MA + LC + FC \quad (5.5)$$

If the above equation is compared with the equation for the Total Production Cost of Injection Molding (equation 4.6), one can notice that it is almost identical. The only difference is that in Rapid Manufacturing there is a variable missing, which is the mold cost (MO). All the other variables, the material cost, the machine cost, the labor cost and the fixed overhead cost, remain the same, however they take different values that need to be calculated once again for every new method.

The equation for machine cost, labor cost and fixed overhead cost are as follows:

$$MA = MAD + MAM + CP \qquad (5.6)$$

$$LC = HW * T_{pre-processing} * u_{pre-processing} + HW * T_{processing} * u_{processing} + HW * T_{post-processing} * u_{post-processing} \qquad (5.7)$$

$$FC = BC + WC + OC \qquad (5.8)$$

If the equations (5.5), (5.6), (5.7) and (5.8) are used, the equation for the Total Production Cost in a Rapid Manufacturing method is calculated as follows:

$$TC = (MC) + (MAD + MAM + CP) + \left(HW * T_{pre-processing} * u_{pre-processing} + HW * T_{processing} * u_{processing} + HW * T_{post-processing} * u_{post-processing}\right) + (BC + WC + OC) \qquad (5.9)$$

In the case of Rapid Tooling, the equations of Rapid Manufacturing can be used to find the Lead Time (equation 5.4) and the Total Production Cost (equation 5.9) of the production of the tool, i.e. the mold. Then, the mold construction time parameter (MOC) in equation (4.2) can be substituted with the Lead Time that is calculated for the tool. One can also use the Total Production Cost that is calculated for Rapid Tooling in the equation (4.8), in order to substitute the mold cost (MO). Afterwards, the process continues as normal with the equations of Injection Molding so that the total Lead Time and cost of the whole process are estimated, i.e. from the moment the customer places the order to the moment that the order is ready to be delivered.

6. Comparison of modern and traditional manufacturing processes

In this section the Lead Time and Total Production Cost of each of the six different scenarios for each product and for each manufacturing method is going to be presented. The six scenarios differ only in the quantity of the produced items.

In order for the calculations to be as accurate as possible, all the information was obtained from real-world companies that operate in the appropriate fields. Some assumptions that were made are:

<u>Injection Molding:</u>

- The cost of an Injection Molding machine is 150,000 Euro and it is depreciated over 10 years. So, the yearly depreciation of the machine is 15,000 Euro/year. However, the company under study operates only 250 days during the year and 8 hours per day (one shift) and so the hourly depreciation of the machine is found to be 7.5 Euro per hour per machine.
- There is a monthly maintenance of the Injection Molding machines and also a yearly maintenance. Both acts are performed by company employees. The maintenance expenses consist of the labor cost and the cost of replacing the machine oil. The total maintenance expenses for each machine are estimated by the company to be 137.5 Euro/year.
- Labor cost is estimated to be 10 Euro/hour. The labor cost is not just the salary of the employee but it includes also other expenses made by the employer, such as insurance, pension funds, etc.
- In the build time estimation it was taken under consideration the fact that the company owns a set of eight Injection Molding machines that can operate simultaneously. In the case where different parts of a product can be built at the same time using different machines, the consolidated time is used in the calculations, as it better reflects the reality.
- As previously stated, the company operates one shift during the day. In the case that the machine setup, the mold setup and the build time exceed in time the 8 hours of the shift, it is considered that the production stops for the day

and continues the next day. This doubles the warm-up time that occurs every morning - or triples it if the production lasts three days and so on. For the productions that last more than one business day, the 16 hours of the day that the factory is closed are also added in the total lead time. This leads to more accurate results since the comparison in the case study will be with AM technologies that can operate unattended and use efficiently even the hours that the factory is closed.

- Regarding the mold construction in Injection Molding two options are examined. The first option considers that the mold is not fabricated yet and measures also the lead time and production cost for the construction of the mold. This is true for new products or existing products that are being customized for the client. The second option takes for granted that the mold already exists and omits the variable MOC in the equation (3.5). This option refers to existing products of the company that are produced and sold exactly as they were first designed. According to which of the above options is chosen each time, the mold cost is depreciated differently. If the first option is chosen, i.e. for new or customized products, the mold construction cost is calculated in the equations as a whole and it is being *depreciated over the exact number of pieces produced* according to the scenario. This is justified because the construction and existence of the specific mold doesn't serve other needs other than the production of this specific batch. On the other side, when the total production cost of an already existing product of the company is calculated, it is true that the specific mold will be used for other batches as well and so, it is *depreciated over the time* that it is being used - just like the depreciation method of the Injection Molding machines.

Rapid Tooling - PolyJet technology

- The cost of a PolyJet 3D printer is 200,000 Euro and it is depreciated straight-line over 10 years. This machine can work for many hours without any supervision and so it is assumed that it can operate during evenings and weekends all year long. Therefore, the hourly machine depreciation is 2.28 Euro per hour.

- The machine maintenance cost is 15,000 Euro per year and it includes service and support from the vendor of the machine. This is also depreciated over hour (1.71 Euro/hour).
- The build area of the specific machine is 255 x 252 x 200 mm. Since the build time is mostly dependent on the height of the build, the most time-efficient orientation of the part is found in every scenario so that the build time is minimized. It should be highlighted here that the most time-efficient orientation may not be the ideal one in real life, because the amount of support material used, the surface quality and other attributes are also dependent on the part orientation.
- Labor Cost in any Additive Manufacturing technology in the case study takes two values, one for the pre-processing, which requires a highly qualified employee and therefore, the labor cost is 12 Euro/hour, and one for the post-processing, which requires an employee with standard qualifications and therefore, the labor cost is 10 Euro/hour.
- Regarding the post-processing activities for the construction of a PolyJet mold, there is only cleaning and it takes around 2 minutes per item.
- After the calculation of the Lead Time and Total Production Cost of the Polyjet mold, these values are entered in the equations (3.5) and (3.11) of Injection Molding so that the total Lead time and Production Cost for all the number of units of each scenario are estimated.
- A PolyJet mold is a very soft tool and as a consequence it can be used only for 50 cycles. That being the case, only one mold is needed for scenarios 1 and 2 (1 piece and 10 pieces accordingly), two molds for scenario 3 (100 pieces), five molds for scenario 4 (250 pieces), ten molds for scenario 5 (500 pieces) and 20 molds for scenario 6 (1000 pieces).

<u>Rapid Manufacturing - FDM, SLA, SLS</u>

- In FDM the 3D printer costs 150,000 Euro, in SLA 240,000 Euro and in SLS 360,000 Euro. All 3D printers are depreciated straight-line over 10 years, as explained above for Rapid Tooling. The maintenance costs of all printers are

15,000 Euro per year, except for the SLA machine, which has maintenance costs of 20,000 Euro per year.

- The build area of the FDM machine is 355 x 254 x 254 mm, of the SLA machine is 250 x 250 x 250 mm and the build area of the SLS machine is 381 x 330 x 457 mm.
- Labor cost is split also here in two categories according to the qualifications needed for each process. Labor cost for pre-processing is 12 Euro/hour and labor cost for post-processing is 10 Euro/hour.
- Post-processing time and cost varies greatly according to the specific Additive Manufacturing technology. In FDM, after the build is finished, it is necessary to remove the breakable support and then put the items in a vibrator in order to obtain a smooth surface. In SLA, there is some special post-processing equipment, in where the finished items are UV cured and afterwards cleaned. In SLS, the post-processing activities are minimum and only a couple of minutes are required for cleaning.

Following the above analysis, in table 3 are presented the results of Lead Time for each scenario and each manufacturing method:

Table 3: Lead time

Product A	**LEAD TIME (in hours)**					
Scenario	**1**	**2**	**3**	**4**	**5**	**6**
Production Volume	**1**	**10**	**100**	**250**	**500**	**1000**
Injection Molding **with** mold construction	2165,18	2166,73	2182,23	2208,07	2251,13	2354,00
Injection Molding **without** mold construction	5,18	6,73	22,23	48,07	91,13	194,00
Rapid Tooling - PolyJet	12,13	13,68	32,96	118,90	225,93	466,36
Rapid Manufacturing - FDM	16,67	53,69	405,40	1040,00	2010,66	4017,24
Rapid Manufacturing - SLA	5,70	23,21	159,50	386,64	771,12	1522,36
Rapid Manufacturing - SLS	7,40	22,21	42,93	101,07	197,98	391,79

The above results are graphically illustrated for greater convenience in the following figure (Figure 1).

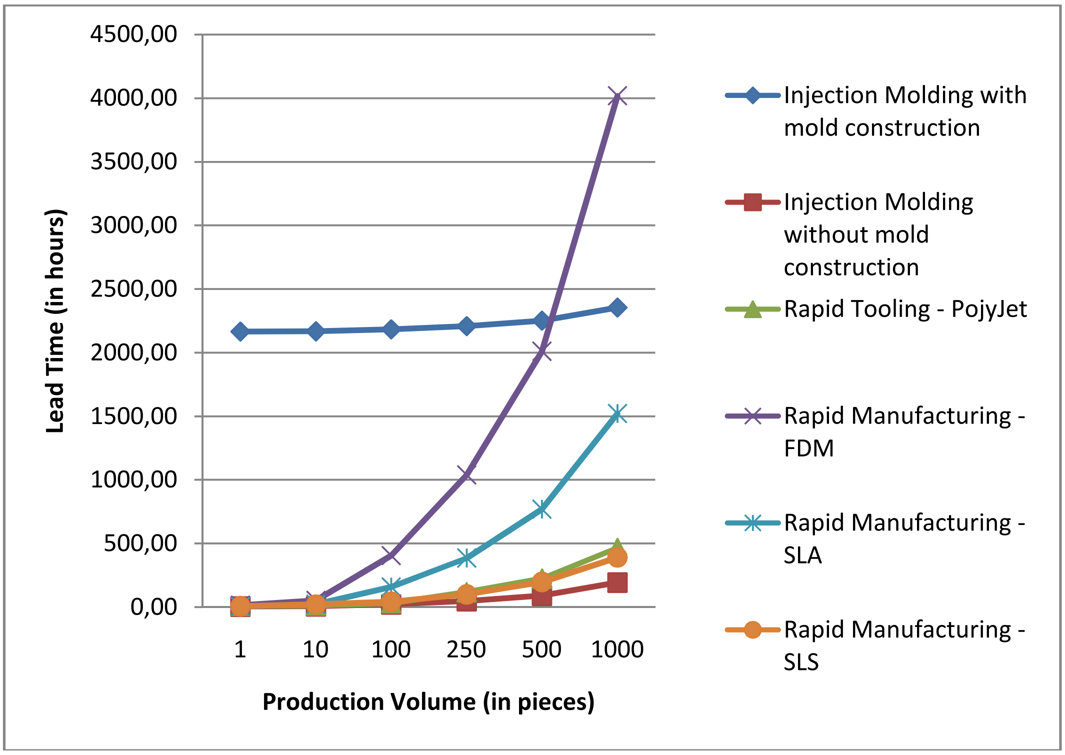


Figure 1: Lead time in hours

The first thing that one notices in Figure 1 is that the most time-consuming manufacturing method for quantities until 500 pieces is Injection Molding. The great time difference that Injection Molding shows is caused by the time its mold construction needs. In order for a mold to be constructed by a traditional method, it needs around 2-3 months, which is a significant amount of time, especially when Injection Molding is compared with tool-less manufacturing methods, like Additive Manufacturing. If the product examined had its mold already fabricated and ready for use, it would need approximately 360 times less time for the production of 1-10 pieces and 25 times less time for the production of 500 pieces. One can see the corresponding values of Injection Molding without the calculation of the mold construction both in Table 3 and Figure 1. As it was stated previously in the assumptions of the research, this report takes under consideration both options regarding Injection Molding. The option that includes in its calculations the mold construction is referred to new products or existing products that need to be customized for a client, while the second option that excludes the mold construction describes existing medium- and high- demand products, in which the company under study has already invested.

Figure 2 illustrates the same data from Table 3, however it has zoomed-in so that more details can be pointed out.

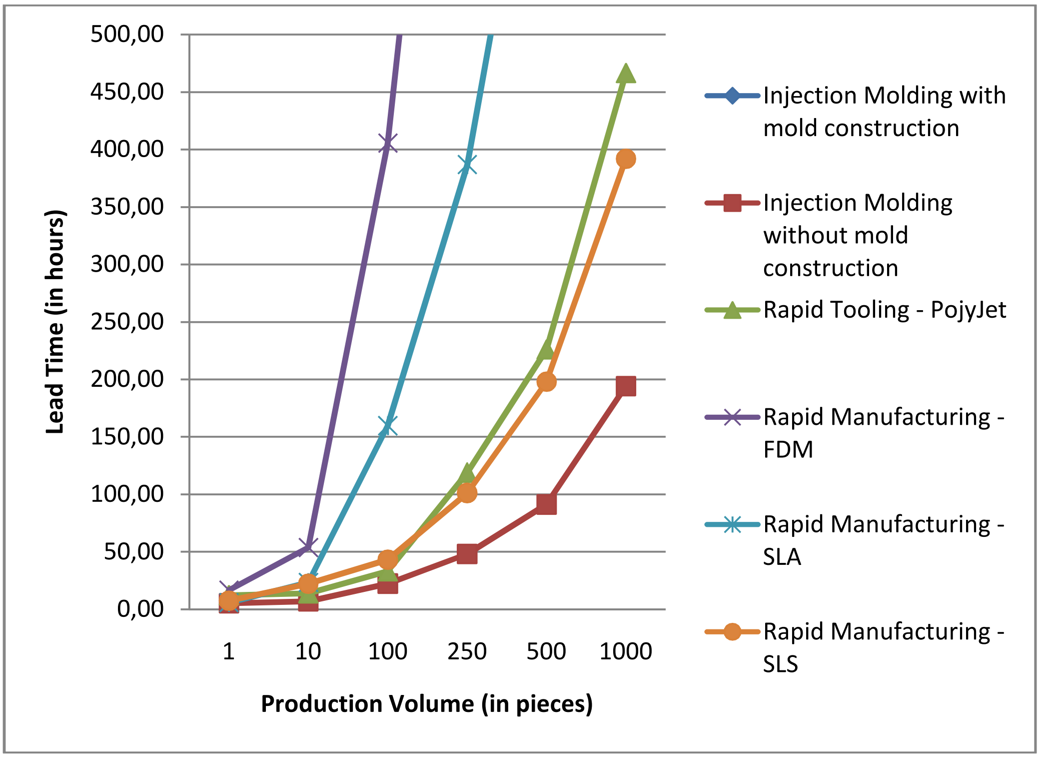


Figure 2: Lead time in hours (zoomed-in)

In Figure 2, one can see that the Lead Time of Injection Molding without the mold construction takes the lowest value for any production volume and compared to any other manufacturing method. After that comes Rapid Manufacturing using Stereolithography (SLA) and Selective Laser Sintering (SLS) for the volume of one (1) product. For the fabrication of one (1) product the longest Lead Time - after Injection Molding with mold construction - has Rapid Manufacturing using the Fused Deposition Modeling (FDM) technology.

The Lead Time for the fabrication of one (1) piece is indicative of the relative speed of each technology. Injection Molding takes under 1 minute for the fabrication of a part, while the rest of the Lead Time is mainly the time needed for the machine and the mold setup. The specific product, whose results are presented, consists of three (3) plastic parts (see Table 1), hence the operator has to setup the machine and place a mold three times. In Figure 3a and Figure 3b one can see the Lead Time of all products under examination for the Injection Molding production of one piece. Figure 3a shows the Lead Time without the mold construction. It is obvious that the longest Lead Time has the product that consists of the most parts, that is Product C. In Figure 3a the results are dependent on the number of molds, as the number of molds affects the number of the mold setups, which in turn affects greatly the Lead Time. Product C comprises of 6 molds, therefore it needs 6 times the mold setup, which takes 1,5 hours for each setup. It is also important to note that the company operates only one shift, therefore it cannot complete the production of one Product C during 8 hours and it needs a second day as well. In the calculations, the 16 hours that the factory is closed are also taken under consideration.

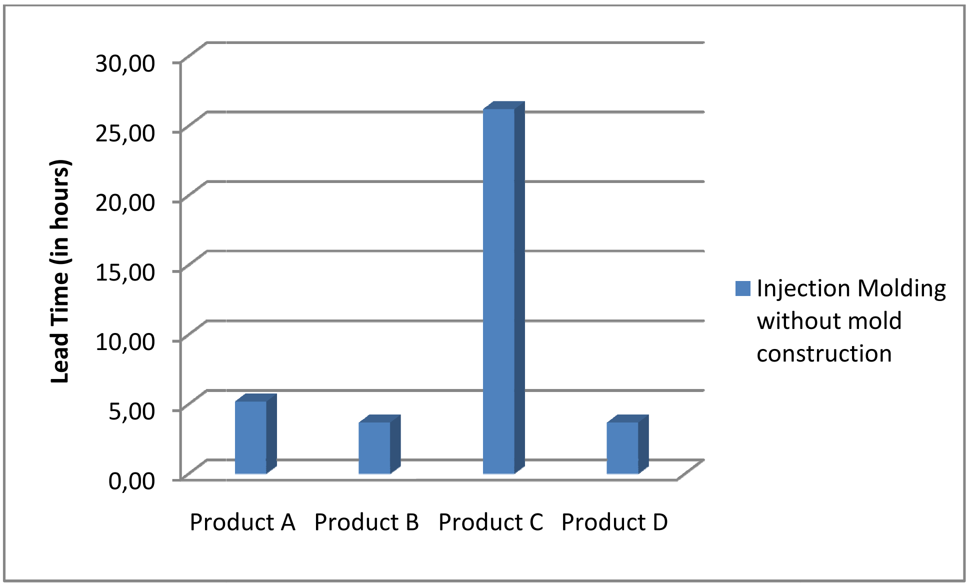


Figure 3a: Lead Time for production volume of 1 piece (in hours)

In Figure 3b, in the Lead Time it is also added the time that it takes for the injection mold to be fabricated. Once again, one can notice that the Lead Time of Product C is significantly longer. The molds of Product C need seven months in order to be manufactured, while the molds of the other three products need three months. The reason for this difference is because Product C has a more intricate geometry, therefore it is more difficult and time-consuming for the mold to be fabricated.

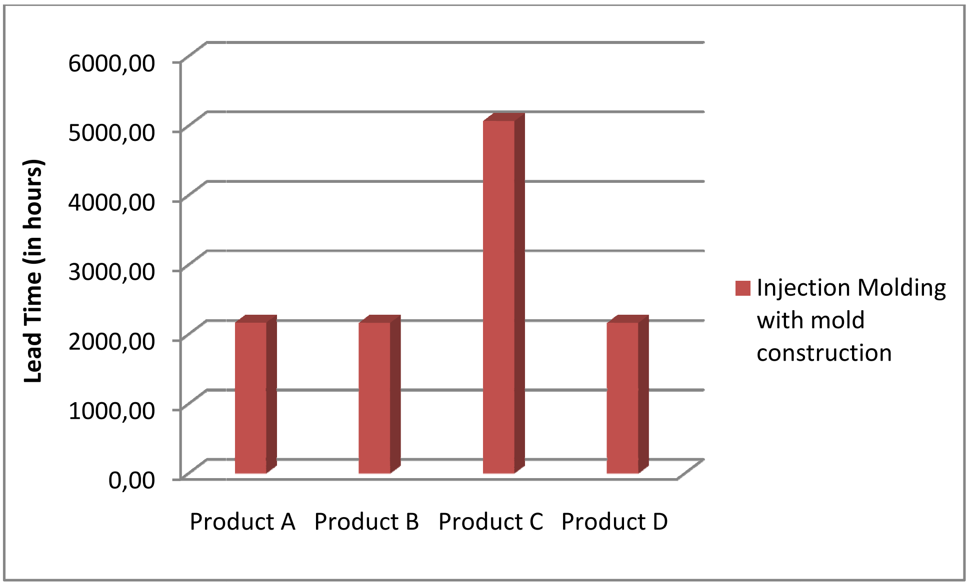


Figure 3b: Lead Time for production volume of 1 piece (in hours)

Back in Figure 2, one can see that regarding the Rapid Manufacturing technologies, SLA is the fastest one and after that comes SLS. In reality the speed of both technologies are almost the same, since they both use a laser, whose speed doesn't differ so much. In this case, the post-processing activities make the greatest difference in Lead Time. Although in SLA the part after the build has to be drained, cured and cleaned, the time needed for all these post-processing activities remains shorter than the time needed in SLS for the part to cool-down (Figure 4).

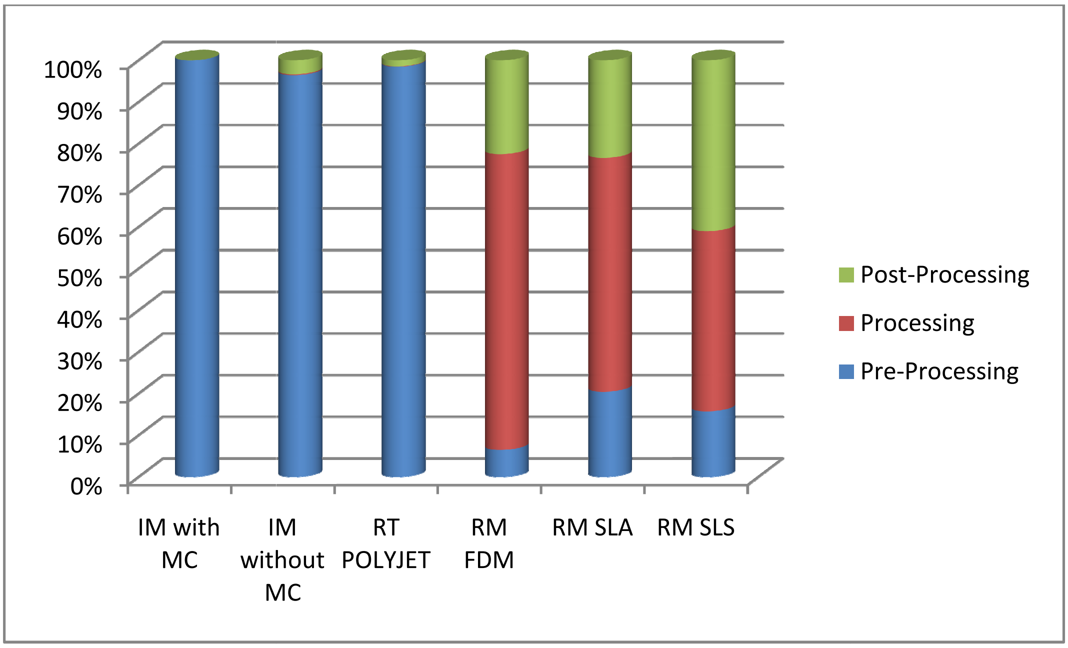


Figure 4: Distribution of Lead Time into Pre-Processing, Processing and Post-Processing time for the production volume of one piece

In Figure 4 one can also see that the FDM technology has the longest Processing time. This result was rather expected since FDM is the only technology from those compared that uses a work head that has to move across the layer in order to deposit the molten build material.

Rapid Tooling with the Polyjet technology has an intermediate value for Lead Time, since it comprises of a medium Lead Time for the fabrication of the 3D printed mold and a very short time for the Injection Molding of each part.

The results in Lead Time change as the production volume increases. For the production of ten (10) pieces, Injection Molding without mold construction continues to have the shortest time, however Rapid Tooling takes now the second place. The reason for this is because the mold created in Rapid Tooling lasts for 50 cycles and so only one 3D printed mold is needed for this quantity. This means that the most time-consuming process of Rapid Tooling remains the same as in the previous scenario, while the small increase in time is due to the Injection Molding part of Rapid Tooling.

It is also important to notice that in every scenario other than the first one, SLS has shorter Lead Time than SLA and specifically, as the production volume increases the difference becomes bigger. This change in Lead Time derives from the available build area of each machine. The bigger the build area the more stacking and nesting is allowed, namely more pieces can be built at once. Thus, the Processing time is being consolidated and the total Lead Time decreases.

Regarding the Total Production Cost for each scenario and each manufacturing method, Table 4 and Figure 5 depict the results:

Table 4: Total Production Cost

Product A	TOTAL COST (in Euro/piece)					
Scenario	**1**	**2**	**3**	**4**	**5**	**6**
Production Volume	**1**	**10**	**100**	**250**	**500**	**1000**
Injection Molding **with** mold construction	23103,79	2312,65	233,57	94,96	48,76	25,67
Injection Molding **without** mold construction	103,80	12,66	3,57	2,97	2,77	2,68
Rapid Tooling - PolyJet	799,00	82,17	17,87	17,89	17,74	17,72
Rapid Manufacturing - FDM	224,54	158,10	150,62	150,99	150,33	150,30
Rapid Manufacturing - SLA	214,31	196,85	192,98	192,72	192,70	192,59
Rapid Manufacturing - SLS	77,83	58,20	47,80	47,73	47,71	47,70

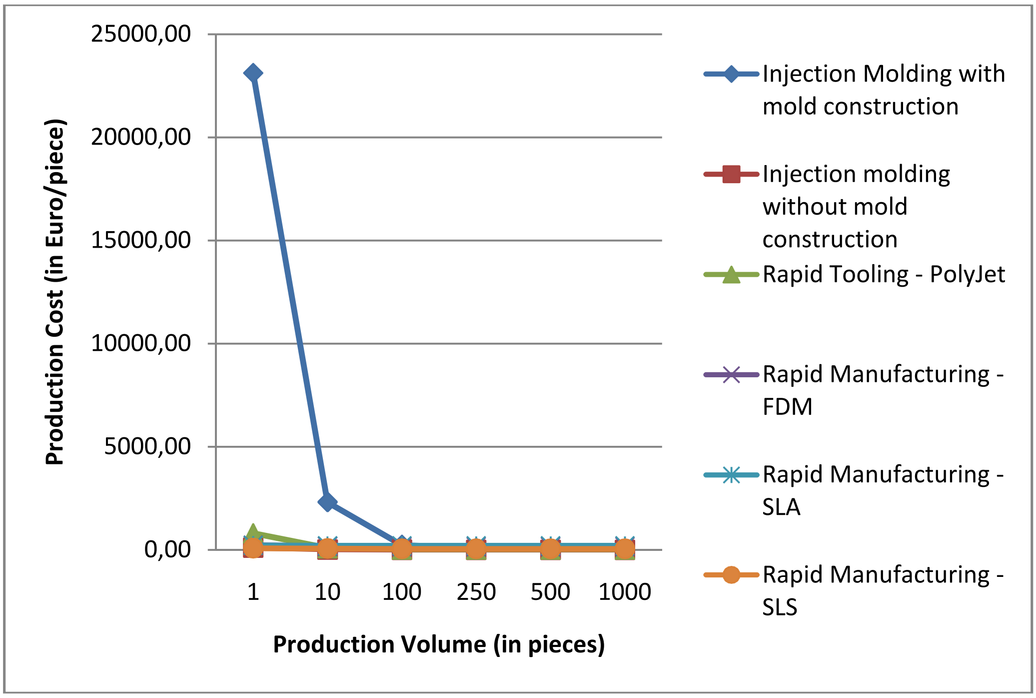


Figure 5: Total Production Cost in Euro/piece

For production volumes of 1 to 100 units of new products the most expensive method is Injection Molding with mold construction. This is quite reasonable, since the fabrication of a hard tool, i.e. a steel mold, costs usually tens of thousands of Euro. Of course the steel mold can last for millions of cycles, however for the production of such a small quantity it is rather inefficient to produce a hard tool.

One alternative is to produce a soft tool with Rapid Tooling, such is a PolyJet mold. As previously stated, the PolyJet mold can last for 50 cycles and for quantities of 100 to 1000 units it becomes the most cost-efficient method for the manufacturing of new products (Figure 6).

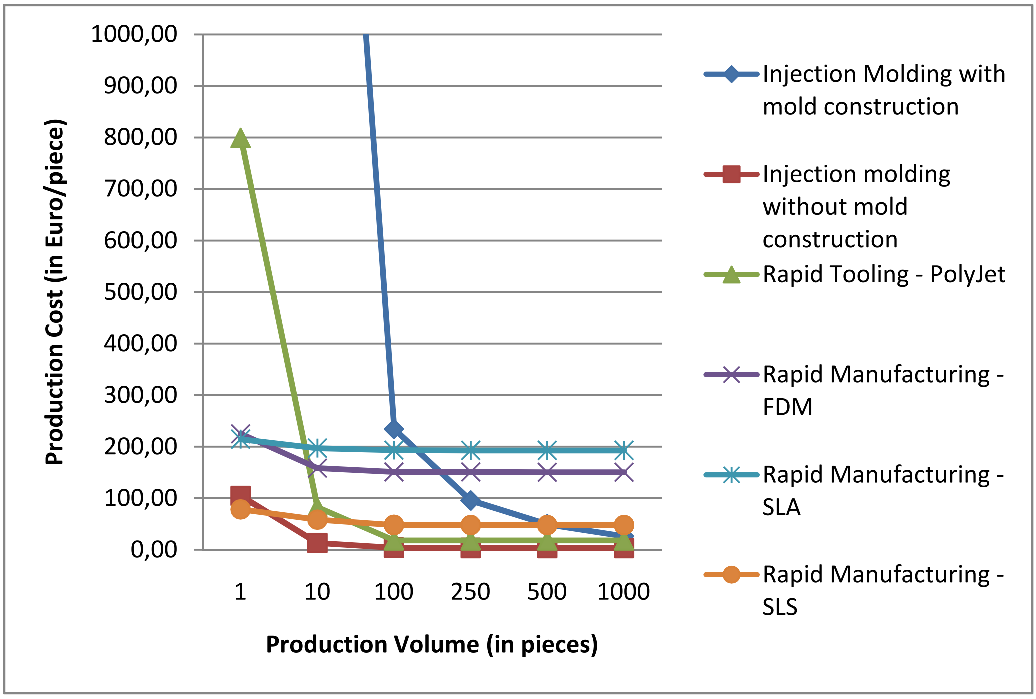
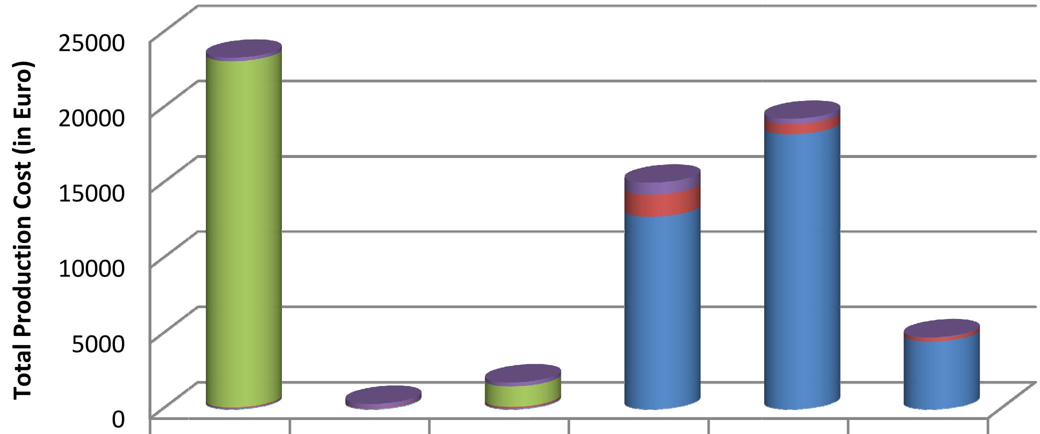


Figure 6: Total Production Cost of new products in Euro/piece (zoomed-in)

In terms of fabricating existing products, i.e. products whose mold is already purchased by the company and stored in the warehouse, Total Production Cost in Injection Molding takes the lowest value for all scenarios depicted except for the production volume of one piece.

Regarding Rapid Manufacturing the results reveal that the SLS technology is the most cost-effective method. In Figure 7, there is a detailed distribution of Total Production Cost for every technology.



	IM with MC	IM without MC	RT POLYJET	RM FDM	RM SLA	RM SLS
Labor Cost	233	233	271	790	348	42
Mold Cost	23000	1	1358	0	0	0
Machine Cost	70	70	104	1475	680	238
Material Cost	54	54	54	12789	18270	4500

Figure 7: Distribution of Total Production Cost for the production volume of 100 pieces

As shown in Figure 7, material cost in SLS is three times less than in FDM and four times less than in SLA. Machine cost is also lower, although the acquisition cost of a SLS machine is much higher than in the other two Rapid Manufacturing technologies. This is reasonable if one considers that machine cost in the equation is a function of the time that it is being used and Lead Time in SLS is considerably lower than in FDM and SLA. The same argument applies also for the difference in the labor cost.

Taking under consideration all of the above results, the research concludes that in terms of Total Production Cost, Additive Manufacturing is not yet as competitive as Injection Molding when it comes to medium- and high-volume production. In contrary, regarding low-volume production, both Rapid Manufacturing and Rapid Tooling might prove more cost-efficient than Injection Molding. Injection Molding starts to compete with Rapid Manufacturing from quantities of 500 and up, while with Rapid Tooling it starts competing from quantities of 1000 and up. In regards of the Lead Time needed for the manufacturing of new products, the research shows that almost all of the alternative production strategies are more time-efficient than Injection Molding. However when it comes to high-demand products that already exist, then a traditional manufacturing method like Injection Molding is more effective than any other method.

7. Conclusions

Additive Manufacturing has evolved greatly during the past years and has managed to become a disruptive force. New technologies are becoming commercially available, the selection of available build material is expanding, processing speeds are improving, the size of the machinery and its available build area are increasing, acquisition costs are lowering and the wide use of internet is allowing now the remote control of the machinery. Although there are numerous benefits and opportunities deriving from Additive Manufacturing, there are also still various barriers and limitations. Processing speed and material selection cannot be yet compared with those of a traditional manufacturing method, i.e. Injection Molding, hence Injection Molding remains still irreplaceable for medium and high production volumes.

In this report the Lead Time and Total Production Cost for six low-volume scenarios is examined. The comparison occurs between a traditional manufacturing technology, i.e. Injection Molding, and four state-of-the-art Additive Manufacturing technologies, i.e. PolyJet, Fused Deposition Modeling, Stereolithography and Selective Laser Sintering. In the case under study, the PolyJet technology is used for Rapid Tooling, hence the fabrication of soft tools that are afterwards inserted and used in Injection Molding, while the other three Additive Manufacturing technologies are used for Rapid Manufacturing, that is the direct fabrication of the end-use products.

The results showed that Selective Laser Sintering is the most time- and cost-effective Additive Manufacturing technology from those compared in the report. This stems mainly from the fact, that the material cost in this technology is relatively low and hence, comparable with the material cost of the Injection Molding. PolyJet and Stereolithography use photosensitive resins as build material, whose cost remains still very high. On the other hand, Fused Deposition Modeling uses the same low-cost material as in Injection Molding, however its Total Production Cost remains very high because of the very slow processing speeds and the great need for post-processing. Rapid Tooling showed also great results both in Lead Time and Total Production Cost, since it combines the flexibility of Additive Manufacturing and the low-cost and short build times of Injection Molding.

These results are an evidence that Additive Manufacturing technology can be used by a company in order to form an alternative business strategy. The low-cost strategy that is followed by many in regards of functional products is not appropriate when it comes for innovative or customized products. The implementation of a new production line equipped with Additive Manufacturing machinery within a focused-factory environment will greatly benefit the organization. It will provide the firm with the competitive advantage of covering the needs of all clients, even those seeking for a customized solution, in a reasonable cost and lead time, without having to invest further in inventory and supply chain management. To be precise, this machinery addition will streamline the operations, it will reduce the physical inventory of low-demand products and it will bring in-house several processes that are otherwise being outsourced, thus providing the company with better control and flexibility.

In conclusion, Additive Manufacturing cannot yet stand as a replacement method for traditional technologies, however it should stand as a supplementary one. Executives and decision-makers should acknowledge that when investing in this state-of-the-art technology and be prepared to plan an alternative business strategy based on the characteristics of Additive Manufacturing.

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Appendix

Table A1: Total Production Cost in Injection Molding, Product A

	Total (euro) for 1	Total (euro) for 10	Total (euro) for 100	Total (euro) for 250	Total (euro) for 500	Total (euro) for 1000
MC	0,435	4,35	43,5	108,75	217,5	435
MAD	34,03	36,56	61,88	104,06	185,63	326,25
MAM	0,27	0,29	0,50	0,83	1,49	2,61
CP	7,29	7,71	11,98	19,09	33,35	57,04
MOD+MOM (without)	0,02	0,17	1,73	4,31	8,63	17,25
MOD+MOM(with)	28000	28000	28000	28000	28000	28000
HW*Tpre*Upre	30,6	30,6	30,6	30,6	30,6	30,6
HW*T*U	0,26	2,55	25,50	63,75	127,50	255,00
HW*Tpost*Upost	1,70	17,00	170,00	425,00	850,00	1700,00
TOTAL (without)	74,60	99,24	345,67	756,39	1454,68	2823,75
TOTAL (with)	28074,58	28099,07	28343,95	28752,08	29446,06	30806,50
TOTAL (without)/part	74,60	9,92	3,46	3,03	2,91	2,82
TOTAL (with)/part	28074,58	2809,91	283,44	115,01	58,89	30,81

Table A2: Lead Time in Injection Molding, Product A

	Total (min) for 1	Total (min) for 10	Total (min) for 100	Total (min) for 250	Total (min) for 500	Total (min) for 1000
MOC	129600	129600	129600	129600	129600	129600
MOS + MAS	180	180	180	180	180	180
WU	30	30	30	30	60	60
BT	0,75	7,5	75	187,5	375	750
CD	0,33	0,33	0,33	0,33	0,33	0,33
AT	10	100	1000	2500	5000	10000
total in min	129821	129917,83	130885,33	132497,83	136175,33	141550,33
Total in hours	2163,68	2165,30	2181,42	2208,30	2269,59	2359,17
total without MOC	221,08	317,83	1285,33	2897,83	6575,33	11950,33
Total without in hours	3,68	5,30	21,42	48,30	109,59	199,17

Table A3: Total Production Cost in PolyJet, Product A

	Total (euro) for 1 (1 mold)	Total (euro) for 10 (1 mold)	Total (euro) for 100 (2 molds)	Total (euro) for 250 (5 molds)	Total (euro) for 500 (10 molds)	Total (euro) for 1000 (20 molds)
MC	662,4	662,4	1324,8	3312	6624	13248
MAD	15,80	15,80	15,80	53,60	82,52	164,04
MAM	11,85	11,85	11,85	40,20	61,89	123,03
CP	0,82	0,82	0,82	2,77	4,26	8,47
HW*Tpre*Upre	4	4	4	4	4	4
HW*T*U	0,00	0,00	0,00	0,00	0,00	0,00
HW*Tpost*Upost	0,34	0,34	0,68	1,70	3,40	6,80
TOTAL	695,21	695,21	1357,95	3414,27	6780,07	13554,34
TOTAL COST/PART	695,21	695,21	678,97	682,85	678,01	677,72

Table A4: Lead Time in PolyJet, Product A

	Total (min) for 1 (1 mold)	Total (min) for 10 (1 mold)	Total (min) for 100 (2 molds)	Total (min) for 250 (5 molds)	Total (min) for 500 (10 molds)	Total (min) for 1000 (20 molds)
FPREP	20	20	20	20	20	20
MPREP	25	25	25	25	25	25
BT	370	370	370	1315	2038	4076
CD	0	0	0	0	0	0
CLT	2	2	4	10	20	40
TOTAL	417	417	419	1370	2103	4161
LT in hours	6,95	6,95	6,98	22,83	35,05	69,35

Table A5: Total Production Cost in FDM, Product A

	Total (euro) for 1	Total (euro) for 10	Total (euro) for 100	Total (euro) for 250	Total (euro) for 500	Total (euro) for 1000
MC	127,89	1278,9	12789	31972,5	63945	127890
MAD	22,50	76,99	588,57	1528,36	2938,04	5874,88
MAM	22,5	76,99	588,57	1528,36	2938,04	5874,88
CP	11,40	39,00	298,14	774,19	1488,27	2975,93
HW*Tpre*Upre	5	5	5	5	5	5
HW*T*U	0,00	0,00	0,00	0,00	0,00	0,00
HW*Tpost*Upost	28,05	96,90	785,40	1932,90	3845,40	7670,40
Vibrator Cost	7,2	7,2	7,2	7,2	7,2	7,2
TOTAL	224,54	1580,98	15061,88	37748,51	75166,96	150298,30
TOTAL COST/PART	224,54	158,10	150,62	150,99	150,33	150,30

Table A6: Lead Time in FDM, Product A

	Total (min) for 1	Total (min) for 10	Total (min) for 100	Total (min) for 250	Total (min) for 500	Total (min) for 1000
FPREP	25	25	25	25	25	25
MPREP	40	40	40	40	40	40
BT	710	2526	19579	50905	97895	195789
CD	60	60	60	60	60	60
SMR	45	450	4500	11250	22500	45000
Vibrator	120	120	120	120	120	120
TOTAL	1000,00	3221,32	24323,95	62400,26	120639,74	241034,47
LT in hours	16,67	53,69	405,40	1040,00	2010,66	4017,24

Table A7: Total Production Cost in SLA, Product A

	Total (euro) for 1	Total (euro) for 10	Total (euro) for 100	Total (euro) for 250	Total (euro) for 500	Total (euro) for 1000
MC	182,7	1827	18270	45675	91350	182700
MAD	11	55	374	905	1808	3562
MAM	8,88	43,71	298,8	723,94	1446,69	2849,66
CP	0,23	1,13	7,71	18,68	37,34	73,55
HW*Tpre*Upre	8	8	8	8	8	8
HW*T*U	0,00	0,00	0,00	0,00	0,00	0,00
HW*Tpost*Upost	3,40	34,00	340,00	850,00	1700,00	3400,00
TOTAL	214,31	1968,49	19298,01	48180,56	96350,38	192593,28
TOTAL COST/PART	214,31	196,85	192,98	192,72	192,70	192,59

Table A8: Lead Time in SLA, Product A

	Total (min) for 1	Total (min) for 10	Total (min) for 100	Total (min) for 250	Total (min) for 500	Total (min) for 1000
FPREP	40	40	40	40	40	40
MPREP	30	30	30	30	30	30
BT	192	1062,86	7440	18068,57	36137,14	71211,43
CD	0	0	0	0	0	0
SMR	20	200	2000	5000	10000	20000
DT						
CLT						
CUT	60	60	60	60	60	60
TOTAL	342,00	1392,86	9570,00	23198,57	46267,14	91341,43
LT in hours	5,70	23,21	159,50	386,64	771,12	1522,36

Table A9: Total Production Cost in SLS, Product A

	Total (euro) for 1	Total (euro) for 10	Total (euro) for 100	Total (euro) for 250	Total (euro) for 500	Total (euro) for 1000
MC	45	450,00	4500,00	11250,00	22500,00	45000,00
MAD	15,54	76,50	150,90	374,10	746,10	1490,10
MAM	6,66	32,79	64,67	160,33	319,76	638,61
CP	2,29	11,28	22,26	55,17	110,04	219,76
HW*Tpre*Upre	8	8,00	8,00	8,00	8,00	8,00
HW*T*U	0,00	0,00	0,00	0,00	0,00	0,00
HW*Tpost*Upost	0,34	3,40	34,00	85,00	170,00	340,00
TOTAL	77,83	581,97	4779,83	11932,60	23853,89	47696,48
TOTAL COST/PART	77,83	58,20	47,80	47,73	47,71	47,70

Table A10: Lead Time in SLS, Product A

	Total (min) for 1	Total (min) for 10	Total (min) for 100	Total (min) for 250	Total (min) for 500	Total (min) for 1000
FPREP	40	40	40	40	40	40
MPREP	30	30	30	30	30	30
BT	192,00	1062,86	2125,71	5314,29	10628,57	21257,14
CD	180	180	180	180	180	180
CLT	2	20	200	500	1000	2000
TOTAL	444,00	1332,86	2575,71	6064,29	11878,57	23507,14
LT in hours	7,40	22,21	42,93	101,07	197,98	391,79