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Additive Manufacturing Opportunities

Mass Customization in the Biomedical Industry

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Introduction

The main topic of this thesis is additive manufacturing. Additive manufacturing, also known as 3D printing, is the process of making products or parts by subsequent depositing of layers of material rather than removing or forming material, as in conventional manufacturing. In other words, this technologies allows to make three dimensional solid objects from a 3D CAD model.

Additive manufacturing has received a great deal of attention recently as one of the protagonists of the Third Industrial Revolution. According to The Economist, it is changing the rules of manufacturing, showing a disruptive effect to conventional manufacturing processes.

Benefits of additive manufacturing involve different types of organizations operating in several fields: architecture, industrial design, education, construction, and so forth. I will deal with the impact of this technology on manufacturing companies, with a focus on those companies operating in the biomedical industry.

The purpose of this work (thesis statement) is to demonstrate that through additive manufacturing companies that operate in the biomedical industry can achieve mass customization.

However, individual uses of this technology (domestic and hobbyist) are also receiving a great of attention and have been defined as the «wow factor of 3D printing» by The New York Times. I will just mention this at the end of the whole work.

In the first chapter, I will briefly retrace the history of manufacturing: the First Industrial Revolution began in Britain in the eighteenth century with a series of innovations that transformed the manufacture of cotton and brought a new mode of production, namely the factory system. The Second Industrial Revolution began in America in the twentieth century with the advent of the assembly line, which led to the era of mass production. According to Jeremy Rifkin, a Third Industrial Revolution is on its way and it involves the digitalization in manufacturing, which will have a dramatic effect as big as in other industries that have gone digital. In this chapter, I will attempt to outline the pattern that led to the Third Industrial Revolution and I will inquire how the technologies that fall within this theoretical framework can drive the emergence of a new concept of firms and can change the role of people involved in the manufacturing process. According to the Special Report on Manufacturing and Innovation issued by The Economist on April 21st 2012, the factory in the feature «will focus on mass customization and may look more like those weaver's cottages than Ford's assembly lines.»

In the second chapter, I will delve into the technical aspects related to additive manufacturing, I will describe the three most common techniques that additive manufacturing is based on and I will then show how they work.

In the third chapter, I will show the three main applications of additive manufacturing in manufacturing companies, which are: rapid prototyping, rapid tooling, and rapid manufacturing. The technology is going to change how manufacturing operates and how it challenges some of the most consolidated paradigms.

Finally, in the fourth chapter, I will inquire into the applications of additive manufacturing in the biomedical industry. According to some, the biomedical industry, along with some other industries, such as the automotive and the aerospace industries, represents a important example of the revolutionizing impact of additive manufacturing. I will demonstrate that, in this industry, additive manufacturing allows the so-called "mass customization" which, in other industries, is far from being achieved.

Chapter I

A brief history of manufacturing

According to The Economist on April 21st 2012: «The First Industrial Revolution began in Britain in the eighteenth century with a series of innovations that transformed the manufacture of cotton and brought a new mode of production, namely the factory system. The Second Industrial Revolution began in America in the twentieth century with the advent of the assembly line, which led to the era of mass production. According to Jeremy Rifkin, a Third Industrial Revolution is on its way and it involves the digitalization in manufacturing, which will have a dramatic effect as big as in other industries that have gone digital.» In this chapter, I will attempt to outline the pattern that led to the Third Industrial Revolution and I will inquire how the technologies that fall within this theoretical framework can drive the emergence of a new concept of firms and can change the role of people involved in the manufacturing process. According to the Special Report on Manufacturing and Innovation issued by The Economist on April 21st 2012, the factory in the feature «will focus on mass customization and may look more like those weaver's cottages than Ford's assembly lines.»

I.1. The Preindustrial Economy

Neither entrepreneurship nor the capitalist enterprise began with the First Industrial Revolution. Many years before the first factories were established, businessmen were already developing new combinations of capital, labor and land in order to provide customers with products and services needed. (Amatori & Colli, 2011)

According to Cipolla (1976), differences between the preindustrial and the postindustrial world involve demographic, economic and social structures. However, one of the most important differences between the modern world and the preindustrial society is in the way things are manufactured. The development of industrial production methods and machinery has given people very different lives from those of their counterparts in preindustrial economic systems.

The preindustrial economy was primarily based on agriculture and communities were mainly settled in rural areas. According to Amatori and Colli (2011), eighty to ninety percent of

Europe's total gross domestic product came from agriculture and seventy percent of the population worked directly in farming productions.

The aspect that characterized the preindustrial production was the small quantity of any item that could be produced. Compared with production in the industrial age, more person-hours were required to produce any particular item. This was because of the poor infrastructures (slow transport) as well as by an inefficient production system that characterized the preindustrial economy. As a result, the infrastructure as well as the equipment were totally inappropriate to reach large dimensions. Hence, preindustrial production was much more limited in quantity than in the industrial economy.

For the most part, production in preindustrial economic systems was accomplished using hand tools. Aside from simple water wheels, there was no mechanical assistance to speed production. Moreover, if a particular task required force beyond what a human or animal could apply with the assistance of levers and pulleys, it probably could not be done at all. Complex machineries did not exist yet and these limitations restricted overall economic productivity.

Another difference of preindustrial production using hand tools was that the people involved in manufacturing were artisans rather than factory workers. This means they had special skills and years of experience that enabled them to use the tools of their profession very effectively. However, this also created a bottleneck to production, because it meant that not just anyone could be a certain task. In the industrial age, automated machinery has taken much of the skill out of the manufacturing process, meaning it is easier to find workers who can do the job. Yet, this allows to greatly increase production across the entire economic system.

One of the results of having artisans rather than machinery produce goods was that the parts for one item would not necessary fit another copy of the same product. In other words, products were made out of non-interchangeable parts. Every thing produced in the preindustrial age was a custom item. This tended to enhance quality, but far fewer goods could be produced by the economic system as a whole.

But the hallmark of the preindustrial production of consumer goods was the so-called putting-out system, that was the most common way of organizing the production at that time.

According to Amatori and Colli (2011), the countryside economy consisted of households in which families of peasants and, less frequently, artisans ran productive activities with few contacts with the market: they were basically closed economic systems that were based on self-consumption and an almost total absence of surplus labor.

The typical rural poor family usually dedicated a significant part of their working time to activities outside the primary agricultural sector and manufacturing work offered an alternative to temporary emigration, particularly when extra income was required. On the other hand, the presence of a cheap and flexible workforce persuaded urban manufacturers to shift their operations into the countryside. This is denominated the putting-out system.

The putting-out system consisted of a master at the top, who is the equivalent of a modern merchant-entrepreneur, and who was the owner of the whole apparatus for the manufacture. Many cottage workers were employed in this system and they were coordinated and controlled by the master. The workers performed some phases of the production process in their homes.

The putting-out system had great success, not only because of the possibility to exploit cheap labor, but also because of its flexibility.

However, there were some hidden costs in this system. Because of this decentralized way of organizing the production, there were agency and transaction costs, which increased with production growth.

Even though the putting-out system with his domestic and decentralized networks was the most common ways of organizing the production of consumer goods, craft production played an important role too and it was characterized by a higher level of sophistication and high value-added. Some industries were also characterized by a higher degree of specialization and capital intensity and often these industries were located close to the source of energy and raw materials.

Consequently, clusters of skilled craftsman set up highly specialized production systems in particular geographic areas, sometimes in the countryside and sometimes they were located inside towns and villages. Productions held in town and villages was mainly characterized by high value-added items such as gold and jewelry, hats, leather, and shoes, as well as other durable goods that were produced either for the urban market itself or sold directly to powerful customers such as the king, the government, the aristocracy, or the army. According to Mokyr (2002), «most of these preindustrial large firms enjoyed a privileged and monopolistic position. When not directly interested in the business, the government or more often the king granted patents to private entrepreneurs. This protection was given in order to stimulate the establishment of factories and plants specializing in the production of particular types of goods. There were various motivations for this strategy, ranging from the necessity to secure the supply of "strategic" items (as in the case of ships and weapons) to the pursuit of mercantilist policies that aimed to limit the purchase of high-value goods produced abroad.»

«For the most part, craft shops were quite simply organized. The master was the owner of capital and raw materials, he managed all of the process of production and he was the only person in charge of selling the goods. He was helped by some apprentices, usually paid on a piece-wage basis, who learned the secrets of the profession on-the-job, and after a long training period, they were able to become masters themselves and start their own businesses.» (Amatori & Colli, 2011)

The shop where the master and the apprentices worked together were normally part of a complex organization, that is the guild. According to Amatori and Colli (2011, p. 34-35), guilds:

- «were based on detailed sets of written rules regarding the quality and quantity of the goods produced in a given city;
- set the prices that masters could charge, resolved conflicts between members, controlled internal regulatory standards, organized apprentice training, and judged the process by which apprentices were promoted to master status;
- were quasi-enterprise that organized labor and capital, regulated craft activities, and managed human capital formation and quality control;
- were successfully able to monitor both the skills of the labor force and the production standards, of their industry. They accomplished this mainly by restricting entry into the labor market through their long-term training process. This in turn helped to lower the customers' information costs.
- were based on the single shop, characterized by a low degree of specialization among its extremely skilled members. The guild system provided these craft producers with a degree of protection and stability in an economy in which few were protected from sharp fluctuations in income.»

However, according to the same authors, several important disadvantages came around too:

- «they were relatively rigid organizations;
- like most monopolies, the guilds restricted production and demand by maintaining relatively high prices;
- they normally inhibited technological innovation by controlling techniques of craft production. Because the guilds system was conservative, innovation was discouraged. Where the guilds succeeded in establishing monopolies within the town walls, they artificially shrank the supply of skilled labor and kept prices high.» (Ibid., p. 35)

Eventually, under the pressure of economic change, the guild system began to fade in Europe during the seventeenth century and was abolished almost everywhere by the end of the eighteenth century.

It is important to remember, however, that «the guild system comprised a limited fraction of the manufacturing activity of preindustrial Europe, which meant that it had a limited impact on the economy as a whole. In addition, the existence of a form of institutional agreement meant that the guild did not influence organization at the shop-floor level. There, masters had a higher degree of control than in the putting-out system and were able to establish the quantity and selection of items they were to produce. They did not depend on a merchant-entrepreneur and dedicated almost all their working hours to manufacturing, which was their primary occupation. Labor division on a systematic scale was not the modus operandi of a guild master's shop. The apprentice was by definition trained in all the secret of the job, as was commonly said, with a "general purpose" approach. The master himself had to demonstrate his ability to manage the entire production of a single item. Consequently, division of labor when it did exist was based on the worker's age and status rather than the individual skills any single worker possessed. Despite the fact that guild membership could range from several hundred to even thousands of members, the production unit remained small.» (Ibid.)

According to the authors, compared with the putting-out system, guilds were inclined to constrain output. On the one hand, single shops could increase the production volume just by adding more units of labour. On the other hand, this was not possible for guild, because of their rules that regulated how many apprentices each master could train. Guilds could increased the production volume by admitting more masters to the guild. However, the guilds were against creating any kind of competition within master.

Along with the guilds and the putting-out system, large enterprises with many workers and high capital intensity existed too, actually even before the Industrial Revolution. They were called "manufactories"; this term is generally used to describe «a concentration of laborers working in the same place", "under the same roof" (ibid., p. 36). Some authors wonder whether those "manufactories" can be considered as precursors of those big businesses that were not established until the Second Industrial Revolution. Even though those large, preindustrial plants did not reach the dimension of Second Industrial Revolution large companies, they actually developed sophisticated methods of management, that were introduced to manage their complex production processes.

These large, preindustrial plants were more the exception than the rule. Moreover, in many of them, only a very small portion of their employees were actually working "in" the plant. The majority were "out" because they worked at home. Hence, the percentage of people employed in manufactories was probably slightly lower than in domestic industry, which was the most common form of organizing preindustrial production.

In some industries, the workforce was more concentrated. According to Mokyr (2002), «in the iron smelting, shipbuilding, mining and construction fields, because of the nature of the activity itself, it was not possible to operate economically on a small scale or from a workshop or household. A concentrations of workers in a single place was necessary.

In the textile industry, some phases of the production had to be performed in centralized plants; but not every phase and a similar combination of system existed, where centralized production was linked to the putting-out system: the central shop in some cases provided semifinished goods that were eventually dispatched to cottage workers.

In metalworking, merchant-entrepreneurs used iron masters to manage the building and operating of smelting plants. These highly skilled men were helped by some apprentices. A blacksmith, who operated at home under the putting-out system, completed the work.»

A «compromise between the domestic system and the need to produce away from home» (Mokyr, 2002) could be seen in several industries, because firms could operate efficiently, thanks to an aggregation of several «teams of skilled artisans or a cluster of small craft shops each performing a specific task» (Mokyr, 2002). Given the status of the technology, these "firms" were not able to realize scale economies by increasing the volume of production. They were in this regard like batch producers today.

The typical preindustrial form of organization was the independent craft shop, with a master assisted by one or more journeymen or apprentices. According to Landes (1969) though, the independence of the master in the craft shop broke down as far back as the thirteenth century, when the artisan «found himself bound to the merchant who supplied his raw materials and sold his finished work." The subordination of the producer to the intermediary was a consequence of the growth of the market. The craftsman never regained his independence; his work was sufficient to support him and he was in fact a proletarian, selling not a commodity, but labor.

The artisan worked for a local clientele, a small and stable group that was bound to him personally as well as by pecuniary interest. The local artisan did not have the opportunity to know and exploit the needs of distant consumers. Only the merchant could deal with the complexity of the demand, «calling for changes in the nature of the final product to meet customers tastes, recruiting additional labor when necessary, supplying tools as well as materials to potential artisans.» (Landes, 1969)

In conclusion, large plants and centralized production facilities existed as independent forms of manufacturing in only a few cases in the Preindustrial Economy. Most often, the central organization complemented the much more diffuse putting-out system. Along with the concentration of employees, coordination and organization became far more complicated, because these plants were made of a group of craftsmen, rather than a coordinated body of skilled or unskilled workers. In other words, manufactories were only ancillary and complementary organizations, as the prevailing pattern of production was based on the domestic system, rather than a different way of coordinating capital, resources, and labor.

I.2. The Industrial Revolution: the age of improvement

According to Landes (1969) an "industrial revolution" can be defined as «the complex of technological innovations which, by substituting machines for human skills and inanimate power for human and animal force, brings about a shift from handicraft to manufacture and, so doing, gives birth to a modern economy.» According to the same author, the material advances that constitute the heart of the First Industrial Revolution took place in three areas:

1. «there was a substitution of mechanical devices for human skills;
2. inanimate power, in particular, steam, took the place of human and animal strength;
3. there was a marked improvement in the getting and working of raw materials, especially in what are now known as the metallurgical and chemical industries.»

According to Mokyr (1990), it is useful to divide the technological changes during the Industrial Revolution into four main groups:

- «power technology;
- metallurgy;
- textiles;
- other industries and services.»

Moreover, according to the author, several scholars attempted to isolate the main technological change that characterized the Industrial Revolutions:

- «substitution of inorganic for organic materials;
- increase in energy inputs, especially inanimate energy;
- focus on the use of machines instead of hand tools;
- new technologies and sources of power to the traditional handicraft production.»

According to McCloskey (1981), «the Industrial Revolution was not the age of cotton, or the age of steam. It was the age of improvement.

Even though aggregate statistics do not reveal a sudden leap between the late eighteenth and early nineteenth, production technologies dramatically changed in many industries and sectors.

According to Amatori and Colli (2011), the First Industrial Revolution transformed the world economy. In particular, «the prosperity of the leading European nations and their Western offshoots opened up a significant gap between the developed and the undeveloped world, where growth rates were much lower. Compared with contemporary rates of economic growth, and especially with those of rapidly developing economies such as China's, the statistics for Europe may not seem especially remarkable. However, if you compare them with those of the preindustrial world, which relied extensively on the agricultural sector, the numbers are quite impressive. A seemingly small difference in the rate of growth between Great Britain and the rest of Europe and between Europe and the rest of the world constituted a truly revolutionary transformation with formidable consequences for the economic and political relations between nations and regions.» (Ibid., p. 40)

Artisans and masters transformed their shops into factories and enlarged the range of their business activities from local to regional, then national and even international levels. Moreover, a large number of former shopkeepers, merchants, the "merchant-entrpreneurs" who were the most active component in the preindustrial manufacturing, became the new entrepreneurial class: their business metamorphosis consisted of an upstream integration with the purpose of establishing control over the most crucial phases of the production process and of the value chain.

According to Landes (1969), «concomitant with these changes in equipment and process went new forms of industrial organization. The size of the productive unit grew: machines and power both required and made possible the concentration of manufacture, and shop and home workroom gave way to mill and factory. At the same time, the factory was more than just a larger work unit. It was a system of production, resting on a characteristic definition of the function and responsibilities of the different participants in the productive process. On the one side was the employer, who not only hired the labour and marketed the finished product, but supplied the capital equipment and oversaw its use. On the other side there stood the worker, no longer capable of owning and furnishing the means of production and reduced to the status of a hand (the word is significant and symbolizes well this transformation from producer to pure laborer). Binding them were the economic relationship, the "wage nexus" and the functional one of supervision and discipline. Discipline, of course, was not entirely new. Certain kinds of work, large construction projects for example, had always required the direction and coordination of the efforts of many people; and well before the Industrial Revolution there were a number of large a number of large workshops or "manufactories" in which traditional unmechanized labor operated under supervision. Yet discipline under such circumstances was comparatively loose (there is no overseer so demanding as the steady click-clack of the machine); and such as it was, it affected only a small portion of the industrial population. Factory discipline was another matter. It required and eventually created a new breed of worker, broken to the inexorable demands of the clock. It also held within itself the seeds of further technological advance, for control of labor implies the possibility of rationalization of labor. From the start, the specialization of productive functions was pushed farther in the factory than it had been in shops and cottages; at the same time, the difficulties of manipulating men and materials within a limited area gave rise to improvements in layout and organization. There is a direct chain of innovation from the efforts to arrange the manufacturing process so that the raw material would move downwards in the plant as it was treated, to the assembly line and transmission belts of today.»

The First Industrial Revolution with the emergence of new technologies and the enlargement of markets revolutionized the unit of production and this led to new challenges and choices for the new entrepreneurs, who also had to find and manage a quantity of fixed assets and a labor force that were considerably larger and growing than they had been in the past. However, it is inappropriate to overemphasize the degree of these increases in the scale of activity and in the organizational and managerial complexity, if compared with what happened during the undoubtedly capital-intensive Second Industrial Revolution. As a matter of fact, as stated by Amatori and Colli (2011): «although it was crucial to the history of economic development, the factory of the First Industrial Revolution was relatively small and usually retained only a few dozen employees. Its most important features were those related to the ownership structure and to the organization of the production process. The relatively small size of the factory meant that necessary financial resources could, in many cases, be provided by individuals of moderate wealth and good connections. The main consequence was that ownership and control of the company generally remained in the hands of the founders and their families. In the absence of the joint-stock company (introduced in England only starting in 1856) and other systems of limited liability, the partnership became the legal device that allowed for the association of other individuals with the company's founder/owner. The partner(s) usually provided the firm with additional capital. These organizations that emerged during the First Industrial Revolution could, with decent leadership, adapt rather easily to new systems of manufacturing. Given the average dimension of the production unit and the complexity of the new technologies employed during the First Industrial Revolution, the bureaucratic structures of companies, even if largely "new", were relatively elementary. Management and ownership rested with the founder/owner and this person sometimes delegated tasks to other family members or partners(s). More often, however, the support provided by some "foremen" was sufficient. These individuals were responsible for organizing the factory's working hours and timetables, managing workers' behavior inside the factory, and ensuring the proper use of machinery and raw materials. These foremen were almost never asked to manage autonomously the production process. As a rule, the entrepreneur was responsible for almost all the crucial company functions, from strategic decision making to day-to-day management.» (Ibid., p. 45)

The new technologies employed in crucial sectors, such as the textile, generated few scale effects and throughput economies. According to Amatori and Colli (2011), for example, in the textile industry «innovations tended to cluster around single stages of the production process (e.g., spinning), without changing the manner in which the products moved through the entire process from raw material to finished cloth. Innovations in one stage of the process, for example the various technical changes in spinning machines, created bottlenecks and pressured the firms to introduce innovations in weaving. Although this "innovation plague" encouraged innovation over the long term, it did not necessarily foster integration in the various stages of production. In the case of textiles, the production process thus remained fragmented. Even if thoroughly mechanized, it was carried on within separate, functionally distinct units. In metallurgy, too, and foremost in machinery, a disconnected process of production, separated into phases, was the rule.» (Ibid., p. 45-46)

Some entrepreneurs owned multiple factories, which operated in stages. These factories allowed to achieve some degree of vertical integration. They lacked in coordination between the stages of production and this was encouraged by the tendency for similar units to cluster in the same geographic area. However, proximity advantages included: benefits derived from having a fast flow of goods and services, an abundance of skilled workers (the best vehicle for the dissemination of knowledge and innovations). Moreover, physical proximity allowed companies to lower the cost of information and to share more knowledge, more efficiently.

Companies were small production units characterized by simple cost structures. According to Marshall's "representative enterprise", companies could rely on a collective strength derived from clustering in "industrial districts" in which knowledge circulated freely and innovations could be kept secret for long. "News traveled fast in an industrial district, where technological and market information was in the air. Industrial districts with these features could be found almost everywhere in Europe during the diffusion of industrialization. Often, their emergence was linked to manufacturing activities that had flourished in the preindustrial period but were now being transformed by new technology and new forms of business organization. Even in the era of the factory, however, such previous forms of manufacture as the putting-out system and the artisan shop had not disappeared entirely. But now these older forms of manufacture had to adjust to the competition of the low-priced, standardized goods pouring out of the new organizations in the manufacturing sector.» (Ibid., p. 46)

Along with the transformation of production occurred during the First Industrial Revolution, distribution and marketing functions changed. The market increased along with the degree of functional specialization and this amplified the tensions between merchants and manufacturers. On the one hand, the main outcome of this phenomenon was the emergence of strategies of downstream vertical integration. On the other hand, the intermediation of merchants was often necessary (the development of long-distance distribution networks required large investments). Hence, the entrepreneurs embarked on such a large investment only if vertical integration was strategic for the producer in order to preserve control over the market or to strengthen his brand name.

Financial issues emerged along with the transformation of production too. Whoever intended to create a new venture or to expand their existing enterprise had to face issues related to the finding of the capital necessary to finance the day-to-day activities of the business.

For the worker, the transformation was even more fundamental. According to Landes (1969), not only his occupational role, but his very way of life changed. «For many, though by no mean for all, the introduction of machinery implied for the first time a complete separation from the means of production. On almost all, however, the machine imposed a new discipline. No longer could the spinner turn her wheel and weaver throw his shuttle at home, free of supervision, both in their own good time. Now the work had to be done in a factory, at a pace set by tireless, inanimate equipment, as part of a large team that had to begin, pause, and stop in unison, all under the close eye of overseers, enforcing assiduity by moral, pecuniary, occasionally even physical means of compulsion.» (Landes, 1969). According to the author, the worker became a hand; the factory a new kind of prison; the clock a new kind of jailer.

According to Landes (1969), the First Industrial Revolution «has been like in effect to Eve's tasting of the fruit of the tree of knowledge: the world has never been the same.» The First Industrial Revolution marked a major turning point in man's history. Before that point, the advances of commerce and industry had been essentially superficial. It was the First Industrial Revolution that initiated a cumulative, self-sustaining advance in technology whose repercussions would be felt in al aspects of economic life.

I.3. The Second Industrial Revolution: the age of steel and chemicals

«In the factories of this new economy, entrepreneurs combined fixed capital (in the form of building and machines) and working capital (raw materials, labor, and semifinished goods) to produce large quantities of standardized goods for domestic and foreign markets. Although organizational differences existed across geographic areas, there were significant structural homogeneities in the various factories. The combined impact of all of these businesses on the European and world economies leaves no doubt that this was a revolutionary development with implications that would spread far beyond the economies involved and would reverberate through the politics and social alignments of the nineteenth century. Both Karl Marx and Joseph Schumpeter well understood that those reverberation would continue to change dramatically all the nations that experienced industrial development.

Modern factories were different from previous workplaces and methods of production. First, the factory gathered a significant number of workers under one roof, many more than had been the norm in any place of business in the past. Neither arsenals nor shipyards employed so many workers, and neither had to coordinate their activities or make use of machinery in the factory style. Craft and domestic manufacturers rarely exceeded the size of an enlarged family.

A second break with the past was the clear separation between units of production and consumption. Contrary to the way that business had operated in the past, the factory system required that workers gather in one centralized place where an energy source (water or sometimes steam power) ran the plant's machinery. Ingenious systems of pulleys and axles made it possible to run a large number of machines from a single water wheel or engine.

The third feature of the factory was the specialization of labor. Each worker was assigned a small number of tasks, in some cases only one, in the style made famous by Adam Smith's description of the pin factory. Machines were specialized, as well as the workers. Employees seldom had the satisfaction of seeing a completed product through the entire manufacturing process. Instead of producing an entire boot, the worker would spend all of his days making only the soles or uppers for standardized piece of footwear. Specialization was a characteristic of entire factories as well as individual tasks. The new technologies encouraged the specialization of the single production unit, as well as the enlargement of the market, as Smith sharply noted.

The mechanization of various stages of the production process was a distinctive characteristic of the modern factory. It was this mechanization that caused many contemporary observers to express amazement about, or to be appalled by, the “noisy hells”. The machines at work were much more sophisticated that the tools used by the craftsmen and guild masters and were certainly more complicated than the rudimentary looms used by farmers weaving in their homes for the merchant-entrepreneurs. The new factory machines were complex from a technical point of view and thus required the presence of workers specialized in the maintenance of the machinery. These new machines were also expensive. At this stage, investment in fixed assets started to be a relevant constraint. On a far greater scale than in the past, the employee could no longer afford to be the owner of the means of production. Additional organizational problems arose when it became clear that in some cases a regulated system of training and supervision was required to ensure proper use of the machinery.

Although it is not possible to talk of “energy intensive” production processes in the case of the First Industrial Revolution, the machines used in this period certainly required more energy than in the past. This energy had to be cheap and almost continuously available, and therefore it necessarily had to be produced by non-animated sources. These needs were often met by locating the factory in areas where it was possible to benefit from power derived from water wheels situated on rivers, streams, and waterfalls. This created a location constraint that often permanently affected the geography of industrial basins. The steam engine, which turned heat into immediately disposable energy, helped to mitigate some of these constraints. In an effort to reduce costs and avoid problems caused by coal shortages, manufacturers often employed a mix of new and old methods of energy production.

The factory system spread rather quickly through the British economy and then diffused more slowly throughout Europe. Unpleasant as factory work was, the new jobs quickly drew workers out of agriculture, just as cheap, standardized goods drove more expensive bespoke work into smaller market niches. There was little question as to the superior efficiency of the factory system, although there were some who clearly preferred the earlier, preindustrial economy. For some, agriculture still seemed to be a more manageable and rewarding style of life. To others, the social, economic, and psychological impact of the factory on the workers (sometimes now identified as “wage slaves”) seemed intolerable.

As European countries pushed into the process of industrialization and began to adjust to the new technologies and systems of production, a series of radical changes took place in their economic systems and social structures.

At the macroeconomic level, most of the major changes involved the rate of economic growth (both in aggregate terms and at the level of the single countries involved), the amount and quality of international trade, and the relative contributions of agriculture and manufacturing to gross domestic product and employment.

At the micro-level, the spread of new technologies and organizational forms generated a variety of issues that employers were forced to confront. Some of these problems soon garnered such general interest that governments became involved in their management. The factory systems required the creation of new kinds of capital-intensive functional structures of production. The owners experimented with various solutions in terms of architecture and factory layout. They also experimented with new ways to properly organize and discipline their workers, largely a commuter population. Individuals of different ages, backgrounds, and genders were now brought together in the limited workspace of factories and, in order for the production process to run smoothly, employers attempted to enforce behavioral rules.

From the perspective of the worker, employment in the factory system often meant a radical transformation of lifestyle. Whether they came from artisans' ranks or from the countryside, they had to quickly adjust their habits to the unusual rhythms imposed by the new technologies. Simultaneously, workers had to undergo an often dramatic and difficult process associated with urbanization. The relative freedom that characterized both peasants' and artisans' working lives, in terms of choosing working hours and leisure time, was replaced by clock, bells, and shift work that took place both night and day. Bosses had to prevent factory workers from leaving the workplace during crop harvest. Employers also struggled to change some of the work patterns that had characterized artisans' lives such as the institution of "Saint Monday", the extension of Sunday's rest through Monday.

Unlike previous forms of production, the factory introduced carefully defined and relatively rigid roles and hierarchies. The machines now dictated the worker's schedule and called for constant application of his or her attention. This was completely different from the organizational systems that had characterized traditional societies. This change, which was not implemented on a systematic basis as it was during the Second Industrial Revolution, created tensions for workers everywhere. As their lives changed, many factory workers had to cope with a new range of mental and physical problems. They were often forced to commute long distances to work or had to adapt to life in crowded dormitories, all without the degree of protection and emotional security that had previously been ensured by extended families and local communities. These precarious working conditions were only part of the problem. It was often difficult to integrate “foreign” workers into the exclusive and hostile local communities in which the factories were located.

In these and many other ways, the First Industrial Revolution indelibly affected the history of western European development. From the social and cultural point of view, the uneasy life and sharp transitions workers experienced in the machine-oriented world of factory system were more important than the wealth generated by this more efficient system of production. As modern industrial society first emerged from the transition to the factory system, it was not at all clear that this new society would improve the lives of the bulk of the population experiencing these profound societal and cultural changes.» (Amatori & Colli, 2011, p. 51-54)

According to the same authors: «Previous forms of manufacturing were not always quickly abandoned. Factories were adopted at varying speeds by each industry, according to the type of business, its stage in the production process, the input’s relative cost, and even local labor practices and cultures. During the First Industrial Revolution, different types of firms could coexist. Smaller, specialized shops succeeded alongside centralized factories that practiced scale-intensive and mechanized process. It is important to recognize how complex the transition from older form of manufacturing to factory production was in the eighteenth and nineteenth centuries. In the cotton textiles, merchant-entrepreneurs were quick to invest in new spinning technologies; this centralized the upstream stages of the production process while maintaining a wide network of subcontractors in weaving and finishing. The putting-out system endured in the cotton industry, partially because the process for mechanizing spinning was discovered before that for weaving, and the weaving could continue to be performed cheaply by a well-trained agricultural labor force. Weaving mills, therefore, employed only a few dozen “internal” workers but employed several hundred who worked at home.

Once a mechanical form of weaving was developed, the textile entrepreneurs consolidated vertically in a manner well explained by transactions cost theory. Through integration, businessmen could better coordinate their operations and control their costs and the quality of their products. Then economies of scale once again came into play, encouraging the businessmen to supplement water with steam power, so that they could keep their mills running on regular schedules. As the scale of operations increased, the machinery became more sophisticated and expensive. For instance, automatic looms required substantial investments and scrupulous maintenance, often by skilled mechanics. Although it provided solutions for many problems, the factory system also created new ones: for maintaining expensive machinery, in delegating authority, in reporting, and in defining entirely new economic roles and procedures. No longer able to use a piece-work system, mass producers had to learn how to maintain discipline in a workforce that frequently did not give its paternalistic employers the respect or systematic effort the bosses thought they deserved.

Marxist historiography provides a different historical paradigm for analyzing the spread of the factory system. According to Marxist theories, entrepreneurs concentrated the workforce in a single location in order to exert a closer control over the workers and to achieve a more efficient exploitation of the labor. As the entrepreneurs now owned the means of production and controlled the workplace, they could progressively introduce new machinery (as they did in weaving) and lower their labor costs per unit of output. Here, at last, was the creation of the true proletariat with class interests inherently opposed to those of the bourgeoisie. Specialization of function further reduced the skill levels of the workers and gave the businessman even greater opportunities to exploit their labor. The fruits of economic progress were thus denied to the working class who would ultimately be unable to buy industrial goods. This Marxist theory indicated, would create a final great crisis for the capitalist system.

From Schumpeter's perspective, of course, the factory system was a successful innovation, one of the truly epochal innovations that generated entrepreneurial profits and this encouraged others to change the way they did business. All, in this view, would benefit as the economy became more efficient. Consumers would have cheaper products. Workers would have new jobs and the money they needed to buy the cheaper consumer goods. Managers would of course continue to have problems that called for continued innovation. Managing the production process through the division of labor required a form of knowledge, a kind of "software" necessary to produce standardized goods in large quantities. This in turn would call for new methods of distribution, new forms of marketing and sales, and new forms of financing enterprise. All would require the new type of knowledge that was radically different from that used before, which had been largely based on practical know-how and not on codification or implementation of general principles. The Industrial Revolution thus profoundly transformed the European training system. While apprenticed workers had learned their trade on the shop floor or at home, the factory became the primary place for the transmission of the most important forms of knowledge, those related to the use of new machines technologies.

As the factory system grew, it would create the wealth that Schumpeter lauded as well as the kinds of conflicts that Marx thought were central features of capitalism in any form. Labor as well as capital would develop new forms of organization suited to the new system. The older forms of business organization would gradually decline in importance as the factories established their dominance of national and international markets. The centralization of production met the requirements of the new technologies and allowed factory owners to better manage their labor forces. They now had greater control over the output and quality of their goods. These features made the factory not an occasional complement to decentralized craft production but the most widespread organizational device in industry society.» (Ibid., p. 56-57)

According to Landes (1969): «In the eighteenth century, a series of inventions transformed the manufacture of cotton in England and gave rise to a new mode of production, that is the factory system. During these years, other branches of industry effected comparable advances, and all these together, mutually reinforcing one another, made possible further gains on an ever-widening front. The abundance and variety of these innovations almost defy compilation, but they may be subsumed under three principles: the substitution of machine (rapid, regular, precise, tireless) for human skill and effort; the substitution of inanimate for inanimate sources of power, in particular, the introduction of engines for converting heat into work, thereby opening to man a new and almost unlimited supply of energy; the use of new and far more abundant raw materials, in particular, the substitution of mineral for vegetable or animal substances. These improvements constitute the Industrial Revolution. They yielded an unprecedented increase in man's productivity and, with it, a substantial rise in income per head. Moreover, this rapid growth was self-sustaining. Where previously, an amelioration of the conditions of existence, hence, of survival, and and increase in economic opportunity had always been followed by a rise in population that eventually consumed the gains achieved, now for the first time in history, both the economy and knowledge were growing fast enough to generate a continuing flow of investment and technological innovation.

The development of mechanized industry concentrated in large units of production would have been impossible without a source of power greater that what human and animal strength could provide and independent of the vagaries of nature. The answer was found in a new converter of energy, the steam-energy; and in the exploitation on a tremendous scale of an old fuel-coal. It is no accident that the world's industry has tended to localize itself on an near the earth's coal measures; or that the growth of capital has been the bread of industry.»

According to Mokyr (1990): «In the years after 1850, technological change began to differ from that of earlier periods in another respect. Economies of scale were, of course, not new. Adam Smith had stressed the gains from the division of labor, and the most casual observer knew that many types of machinery could not be made as cheaply in small sizes and doses. The factory system emerged when cottage industry, in which the firm size had been constrained by the size of the household, found it increasingly difficult to adopt new techniques as rapidly as the factories. Mass production was slow in evolving, and was still quite rare by 1870. In the last third of the century, however, these effects became more pronounced. To an ever-growing degree learning by doing, large fixed costs in plant and equipment, positive spillover effects (externalities) among different producers, network technologies, and purely technical factors, such as the inherent scale economies in the railroads, in the metallurgical and chemical industries, and in mass production employing interchangeable parts and continuous flow processes, all operated together to reduce average costs at the level of the industry as well as the firm.

The relevance of this observation is that under conditions of increasing return to scale the history of technology becomes a different tale. Simply put, increasing returns and economies of scale mean that larger firms are more efficient and can produce cheaper. It has been long known that increasing returns are incompatible with equilibrium economics. This holds, a fortiori, for the economies of technological change. In other words, the standard tools of economic analysis become inadequate in explaining the observed patterns of research and development, diffusion, and adoption.

In the second half of nineteenth century, mass production became an important feature of Western technologies, yet its progress was neither inevitable nor ubiquitous. In many industries the small firm clung tenaciously to life. In part, mass production guaranteed the survival of small firms because, as Sabel and Zeitlin (1985) have pointed out, much of the special-purpose machinery needed for mass production could not itself mass produced, but catered to a small market that demanded flexibility and custom-made design. In part, indivisibilities in equipment could be overcome by the pooling and sharing of equipment, by forming cooperatives, and by renting rather than purchasing expensive inputs. Such arrangements were often costly, and eventually gave rise to large-scale firms, but not before a long struggle. At times, technological progress favored the small firm: electricity brought elastically-supplied energy to every customer, and the bicycle and the automobile allowed the survival of small-scale production in transportation.

The Second Industrial Revolution was, in many ways, the continuation of the first. In many industries there was direct continuity. Yet it differed from it in a number of crucial aspects. First, it had a direct effect on real wages and standards of living which clearly differed significantly in 1914 from 1870. Second, it shifted the geographical focus of technological leadership away from Britain to a more dispersed locus, though leadership remained firmly the monopoly of the industrialized Western world. Finally, by changing the relation between knowledge of nature and how it affected technological practices, it irreversibly changed the way technological change itself occurs. In so doing, what was learned in these years prepared the way for many more Industrial Revolutions to come.

The Second Industrial Revolution is usually dated between 1870 and 1914, although a number of its characteristic events can be dated to the 1850s. It is, however, clear that the rapid rate of pathbreaking inventions (macro-inventions) slowed down after 1825, and picked up steam again in the last third of the century. This says little about the rate of technological progress as commonly defined in terms of productivity increase and the improvements in product quality, which depends much more on the smaller, cumulative, anonymous changes known as micro-inventions. Yet the great pathbreaking inventions in energy, materials, chemicals, and medicine described below were crucial not because they themselves had necessarily a huge impact on production, but because they increased the effectiveness of research and development in micro-inventive activity. Eventually such activity like everything else runs into diminishing marginal product, unless a major new breakthrough opens new horizons. Technology is knowledge. Modern economic growth, Simon Kuznets (1965) argued more than 30 years ago, depends on the growth of useful knowledge. Yet as knowledge, technology differs from the knowledge of nature we think of as science, geography or a more pragmatic knowledge of natural phenomena. With some simplification we may divide all useful knowledge into knowledge which seeks to catalog and explain natural phenomena and regularities, and knowledge which should be thought of as huge compilation of recipes, instructions, blueprints and which constitute the totality of the techniques available to society (see Mokyr, 1998). The two forms of knowledge are of course related: on the whole, useful natural knowledge leads to or the development of novel techniques. Yet there are two important qualifications to that somewhat mechanistic image. First, there was considerable feedback from technology to science. This took the form of refocusing scientific thinking in the light of novel inventions, as well as technology creating better instruments and equipment with which to register scientific facts and regularities, as well to test hypotheses. Second, a substantial number of techniques emerge with fairly little base in the understanding of the natural phenomena. The First Industrial Revolution, and most technological developments preceding it, had little or no scientific base. It created a chemical industry with no chemistry, an iron industry without metallurgy, power machinery without thermodynamics. Engineering, medical technology, and agriculture until 1850 were pragmatic bodies of applied knowledge in which things were know to work, but rarely was it understood why they worked. This meant that often people did not know which things did not work: enormous amounts of energy and ingenuity were wasted on alchemy, perpetual mobiles, the stones of the wise and fountains of youth. Only when science demonstrated that such pipe-dreams were impossible, research moved into a different direction.

Moreover, even when things were known to work, they tended to be inflexible and slow to improve. It was often difficult to remove bugs, improve quality, and make products and processes more user-friendly without a more profound understanding of the natural processes involved. The second Industrial Revolution, 1870-1914. It was in this regard that the inventions after 1870 were different from the ones that preceded it. The period 1859-1873 has been characterized as one of the most fruitful and dense in innovations in history (Mowery and Rosenberg, 1989, p. 22). From the point of view of useful knowledge that mapped into new technology, this view is certainly correct. The second Industrial Revolution accelerated the mutual feedbacks between these two forms of knowledge or between (very broadly defined) and technology. It should be stressed that the difference was one of degree. Even before 1870, some natural processes were sufficiently understood to provide some guidance as to how to make technology more effective. And certainly after 1870 there was still a role to play for luck, serendipity, and type of inventions. Yet degree is everything here, and the persistence and acceleration of technological progress in the last third of the nineteenth century was due increasingly to the steady accumulation of useful knowledge. Some of this knowledge was what we could call today but a lot was based on less formal forms of experience and information. Inventors like Edison and Felix Hoffman relied on some of the findings of formal science, but a lot more was involved. As a result, the second Industrial Revolution extended the rather limited and localized successes of the first to a much broader range of activities and products. Living standards and the purchasing power of money increased rapidly, as the new technologies reaches like never before into the daily lives of the middle and working classes. The other aspect of the second Industrial Revolution worth stressing is the changing nature of the organization of production.

The Second Industrial Revolution witnessed the growth in some industries of huge economies of scale (to use Alfred Chandler's well-known term). Some vast concerns emerged, far larger than anything seen before. This change occurred because of ever more important economies of scale in manufacturing. Some of these were purely physical such as the fact that in chemicals, for instance, the cost of construction of containers and cylinders is proportional to the surface area while capacity is proportional to volume. Since the first depends on the square of the diameter and the latter on the cube, costs per unit of output decline with output. With the rise of the chemical industry, oil refining, and other industries using containers, as well as engines of various types, size began to matter more and more. Some economies of scale were organizational, such as mass production by interchangeable parts technology. Others were more in the nature of marketing advantages, or even the ruthless pursuit of monopolies. Yet it should be stressed that even with rise of giant corporations such as Carnegie Steel, Dupont, Ford Motors, and General Electric in the U.S. and their equivalents in Europe, these firms employed but a small fraction of the labor force and the typical firm in the industrialized West by 1914 remained relatively small, a niche player, often specialized yet flexible and catering more often than not to a localized or specific section of the market (Scranton, 1997; Kinghorn and Nye, 1995). The consequence of changing production technology was the rise of technological systems (Hughes, 1983, 1987). Again, some rudimentary of this nature were already in operation before 1870: railroad and telegraph networks and in large cities gas, water supply, and sewage systems were in existence. These systems expanded enormously after 1870, and a number of new ones were added: electrical power and telephone being the most important ones. The second Industrial Revolution turned the large technological system from an exception to a commonplace. Systems required a great deal of coordination that free markets did not always find easy to supply, and hence governments or other leading institutions ended stepping in to determine railroad gauges, electricity voltages, the layout of typewriter keyboards, rules of the road, and other forms of standardization. The notion that technology consisted of separate components that could be optimized individually, never quite literally true, became less and less appropriate after 1870.»

According to Landes (1969): «The declining momentum of the early-modernizing branches in the late nineteenth century was more than compensated by the rise of new industries based on spectacular advances in chemical and electrical science and on a new, mobile source of power, the internal combustion engine. This is the cluster of innovations is often designated as the Second Industrial Revolution.

In the last quarter of the nineteenth century, large corporations began appearing in some of the most advanced industrialized nations. Over a relatively short period of time, they were destined to become multiunit, multifunctional, multi-product, and multinational entities. The arrival of these large and complex organizations meant that, for the first time in history, it was necessary to adopt some form of governance via salaried managers (non-owners) who had specific technical skills.

Before the Industrial Revolution, there were a few examples of large corporations of these dimensions. In most cases, they were banks, overseas companies such as the East India Company (created by the English during the reign of Elizabeth I), or state manufacturers. Even though the “giants” of preindustrial capitalism could be extremely potent, it was possible for a few managers and clerks to direct their activities because the number of operating units and the quantity of transactions were small by modern standards.

[...] The use of new sources of energy (like fossil fuels), the use of steam in production processes, the introduction of new machinery, and the expansion of the factories represented significant benchmarks in the history of mankind. As two astute observers noted, the bourgeoisie in the First Industrial Revolution had accomplished wonders for surpassing Egyptian pyramids, Roman aqueducts, and Gothic cathedrals; it has conducted expeditions that put in the shade all former Exoduses of nations and crusades.»

«But the large firm as we know it today was not born because of the changes that occurred in England at the end of the eighteenths century. The productive factories were still of somewhat limited dimensions in all the sectors typical of the First Industrial Revolution. The cost, as well as the uncertainty, of transportation constrained companies attempting to extend their market range. The typical firm still employed a relatively small number of workers, especially compared with the normal workforce in the twentieth century. For example, the typical cotton mills in Manchester in the 1830s usually gave work to less than 200 people; by the beginning of the 1970s, there were 401 companies in market economies around the world that each employed more than 20,000 persons. By the same token, the manufacturing capacity of the early industrial firm was much more limited than would become the norm a century later. In the 1840s, very few English ironworks produced more than 10,000 tons annually; by the 1980s, the minimum amount necessary for an efficient integrated cycle steel plant in Japan was approximately 6 millions tons per annum. Even the substantial increases in production and trading in the first decades of the 1800s did not give rise to a significant concentration of economic activity. In the early nineteenth century, firms continued to be concerned with a single function and a single product while neither ownership structures nor internal organization was significantly different from preindustrial times. As historian Sidney Pollard explains, there was so little business administration in early industrialization that there was not a managerial theory associated with the Industrial Revolution.

The fundamental prerequisite for the emergence of modern big business and its managerial hierarchy were advances in technology and markets that finally permitted firms to reach dimensions and complexity that were previously impossible to imagine. It was the large variety of processes (in production, machinery, electricity, and chemicals) that came about in the United States and Western Europe after 1870 that became the decisive element in the growth of large corporations. This turning point would not have been possible without accompanying changes in communication and transportation systems. It was the radical transformation brought about by steam navigation, by railroads, by telegraphs, and telephones that made it possible for firms to reach a much larger market, in a much more extensive area. Firms were able to count on more solid relationships with both suppliers and clients; they could organize their internal operations on a more regular schedule. With this kind of foundation, a firm could grow in size. The subsequent transformation led to important changes in decision-making processes and internal structures, changes that were essential aspects of management in the modern large corporation.»

According to Amatori and Colli: «New transportation and communication systems rapidly set off the transformation of entire sectors of the economy toward the end of the 1800s. First, they were a success in commercial distribution. In fact, in the last decades of the nineteenth century new sales vendors took the place of traditional traders. Departments stores started to appear in the second half of the century and quickly gained popularity thanks to innovations like free admittance, fixed prices, a vast assortment of goods, special sales, and low margins which made it possible for quick turnover of inventory. [...]

The area where the transportation and communication infrastructure made its biggest impact was in manufacturing. In this era, the birth of large manufacturing firms, over the course of a short period of time, gave a significant push to economic growth in the three most important industrialized nations, the United States, Germany, and Great Britain. At the end of the nineteenth century these three accounted for two-thirds of world industrial production.

The impact that these new networks had on the transformation of the industrial world was even more significant than what occurred in the area of trade. This is due in part to the fact that a large variety of manufacturing processes in sectors like machinery, chemicals, electricity, and electro-chemicals in the 1870s were invented or refined in such a way as to be easily put to use by manufacturing firms. This in turn offered a chance for growth unlike anything previously available for these enterprises. For example, the invention of automatic packaging machinery transformed the food industry and had a similar impact on consumer goods produced by chemical companies. Other new processes became more widely available. For example, distillation was now used by firms that operated in sectors as varied as oil, sugar, vegetable oils, and alcoholic beverages. Important changes took place in firms that produced and assembled interchangeable parts used in manufacturing various types of machinery and even automobiles. The availability of a new and more flexible energy source like electricity made possible interactions between chemicals and metallurgy; this impacted products made on a vast scale such as chlorine and aluminum.

This complex interconnection of innovations, currently defined as the "Second Industrial Revolution", differentiated itself from the previous phase of industrial change by the fact that volumes were significantly increased and the rate of change was much faster. By combining these new technologies to the regularity, greater volume, and increased speed of shipping goods that was made possible by new transportation systems, big manufacturing plants were able to develop new processes, fine-tuning them to produce goods at much lower per unit costs than their small factory competitors. Their competitive advantages was made possible by the pursuit of important economies of scale, due to the reduction of manufacturing or distribution costs thanks to the greater volume, and the associated economies of scope that came about by using a single operating unit that was capable of producing or distributing several different products.

The impact of the technologies of the Second Industrial Revolution differed across industries. It created a deep dichotomy between sectors that was destined to last for all of the twentieth century and it marked a distinction between those areas where the large corporation predominated and the other sectors. Already at the beginning of the twentieth century the biggest firms operating in the United States, Germany, and Great Britain were concentrated in the same sectors where they would remain predominant into the 1970s, food, chemicals, oil, metallurgy, machinery, and transportation vehicles.

In other industries where the mechanization process was simpler and machinery was used to help workers rather than replace them (sectors like clothing, woodworking, textiles, leather goods tanning, saddle making, furniture, construction, panels, and printing), neither the quantities produced nor the speed at which they were produced would significantly change. These were, in fact, sectors that were characterized by a high level of manpower and where technology meant the ability to refine or fine-tune the machinery used. But these innovations did not lead to building bigger plants that would allow for the continuous, rapid manufacturing that would lead to economies of scale. Increasing production in these sectors meant adding more workers and machinery dedicated to the process. In short, it would be necessary to add operating units while reassessing the minimum efficient scale of the machinery. During the twentieth century, industry sectors traditionally characterized by technologies of this type continued to be highly labor intensive and conducted in small- to medium-size plants.

In contrast, in sectors where manufacturers were able to take advantages of the new technologies of the Second Industrial Revolution, very large firms dominated as the introduction of modern manufacturing techniques rapidly spread. This happened especially in industries where a large quantity produced in a single plant was not only possible but, more importantly, necessary. For this type of firm, multiplying its manufacturing capacity yielded lower unit costs obtained through economies of scale. Factories, therefore, started to grow and be structured specifically so as to take advantage of the full potential of the new technologies. Fossil fuels were increasingly used, machinery was improved, and operations were moved into bigger plants with layouts adequate for the new processes.

This transformation was especially notable in the oil industry. In the United States the process of restructuring the industry and constructing refineries that could obtain bigger economies of scale was decisive. An intensive use of energy was involved in introducing distillation through heated steam and high-temperature cracking which then led to the creation of larger size distillers. This, combined with better factory design, enabled petroleum producers to increase both speed and volume of production. In the decade between 1860 and 1870, the fixed costs for constructing a refinery grew from 30-40,000 dollars to almost 60,000 dollars. But the increased costs could still be recovered; in the same period, a refinery went from producing 900 barrels per week to 500 barrels per day. At the same time, the cost of a barrel dropped from 6 to 3 cents. Similar trends were seen in related industries, including sugar, whiskey, alcohol for industrial use, cottonseed and linseed oils, sulfuric acid, and other chemical products. Each of these industries used distillation and refining processes.

An entrepreneur eager to take advantage of the lower costs made possible by the new mass-production technologies was most likely to make investments in three correlated activities: building new plants at the minimum efficient scale, integrating production and mass distribution, and growing and fine-tuning the management hierarchy operative in its central offices and functional departments.

The first objective that these large corporations sought to achieve was to reach a high level of manufacturing and keep it stable so as to fully exploit economies of scale and diversification. The initial capital investment in these sectors during the Second Industrial Revolution and the fixed costs for operating and maintaining their factories were much higher than in their labor-intensive counterparts. The only way to benefit from these investments was by a full use of the plants. Two consideration were decisive in determining costs and profits. The first was the nature of the manufacturing capacity that was installed and the second was throughput, the quantity of raw materials put into the manufacturing operations in a given amount of time. The only way to take full advantages of the potential cost reduction was by a constant and elevated flow of materials in the plant. [...]

[...] over the course of the 1880s and 1890s, the new technologies of the Second Industrial Revolution in the area of mass production allowed for a net reduction in costs once the size of a plant reached the minimum efficient size. In many industrial branches the volumes produced by a single fast and continuous cycle plant were sufficient and permitted a small number of these plants to satisfy national, or even global, demand. Sectors with these kinds of characteristics quickly became oligopolies, with just a few big firms in competition between themselves on a global basis.

Even if access to these technologies had been available decades earlier, it would have been impossible for these same firms to realize economies of scale and scope in capital-intensive industries. This was due primarily to the fact that only the completion of a modern network of transportation and communication, together with the organizational and technological innovations required for managing an integrated system, all of which appear in 1870s, allowed for the creation and maintenance of fast, continuous production cycles in some sectors. Clearly, it would not have been possible to achieve a similar outcome if procurement and distribution had continued to operate under the conditions of uncertainty that existed with the unreliable transportation systems before the arrival of the railways.

One important consequence of the magnitude of these investments was their impact on labor organization at the workshop level. No longer could control be delegated to a foreman and remain an unknown for management. At the end of the nineteenth century Frederick W. Taylor's gospel of the "scientific organization" of work was diffused. On the basis of a careful study of the reality of factory manufacturing, Taylor argued that work should be divided into essential tasks. All the organizational know-how was to be collected by management, which could then impose a new and more efficient order on the workers; in this way operational autonomy on the shop floor was eliminated. To make up for dehumanizing the labor process, the worker was to be compensated with the higher salary rendered possible by the additional earnings produced by "scientific organization". As is well know, Taylor's philosophy became a reality with the arrival of the assembly line for automobile production in Henry's Ford factory. The assembly of Ford's Model-T brought higher salaries for workers, but there was also no interference in plant operations by the foremen, the workers, or unions.

The investment made in machinery and plants of ample size for large-scale production were not sufficient to guarantee good economic results to big firms. As the history of the first modern large corporations demonstrates, to achieve profitable economies of scale and scope firms could not put off for long adopting a higher level of vertical integration (upstream and downstream) in order to maintain a constant throughput within the manufacturing process. Thus they could avoid obstacles or delays in supplies or distribution that would affect regularity. When the distribution channels that already existed started to become less convenient and showed signs that they were insufficient for selling and distributing large quantities of merchandise made by modern industrial processes, it became necessary to make a significant investment in distribution activities, integrating them vertically.

Before the technologies of the Second Industrial Revolution reigned supreme, the typical intermediary was concerned with commercializing products of many manufacturers. By gathering the merchandise of numerous firms, sellers could count on a greater volume than what a single firm could generate. This allowed distributors, as well, to realize economies of scale and lower per unit costs by handling more than what the single manufacturer could offer. The greater variety of products distributed also allowed intermediaries to foot the cost of marketing and gave them lower distribution costs than those of the manufacturers. Distributors could achieve their own economies of scope by large-scale distribution both on a wholesale as well as a retail basis.

The intermediaries' advantages of scale and scope quickly disappeared as the technologies of the Second Industrial Revolution took hold. On one side, the greater volume produced by firms gave them the same advantages of scale as the retailers. On the other side, some new products required that new structures and special competencies for their marketing and distribution be developed. It was easier for a manufacturer to do this in-house than for retailers to develop a set of similar skills. The ability of intermediaries to distribute a large variety of related products for different entrepreneurs quickly became less important as each firm started to differentiate its products from its competitors. Product characteristics were more personalized and this called for special skills related to how they were sold and installed. In some cases, they also needed special structures for transportation or storage or even, at times, special credit plans for their purchase.

In the beginning, trade intermediaries were forced to cover the high costs of building these structures necessary for the distribution of products and they hired employees with the applicable technical skills. However, the new structures and skills could only be used for a single line of products and this made the traders more dependent on the manufacturers for whom they were distributors. In short, the advantage once held by distributors moved from retailers back to the manufacturing entrepreneurs who could count on their improved know-how of the techniques, tools, and services needed for marketing and distributing their products. Marketing and distributing these new products called for greater investments and ended up discouraging intermediaries while, at the same time, giving incentives to manufacturers to take over the expenditures themselves.

The cases of machinery firms illustrates well what happened in many capital-intensive sectors. The machinery that was produced in the last decades of the 1800s was in fact new and relatively complex compared with its predecessors; for the first time specialized services of marketing were necessary. Their complexity and innovative features necessitated that the sales process start with a demonstration. After the product was sold, it had to be installed, was subject to periodic maintenance, and, in the event of a problem, would need to be repaired by a specialized technician. Given the high prices of these machines, the purchaser often needed financing. While manufacturers had the resources and skills to offer all these services for selling their own products, wholesalers were seldom in a similar situation to take upon themselves the costs of demonstrating, maintaining, repairing, and even offering credit to purchase this specialized machinery.

In the United States, sewing machine manufacturers were among the first to integrate into the distribution system. [...]

The decision to incorporate distribution internally had another advantage for these companies: a constant flow of information regarding customers' likes, preferences, and needs. by investing in distribution functions, the structures of these firms underwent a transformation. In a short period of time, they needed to hire employees to take orders from customers, oversee advertising, organize product deliveries, coordinate installation, maintenance, and repairs of the products, and plan financing programs for customers.

The effects of integrating distribution's activities could be seen in corporate strategies as regarded vertical integration upstream or improvements in organizing the procurement process. When a large corporation decided to create a national, or even global, distribution network, it also needed to organize an equally extensive supply system. Maintaining a high volume of manufacturing required a stable and constant supply of raw materials and the ability to coordinate production flows within the various plants. Large corporations created centralized offices with specialized personnel responsible for procurements. These buyers would find sources for raw materials and negotiate requirements, prices, and delivery dates with suppliers. They also worked closely with other employees who oversaw the logistics and were responsible for shipping goods to various plants. Specializing supply activities by single product lines was as important and complex as the distribution function. There were complex steps necessary in working with raw materials in corporations that transformed them into final products like cigarettes, distilled beverages, canned vegetables and meats, cheeses, and chocolate confections. As soon as the raw materials for these perishable were received, they required adequate warehousing facilities where they could be stored in appropriate conditions until the firm made sure that they flowed towards the plants where they would be transformed into a finished product. If the system was successful, the company that purchased large quantities of semifinished goods could lower costs significantly.

In this way the upstream integration toward suppliers and the downstream integration toward distribution allowed businesses to eliminate the middlemen and to assure that the production process would not be interrupted. They could thus avoid the substantial economic losses they might have experienced in their supply and distribution functions.» (Ibid., p. 71-78)

According to the same authors: «The modern industrial corporation of our era has its origins in the year bridging the nineteenth and twentieth centuries. It appeared in firms where the entrepreneurs decided to invest in manufacturing plants that were big enough to achieve economies of scale and scope, in distribution systems and specialized workers for single product lines, and in a managerial organization that was able to coordinate all these activities. The pioneers of these expensive and risky investments frequently acquired significant competitive advantages, often referred to as the advantages of “first movers”. In order to compete with a first mover, potential rivals were obliged in the next decades to build plants of similar dimensions, to make investments in distribution and research, and to hire and form a managerial hierarchy. Still, by constructing factories of the size that would achieve economies of scale and scope, these companies found found themselves with excess production; they had soon to embark on a plan of stealing clients from the first movers.

The dynamics of competition were thus ever bitterer in the period between the end of the 1800s and the first decades of the twentieth century. There was a progressive saturation of national markets that stimulated corporations to pursue various new strategies to growth. This tension continued for much of the twentieth century as firms added new units according to the plans used in the past or even inventing new models of industrial organization. In some cases these choices were driven by defensive reasons, for example when a company decided to integrate horizontally so as to protect investments already made; the firm could acquire or merge with other firms that in large part utilize the same manufacturing processes to produce the same goods that were destined for the same markets. Other firms opted for vertical integration, bringing together units involved in the activity either upstream or downstream in the manufacturing process and competing on the basis of their superior technology, organization, and products. Still other firms sought to utilize their own resources and, above all, their specific organizational abilities to enter new markets, undertake new activities, or push into new geographical areas.» (Ibid., p. 80-81)

I.4. Toward a Third Industrial Revolution: the age of collaboration

On April 21st 2012, The Economist issued a Special Report discussing manufacturing and innovation issues related to the so-called “Third Industrial Revolution”.

The article claims: «The first industrial revolution began in Britain in the late 18th century, with the mechanization of the textile industry. Tasks previously done laboriously by hand in hundreds of weavers' cottages were brought together in a single cotton mill, and the factory was born. The second industrial revolution came in the early 20th century, when Henry Ford mastered the moving assembly line and ushered in the age of mass production. The first two industrial revolutions made people richer and more urban. Now a third revolution is under way. Manufacturing is going digital. [...] The factory of the future will not do bashing, bending and cutting material anymore nor parts will screwed and welded together."»

Jeremy Rifkin identifies for pillars that define the Third Industrial Revolution:

I. Renewable Energy. The renewable forms of energy, i.e. solar, wing, hydro, geothermal, ocean waves, biomass, et cetera, can not be considered established forms of renewable energy yet, and they actually account for a small percentage of the global energy mix.

II. Buildings as Positive Power Plants. The building industry will have to deal with the issue of creating new infrastructures: renewable energy can be found almost anywhere, yet there is no a clear answer on how to harness and store it. In 25 years, buildings will serve as both "power plants" and habitats; meaning that they will locally generate enough energy to provide for their power needs as well as to share any energy surplus they might produce.

III. Hydrogen Storage. «To maximize renewable energy and to minimize cost it will be necessary to develop storage methods that facilitate the conversion of intermittent supplies of these energy sources into reliable assets. Batteries, differentiated water pumping and other media, can provide limited storage capacity. There is, however, one storage medium that is widely available and can be relatively efficient. Hydrogen is the universal medium that "stores" all forms of renewable energy to assure that a stable and reliable supply is available for power generation and, equally important, for transport. Hydrogen is the lightest and most abundant element in the universe and when used as an energy source, the only by-products are pure water and heat. Our spaceships have been powered by high-tech hydrogen fuel cells for more than 30 years.»

IV. Smart-grids and Plug-in Vehicles. The next challenge is to create a new power grid in order to allow business and homeowners to produce their own energy and share it with each other. The inter-grid makes possible a broad redistribution of power. Today, as a consequence of the Second Industrial Revolution, power producers are centralized, and this top-down flow of energy is becoming increasingly obsolete. In the new era, businesses, municipalities and homeowners become the producers as well as the consumers of their own energy, so-called "distributed generation".

According to Rifkin (2012), every time a new energy regime emerges, it somehow shapes the nature of civilization, that means how people are organized, how commerce and trade are conducted, how political power is exercised and even how social relations are conducted.

The energy regime we are used to, that is the one that emerged during the Second Industrial Revolution[1] led to the necessity to centralize production and distribution which is the essence of modern capitalism. Because of those reasons, the modern capitalism is associated to the concept of economies of scale. The concept of economies of scale is being widely criticized now that a new energy regime is coming up.

Moreover, the distributed nature of renewable energies necessitates collaborative rather than hierarchical command and control mechanisms. This new lateral energy regime establishes the organizational model for the countless economic activities that multiply from it. A more distributed and collaborative industrial revolution, in turn, invariably leads to a more distributed sharing of the wealth generated. The shrinking of transaction costs is wreaking havoc on these traditional industries. We can expect similar disruptive impacts as the diminishing transaction costs of green energy allow manufacturers, service industries, and retailers to produce and share goods and services in vast economic networks with very little outlay of financial capital.

According to The Economist (2012), manufacturing jobs will not be on the factory floor anymore. Yet, highly skilled designers and engineers will together constitute the new "digital craftsman", that is an high-tech artisan that:

- similarly to the preindustrial artisan and differently from the factory worker, will be able to create highly customized goods;
- differently from the preindustrial artisan and similarly to the factory worker, will operate on a global value chain that will allow to "mass customize".

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[1] Fossil fuels (coal, oil, natural gas). Those are considered "elite" energies (Rifkin, 2012) because:

- they are found in selected places;
- they require a significant military investment to secure their access;
- they require continual geopolitical management to assure their availability;
- they require top down command and control systems and massive concentrations of capital to move them from underground to the end users.

With the internet allowing collaboration, entry barriers to manufacturing will fall and something called “social manufacturing” might be emerge. The lines between manufacturing services and manufacturing are blurring.

According to Rifkin (2012): «While the Third Industrial Revolution economy allows millions of people to produce their own virtual information and energy, a new digital manufacturing revolution now opens up the possibility of following suit in the production of durable goods. In the new era, everyone can potentially be their own manufacturer as well as their own internet site and power company. The process is called 3D printing; and although it sounds like science fiction, it is already coming online, and promises to change the entire way we think of industrial production. Think about pushing the print button on your computer and sending a digital file to an inkjet printer, except, with 3D printing, the machine runs off a three-dimensional product. Using computer aided design, software directs the 3D printer to build successive layers of the product using powder, molten plastic, or metals to create the material scaffolding. The 3D printer can produce multiple copies just like a photocopy machine. All sorts of goods, from jewelry to mobile phones, auto and aircraft parts, medical implants, and batteries are being “printed out” in what is being termed “additive manufacturing,” distinguishing it from the “subtractive manufacturing,” which involves cutting down and pairing off materials and then attaching them together. [...]

In the same way that the Internet radically reduced entry costs in generating and disseminating information, giving rise to new businesses like Google and Facebook, additive manufacturing has the potential to greatly reduce the cost of producing hard goods, making entry costs sufficiently lower to encourage hundreds of thousands of mini manufacturers small and medium size enterprises (SMEs) to challenge and potentially outcompete the giant manufacturing companies that were at the center of the First and Second Industrial Revolution economies.»

Chapter II

Additive manufacturing techniques

In the following paragraphs, I will tackle the technical issues related to additive manufacturing.

II.1. Classification and terminology

A distinction between subtractive, formative and additive

There are three fundamental manufacturing processes:

- Subtractive: «one starts with a single block of solid material larger than the final size of the desired object and material is removed until the desired shape is reached. [...] Subtractive fabrication processes include most forms of machining processes, CNC or otherwise. These include: milling, turning, drilling, planning, sawing grinding, EDM, laser cutting, water jet cutting, et cetera.»
- Additive: «the end product is much larger than the material when it started. A material is manipulated so that successive portions of it combine to form the desired object.»
- Formative: «mechanical forces or restricting forms are applied on a material so as to form into the desired shape. [...] Examples of formative manufacturing processes are: bending, forging, electromagnetic forming and plastic injection molding. These include both bending of sheet materials and molding of molten or curable liquids. The examples given are not exhaustive but indicative of the range of processes. Hybrid machines combining two or more fabrication processes are also possible. For example, in progressive press working, it is common to see a hybrid of subtractive (as in blanking or punching) and formative (as in bending and forming) processes.» (Chua, Leong & Lim, 2003, p. 25-26)

As for conventional manufacturing, Rhoades states:

- «Casting or molding produces an object by transforming a material from a liquid to a solid. A material in liquid form is poured or injected into a preformed mold (or die), allowed to solidify (normally by cooling, but sometimes by heating or chemical curing), and, once solidified, removed from the mold as a solid object. The mold is typically made from a metal with a higher melting temperature than the formed material. Sometimes the mold is disposable (e.g., sand or ceramic) and is destroyed during the removal of the formed part. In these cases, the mold itself is "molded" from a durable, preformed pattern.

- Forming is a process of applying force, and sometimes heat, to reshape, and sometimes cut, a ductile material by stamping, forging, extruding, or rolling. Like the tools used in casting or molding, the tools used in forming are preformed and durable.
- Machining is used to "cut" specific features into preformed blanks (e.g., slabs, bars, tubes, sheets, extrusions, casting, forging, etc.) by manipulating a fast-moving cutting tool relative to the work piece on a special (usually computer-controlled) machine tools, such as a lathe, mill, or grinder. In the machining process, even though the cutting-tool material is considerably more durable than the work piece material, the tool is subject to wear and tear. Typically, many different tools are used, and a specific "cutter path" is programmed for each feature and each tool. Compensation is made for tool wear.
- Joining include welding, brazing, and mechanical assembly of parts (made by molding, forming, or machining) to make more complex parts than would otherwise be possible with those methods. Typically, special fixtures or special tooling and programming of assembly machines or robots are used for each assembled part.

The common theme in the methods widely used to manufacture discrete parts is a significant up-front effort, which can take several forms: tooling (e.g., dies, molds, cutting tools); special-purpose machining; part-specific programming (e.g., tool selection, "feeds and speeds," cutter paths, tool wear compensation); and "design for manufacturing" (i.e., iterating product designs so that fewer, less expensive manufacturing operations are required to produce a product). To justify the up-front investment of time and money in planning, designing, tooling, buying, programming, installing, and proving out production lines and cells for making products, production volumes must be sufficient to amortize the investment at a reasonable cost per part. Manufacturers are constantly struggling to achieve an appropriate balance between scale and flexibility. "Just-in-time" manufacturing and "flexible manufacturing systems" are two of the best known strategies in the struggle.

The heart of the problem is that there are dozens, sometimes hundreds of steps in the production cycle, even for simple products, that require many different machines and worker skills. High-volume production scale unavoidably limits flexibility, and many machines and people must be gathered in one place to make many, many parts and products with limited variation. even though individual steps in the production process have been dispersed in recent decades from the centralized, fully integrated factories of the 1950s into the "extended enterprise supply chains" of the 1990s (because the added cost of handling and shipping from component suppliers to assembly sites is outweigh by the flexibility of the supply chain and lower cost of labor), the volume of parts going through each process step at any point in the supply chain is the same (if not higher, thanks to "global" product platform designs). Production is typically done in or near cities where large suppliers of labor and supplier networks or, at least, a dependable transportation infrastructure, are available.

Once products are completed, usually in factories where hundreds or thousands of people gather to make thousands or millions of parts, they are shipped great distances, often across oceans, to the customers who want them. [...] A manufactured product has no more value than its untransformed materials and components unless it is purchased by a customer who actually wants it in that form. Products made, but not sold, represents an inventory risk.

Because the cost of distribution often exceeds the cost of production, a better definition of manufacturing might be the creation of value through the transformation of materials from one form to another and the delivery of that more valuable product to a buyer. [...]» (Rhoades, 2005, p. 13-14)

There are several ways to classify additive manufacturing techniques. According to Gibson, Rosen and Stucker (2010, p. 27), «a popular approach is to classify according to baseline technology, like whether the process uses lasers, printer technology, extrusion technology, etc. Another approach is to collect processes together according to the type of raw material input. The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like selective laser sintering being grouped together with 3D printing) or that some processes that may appear to produce similar results end up being separated (like stereolithography and objet). It is probably inappropriate, therefore, to use a single classification approach.»

While there are many ways in which additive manufacturing techniques can be classified, Chua, Leong and Lim classified additive manufacturing technologies into three main groups, by the initial form of its material:

- «Liquid-based have the initial form of its material in liquid state. Through a process commonly known as curing, the liquid is converted into the solid state.» Technologies that fall into this category are: stereolithography (SLA), solid ground curing (SGC), solid, creation system (SCS), solid object ultraviolet-laser printer (SOUP), the Autostrade's e-darts, Teijin's soliform system, Meiko's rapid prototyping system for the jewelry industry, Denken's SLP, Mitsui's COLAMM, Fockele & Schwarze's LMS, light sculpting, aaroflex, rapid freeze, two laser beams, micro-fabrication." (Chua, Leong and Lim, 2003, p. 19-20) [...] "Most liquid-based additive manufacturing systems build parts in a vat of photo-curable liquid resin, an organic resin that cures or solidifies under the effect of exposure to laser radiation, usually in the UV range. The laser cures the resin near the surface, forming a hardened layer. When a layer of the part is formed, it is lowered by an elevation control system to allow the next layer of resin to be similarly formed over it. This continues until the entire part is completed. The vat can then be drained and the part removed for further processing, if necessary. There are variations to this technique by the various vendors and they are dependent on the type of light or laser, method of scanning or exposure, type of liquid resin, type of elevation and optical system used.» (Ibid., p. 35)

- «Solid-based are meant to encompass all forms of material in the solid state. In this context, the solid form can include the shape in the form of a wire, a roll, laminates and pellets." (Ibid., p. 20) "Solid based rapid prototyping systems are very different from the liquid-based photo-curing systems [...]. They are also different from one another, though some of them do use the laser in the prototyping process. The basic common feature among these systems is that they all utilize solids (in some forms or another) as the primary medium to create the prototype.» (Ibid., p. 111) Technologies that fall into this category are: Cubic Technologies' laminated object manufacturing (LOM), Stratasys' fused deposition modeling (FDM), Kira Corporation's paper lamination technology (PLT), 3D Systems' multi-jet modeling system (MJM), Solidscape's ModelMaker and PatternMaster, Beijing Yinhua's slicing solid manufacturing (SSM), melted extrusion modeling (MEM) and multifunctional RPM systems (M-RPM).
- «Powder-based: powder is by-and-large in the solid state. However, it is intentionally created as a category outside the solid-based additive manufacturing technologies to mean powder in grain-like form.» (Ibid., p. 21) Technologies that fall into this category are: selective laser sintering (SLS), EOS's EOSINT systems, Z Corporation' three-dimensional printing (3DP), Optomec's laser engineered net shaping (LENS), Soligen's direct shell production casting (DSPC), Fraunhofer's multiphase jet solidification (MJS), Acram's electron beam melting (EBM), Aeromet Corporation's technology, Precision Optical Manufacturing's direct metal deposition (DMD™), Generis' rapid prototyping systems (GS), Therics' Inc.'s technology, Extrude Hone's Prometal™ 3D printing process.

II.2. Techniques: SLA, FDM and SLS

Stereolithography (SLA)

Stereolithography was invented in 1986 by inventor Charles W. Hull and entrepreneur Raymond S. Freed who founded 3D Systems Corporation.

According to Chua, Leong and Lim (2003), the main advantages of using stereolithography are:

- «Round the clock operation;
- Good user support;
- Build volumes;
- Good accuracy
- Surface finish (actually, between other additive manufacturing techniques);
- Wide range of materials.»

While, main disadvantages are:

- «Requires support structures;
- Requires post-processing (e.g., removal of supports and other unwanted materials);
- Requires post-curing (in order to ensure the integrity of the structure).»

«The stereolithography process «creates three-dimensional plastic objects directly from CAD data. The process begins with the vat filled with the photo-curable liquid resin and the elevator table set just below the surface of the liquid resin. The operator loads a three-dimensional CAD solid model into the system. Supports are designed to stabilize the part during building. The translator converts the CAD files into a STL file. The control unit slices the model and support into a series of cross sections from 0.025 to 0.5 mm thick. The computer-controlled optical scanning system then directs and focuses the laser beam so that it solidifies a two-dimensional cross-section corresponding to the slice on the surface of the photo-curable liquid resin to a depth greater than one layer thickness. The elevator table then drops enough to cover the solid polymer with another layer of the liquid resin. A leveling wiper or vacuum blade [...] moves across the surfaces to re-coat the next layer of resin on the surface. The laser then draws the next layer. This process continues building the part from bottom up, until the system completes the part. The part is then raised out of the vat and cleaned of excess polymer. The main components of the stereolithography system are a control computer, a control panel, a laser, an optical system and a process chamber.» (Ibid., p. 42-43)

According to Chua, Leong and Lim, the stereolithography process may be summarized in the two following principles:

1. «Parts are built from a photo-curable liquid resin that cures when exposed to a laser beam (basically, undergoing the photo-polymerization process) which scans across the surface of the resin.» (Chua, Leong & Lim, 2003, p. 44-45)
   As for this first principle, «there are many types of liquid photopolymers that can be solidified by exposure to electro-magnetic radiation [...]. The vast majority of photopolymers used in most additive manufacturing, including stereolithography machines, are curable in the UV range. UV-curable photopolymers are resin which are formulated from photo-initiators and reactive liquid monomers. There are a large variety of them and some may contain fillers and other chemical modifiers to meet specified chemical and mechanical requirements. The process through photopolymers are cured is referred to as the photo-polymerization process. Loosely defined, polymerization is the process of linking small molecules, (known as monomers). When the chain-like polymers are linked further to one another, a cross-linked polymer is said to be formed. photo-polymerization is polymerization initiated by a photochemical process whereby the starting point is usually the induction of energy from the radiation source. Polymerization of photopolymers is normally an energetically favorable or exothermic reaction. However, in most cases, the formulation of a photopolymer can be stabilized to remain unreacted at ambient temperature. A catalyst is required for polymerization to take place at a reasonable rate. This catalyst is usually a free radical which may be generated either thermally or photochemically. The source of photochemically generated radical is a photo-initiator, which reacts with an actinic photon to produce the radicals that catalyze the polymerization process.» (Ibid., p. 45-46)
2. «The building is done layer by layer, each layer being scanned by the optical scanning system and controlled by an elevation mechanism which lowers at the completion of each layer.” (Ibid., p. 44-45) As for this second principle, «every additive manufacturing technique uses layering technology in the creation of prototypes, parts and finished goods. “The basic principles is the availability of computer software to slice a CAD model into layers and reproduce it in an output device like a laser scanning system. The layer thickness is controlled by a precision elevation

mechanism. It will correspond directly to the slice thickness of the computer model and the cured thickness of the resin. The limiting aspect tends to be the curing thickness rather than the resolution of the elevation mechanism. The important component of the building process is the laser and its optical scanning system. The key to the strength of stereolithography is its ability to rapidly direct focused radiation of appropriate power and wavelength onto the surface of the liquid photopolymer resin, forming patterns of solidified photopolymer according to the cross-sectional data generated by the computer. In the stereolithography, a laser beam with a specified power and wavelength is sent through a beam expanding telescope to fill the optical aperture of a pair of cross axis, galvanometer driven, beam scanning mirrors. These form the optical scanning system of the stereolithography. The beam comes to a focus on the surface of a liquid photopolymer, curing a predetermined depth of the resin after a controlled time of exposure (inversely proportional to the laser scanning speed). The solidification of the liquid resin depends on the energy per unit area (or “exposure”) deposited during the motion of the focused spot on the surface of the photopolymer. There is a threshold exposure that must be exceeded for the photopolymer to solidify. To maintain accuracy and consistency during part building using the stereolithography, the cure depth and the cured line width must be controlled. As such, accurate exposure and focused spot size become essential. Parameters which influence performance and functionality of the parts are the physical and chemical properties of the resin, the speed and resolution of the optical scanning system, the power, wavelength and type of the laser used, the spot size of the laser, the re-coating system, and the post-curing process.» (Ibid., p. 45-46)

Fused deposition modeling (FDM)

According to Chua, Leong and Lim (2000, p. 124): «Stratasys Inc. was founded in 1989 and has developed most of the company’s products based on the fused deposition modeling technology. The technology was first developed by Scott Cramp in 1988 and the patent was awarded in the U.S. in 1992. FDM uses the extrusion process to build 3D models.»

«A geometric model of a conceptual design is created on a CAD software which uses workstation where it is processed through some propriety software before loading to the FDM machine. [...]

Within the software, the CAD file is sliced into horizontal layers after the part is oriented for the optimum build position, and any necessary support structures are automatically detected and generated. The slice thickness can be set manually to anywhere between 0.172 to 0.365 mm depending on the needs of the models. Tool paths of the build process are then generated which are downloaded to the FDM machine.

The modeling material is in spools, very much like a fishing line. The filament on the spools is fed into an extrusion head and heated to a semi-liquid state. The semi-liquid material is extruded through the head and then deposited in ultra thin layers from the FDM head, one layer at a time. Since the air surrounding the head is maintained at a temperature below the materials' melting point, the exiting material quickly solidifies. Moving on the X-Y plane, the head follows the path generated the software generating the desired layer. When the layer is completed, the head moves on to create the next layer. The horizontal width of the extruded material can vary between 0.250 to 0.965 mm depending on model. This feature, called "road width", can vary from slice to slice. Two modeler materials are dispensed through a dual tip mechanism in the FDM machine. A primary modeler material is used to produced the model geometry and a secondary material, or release material, is used to produce the support structures. The release material forms a bond with the primary modeler material and can be washed away upon completion of the 3D models.» (Ibid., p. 129)

«The principle of the FDM is based on surface chemistry, thermal energy, and layer manufacturing technology. The material in filament (spool) form is melted in a specially designed head, which extrudes on the model. As it is extruded, it is cooled and thus solidifies to form the model. [...] Parameters which affect performance and functionalities of the system are material column strength, material flexural modulus, material viscosity, positioning accuracy, road widths, deposition speed, volumetric flow rate, tip diameter, envelope temperature, and part geometry.» (Ibid., p. 130)

The authors identify the following advantage of this technique:

- «Fabrication and functional parts: FDM process is able to fabricate prototypes with materials that are similar to that of the actual molded product. [...].
- Minimal wastage: the FDM process build parts directly by extruding semi-liquid melt onto the model. Thus only those material needed to build the part and its support are needed, and material

wastage are kept to a minimum. There is also little need for cleaning up the model after it has been built.

- Ease of support removal. [...] Support structures generated during the FDM building process can be easily broken off or simply washed away. This makes it very convenient for users to get to their prototypes very quickly and there is very little or no post-processing necessary.
- Ease of material change: build materials, supplied in spool form [...], are easy to handle and can be changed readily when the materials in the system are running low. This keeps the operation of the machine simple and the maintenance relatively easy.» (Ibid., p. 130-131)

They also identify some disadvantages of using FDM technique:

- «Restricted accuracy: parts built with the FDM process usually have restricted accuracy due to the shape of the material used, i.e., the filament form. Typically, the filament used has a diameter of 1.27 mm and this tends to set a limit on how accurately the part can be built.
- Slow process: the building process is slow, as the whole cross-sectional area needs to be filled with building materials. Building speed is restricted by the extrusion rate or the flow rate of the build material from the extrusion head. As the build material used are plastics and their viscosities are relatively high, the build process cannot be easily speeded up.
- Unpredictable shrinkage: as the FDM process extrudes the build material from its extrusion head and cools them rapidly on deposition, stresses induced by such rapid cooling invariably are introduced into the model. As such, shrinkage and distortions caused to the model built are a common occurrence and are usually difficult to predict, though with experience, users may be able to compensate for these by adjusting the process parameters of the machine.» (Ibid., p. 131)

Selective laser sintering (SLS)

Selective laser sintering, similarly to stereolithography, was created by 3D Systems Corporation, a company established in 1986 by inventor Charles W. Hull and entrepreneur Raymond S. Freed.

Chua, Leong and Lim (2003, p. 174-176) identify the following advantages of this technique:

- «Good part stability: parts are created within a precise controlled environment. The process and materials provide for directly produced functional parts to be built;

- Wide range of processing materials: a wide range of materials including nylon, polycarbonates, metals and ceramics are available, thus providing flexibility and a wide scope of functional applications;
- No parts supports required: the system does not require CAD-developed support structures. This saves the time required for support structure building and removal;
- Little post-processing required: the finishing of the part is reasonably fine and requires only minimal post-processing such as particle blasting and sanding;
- No post-curing required: the completed laser sintered part is generally solid enough and does not require further curing.»

They also identify the following disadvantages:

- «Large physical size of the unit: the system requires a relatively large space to house it. Apart from this, additional storage space is required to house the inert gas tanks used for each builds;
- High power consumption: the system high power consumption due to the high wattage of the laser required to sinter the powder particles together;
- Poor surface finish: the as-produced parts tend to have poorer surface finish due to the relatively large particle sizes of the powders used.»

The laser sintering process might be summarized into the following steps:

1. «A thin layer of heat-fusible powder is deposited onto the part-building chamber;
2. The bottom-most cross sectional slice of the CAD part under fabrication is selectively "drawn" (or scanned) on the layer of powder by a heat-generating CO_2 laser. The interaction of the laser beam with the powder elevates the temperature to the point of melting, fusing the powder particles to form a solid mass. The intensity of the laser beam is modulated to melt the powder only in areas defined by the part's geometry. Surrounding powder remain a loose compact and serve as supports;
3. When the cross-section is completely drawn, an additional layer of powder is deposited via a roller mechanism on top of the previously scanned layer. This prepares the next layer for scanning;
4. Step 2 and 3 are repeated, with each layer fusing to the layer below it. Successive layers of powder are deposited and the process is repeated until the part is completed.

[...]

As SLS materials are in powdered form, the powder not melted or fused during processing serves as a customized, built-in support structure. There is no need to create support structures within the CAD design prior to or during processing and thus no support structure to remove when the part is completed.

After the SLS process, the part is removed from the build chamber and the loose powder simply falls away. SLS parts may then require some post-processing or secondary finishing, such as sanding, lacquering and painting, depending upon the application of the prototype built.

The SLS system contains the following hardware components: build chamber dimensions, process station, computer cabinet, chiller.» (Ibid., p. 176-177)

As for the materials that can be used in the process, Chua, Leon and Lim argue that "a wide range of thermoplastic, composites, metals and ceramics can be used in this process, thus providing an extensive range of functional parts to be built." These are as follows:

- «Polyamide. [...] this material is used to create rigid and rugged plastic parts for functional engineering environments. This material is durable, can be machined or even welded where required. A variation of this material is the polyamide-based composite system, incorporating glass-filled powders, to produce even more rugged engineering parts. This composite material improves the resistance to heat and chemicals.
- Thermoplastic elastomer. Flexible, rubber-like parts can be prototyped using the SLS. [...] the material produces parts with high elongation. Yet, it is able to resist abrasion and provides good part stability. The material is impermeable to water [...].
- Polycarbonate: [...] These are suitable for creating concept and functional models and prototypes, investment casting patterns for metal prototypes and cast tooling [...], masters for duplication processes, and sand casting patterns. These materials only require a 10-20 W laser to work and are useful for visualizing parts and working prototypes that do not carry heavy loads. These parts can be built quickly and are excellent for prototypes and patterns with fine features.
- Nylon: [...] This material is suitable for creating models and prototypes that can withstand an perform in demanding environment. It is one of the most durable rapid prototyping materials currently available in the industry, and it offers substantial heat and chemical resistance. [...]
- Metal: this is a material where polymer coated stainless steel powder is infiltrated with bronze. [...] the material is excellent for producing core inserts and preproduction tools for injection molding prototype polymer parts. The material exhibits high durability and thermal conductivity and can be used for relatively large-scale production tools. An alternative material is the copper

polyamide metal-polymer composite system which can be applied to tooling for injection molding small batch production of plastic parts.

- Ceramics. [...] these use zircon and silica coated with phenolic binder to produce complex sand cores and molds for prototype sand casting of metal parts.» (Chua, Leong & Lim, 2003, p. 178-179)

According to the same authors, the SLS process is based on the following principles:

1. «Parts are built by sintering when a CO_2 laser beam hits a thin layer of powdered material. The interaction of the laser beam with the powder raises the temperature to the point of melting, resulting in particle bonding, fusing the particles to themselves and the previous layer to form a solid.” (Ibid., p. 179)

   «In the process, particles in each successive layer are fused to each other and to the previous layer by raising their temperature with the laser beam to above the glass-transition temperature. The glass-transition temperature is the temperature at which the material begins to soften from a solid to jelly-like condition. This often occurs just prior to the melting temperature at which the material will be in a molten or liquid state. As a result, the particles begin to soften and deform owing to their weight and cause the surfaces in contact with other particles or solid to deform and fuse together at these contact surfaces. One major advantage of sintering over melting and fusing is that it joins powder particles into a solid part without going into the liquid phase, thus avoiding the distortions caused by the flow of molten material during fusing. After cooling, the powder particles are connected in a matrix that has approximately the density of the particle material. As the sintering process requires the machine to bring the temperature of the particles to the glass-transition temperature, the amount of energy needed is considerable. The energy required to sinter bond a similar layer thickness of material is approximately between 300 to 500 times higher than that required for photo-polymerization. This high laser powder requirement can be reduced by using auxiliary heaters at the powder bed to raise the powder temperature to just below the sintering temperature during the sintering process. However an inert gas environment is needed to prevent oxidation or explosion of the fine powder particles. Cooling is also necessary for the chamber gas. The parameters which affect the performance and functionalities are the properties of powdered materials and its mechanical properties after sintering, the accuracy of the laser beam, the scanning pattern, the exposure parameters and the resolution of the machine.» (Ibid., p. 179-180)

2. «The building of the part is done layer. Each layer of the building process contains the cross-sections of one or many parts. The next layer is then built directly on top of the sintered layer after an additional layer of powder is deposited via a roller mechanism on top of the previously formed layer.» (Ibid., p. 179)

«The packing density of particles during sintering affects the part density. In studies of particle packing with uniform sized particles and particles used in commercial sinter bonding, packing densities were found to range typically from 50% to 62%. Generally, the higher the packing density, the better would be the expected mechanical properties. However, it must be noted that scan pattern and exposure parameters are also the major factors in determining the mechanical properties of the part.» (Ibid.)

Gibson, Rosen and Stucker (2010, p. 385) identify a list of parameters that might take into consideration while comparing different additive manufacturing techniques:

- «Cost: since some machines employ more expensive technologies, like lasers, they will inevitably cost more than others.
- Range of materials: some machines can only process one or two materials, while others can process more, including composites.
- Maintenance: with some machines being more complex than others, the maintenance requirements will differ. Some companies will add cost to their machines to ensure that they are better supported.
- Speed: due to the technologies applied, some machines will build parts faster than others.
- Versatility: some machines have complex setup parameters where part quality can be balanced against other parameters, like build speed. Other machines have fewer setup variations that make them easier to use but perhaps less versatile.
- Layer thickness: some machines have a limitation on the layer thickness due to the material processing parameters. Making these layers thinner would inevitably slow the build speed.
- Accuracy: aside from layer thickness, in-plane resolution also has an impact on accuracy. This may particularly affect minimum feature size and wall thickness of a part. For example, laser-based systems have a minimum feature size that is based on the diameter of the laser beam.»

II.3. The general process

According to Chua, Leong and Lim (2003, p. 26-33), «there are a total of five steps in the chain and these are 3D modeling, data conversion and transmission, checking and preparing, building and post-processing. [...]

1. 3D geometric modeling: advanced 3D modeling is a general prerequisite in rapid prototyping processes and, usually is the most time-consuming part of the entire process chain. It is most important that such 3D geometric models can be shared by the entire design team for many different purposes, such as interference studies, stress analyses, FEM analyses, detail design and drafting, planning for manufacturing, including NC programming, etc. Many CAD/CAM systems now have a 3D geometrical modeler facility with these special purpose modules. [...]
2. Data conversion: the solid or surface model to be built is next converted into a format dubbed the STL file format. This format originates from 3D Systems which pioneers the STereoLithography system. The STL file format approximates the surfaces of the model using tiny triangles. Highly curved surfaces must employ many more triangles, which mean that STL files for curved parts can be very large. [...] Almost, if not all, major CAD/CAM vendors supply the CAD-STL interface. Since 1990, almost all major CAD/CAM vendors have developed and integrated this interface into their systems. This conversion step is probably the simplest and shortest of the entire process chain. However, for a highly complex model coupled with an extremely low performance workstation or PC, the conversion can take several hours. Otherwise, the conversion to STL file should take only several minutes. Where necessary, supports are also converted to a separate STL file. Supports can alternatively be created or modified in the next step by third party software which allows verification and modifications of models and supports. The transmission step is also fairly straightforward. The purpose of this step is to transfer the STL files which reside in the workstation to the rapid prototyping system's computer. It is typical that the workstation and the rapid prototyping system are situated in different locations. The workstation, being a design tool, is typically located in a design office. The rapid prototyping system, on the other hand, is a process or production machine, and is usually located on the shop-floor. Data transmission via agreed data formats such as STL or IGES may be carried out through a diskette, email or LAN. No validation of the quality of he STL file is carried out at this stage.
3. Checking and preparing: [...] the CAD model errors are corrected by human operators assisted by specialized software such as MAGICS [...]. This process of manual repair is very tedious and

time consuming especially if one considers the great number of geometric entities (e.g., triangular facets) that are encountered in a CAD model. [...] Once the STL files are verified to be error-free, the rapid prototyping system's computer analyses the STL files that define the model to be fabricated and slices the model into cross-sections. The cross-sections are systematically recreated through the solidification of liquids or binding of powders, or fusing of solids, to form a 3D model. [...] Generally, the model is sliced into the thinnest layer (approximately 0.12 mm) as they have to be very accurate. The supports can be created using coarser settings. An internal cross hatch structure is generated between the inner and the outer surface boundaries of the part. This serves to hold up the walls and entrap liquid that is later solidified with the presence of UV light. Preparing building parameters for positioning and stepwise manufacturing in the light of many available possibilities can be difficult if not accompanied by proper documentation. These possibilities include determination of the geometrical objects, the building orientation, spatial assortments, arrangement with other parts, necessary support structures and slice parameters. They also include the determination of technological parameters [...].

4. Building: this step is fully automated. It is usual to leave the machine on to build a part overnight.
5. Post-processing: [...] At this stage, generally some manual operations are necessary. As a result, the danger of damaging a part is particularly high. Therefore, the operator for this last process step has a high responsibility for the successful process realization. [...] The cleaning task refers to the removal of excess parts which may have remained on the part.» (ibid., p. 31-33)

Gibson, Rosen & Stucker identify eight steps:

1. «CAD: all additive manufacturing parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.
2. Conversion to STL: nearly every additive manufacturing machine accepts the STL file format, which has become a de facto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.
3. Transfer to additive manufacturing machine and STL file manipulation: the STL file describing the part must be transferred to the additive manufacturing machine. Here, there may be some

general manipulation of the file so that it is the correct size, position, and orientation for building.

4. Machine setup: the additive manufacturing machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.
5. Build: building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.
6. Removal: once the additive manufacturing machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.
7. Post-processing: once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.
8. Application: parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding. They may also be required to be assembled together with other mechanical or electronic components to form a final model or product.»

«While the numerous stages in the additive manufacturing process have now been discussed, it is important to realize that many additive manufacturing machines require careful maintenance. Many additive manufacturing machines use fragile laser or printer technology that must be carefully monitored and that should preferably not be used in a dirty or noisy environment. While machines are designed to operate unattended, it is important to include regular checks in the maintenance schedule, and that different technologies require different levels of maintenance. It is also important to note that additive manufacturing processes fall outside of most materials and process standards; explaining the recent interest in the ASTM F42 Technical Committee on Additive Manufacturing Technologies, which is working to address and overcome this problem.

However, many machine vendors recommend and provide test patterns that can be used periodically to confirm that the machines are operating within acceptable limits. In addition to the machinery, materials may also require careful handling. The raw materials used in some additive manufacturing processes have limited shelf-life and must also be kept in conditions that prevent then from unwanted chemical reactions. Exposure to moisture, excess light, and other contaminations should be avoided. Most processes use materials that can be reused for more than one build. However, it may be that reuse could degrade the properties if performed many times over, and therefore a procedure for maintaining consistent material quality through recycling should also be observed.» (Gibson, Rosen, Stucker, 2010, p. 3-6)

The process mentioned above may refers to any commercial additive manufacturing technique. «As has been noted, different technologies may require more or less attention for a number of these stages. Here we discuss the implications of these variations, not only from process to process but also in some cases within a specific technology. The nominal layer thickness for most machines is around 0.1 mm. However, it should be noted that this is just a rule of thumb. For example, the layer thickness for most FDM dimension is 0.254 mm. Contrast that with standard layer thickness between 0.05 and 0.1 mm for SL technology. Many technologies have the capacity to vary the layer thickness. The reasoning is that thicker layer parts are quicker to build but are less precise. This may not be a problem for some applications where it may be more important to make the parts as quickly as possible.

Fine detail in a design may cause problems with some additive manufacturing technologies, such as wall thickness; particularly if there is no choice but to build the part vertically. This is because even though positioning within the machine may be very precise, there is a finite dimension to the droplet size, laser diameter, or extrusion head that essentially defines the finest detail or thinnest wall that can be fabricated.

There are other factors that may not only affect the choice of process but also influence some of the steps in the process chain. In particular, the use of different materials even within the same process may affect the time, resources, and skill required to carry out a stage. For example, the use of water soluble supports in FDM may require specialist attention, like the use (or avoidance) of particular solvents or infiltration compounds. A number of processes benefit from application of sealants or even infiltration of liquid polymers. These materials must be compatible with the part material both chemically and mechanically. Post-processing that involves heat must include awareness of the heat resistance or melting temperature of the materials involved. Abrasive or machining-based processing must also require knowledge of the mechanical properties of the materials involved. If considerable finishing is required, it may also be necessary to include an allowance in the part geometry, perhaps by using scaling of the STL file or offsetting of the part's surfaces, so that the part does not become worn away too much.» (Ibid., p. 47-48)

II.4. Other technical issues

STL file

«Representation methods used to describe CAD geometry vary from one system to another. A standard interface is needed to convey geometric descriptions from various CAD packages to rapid prototyping systems. The STL (Stereolithography) file, as the de facto standard, has been used in many, if not all, rapid prototyping systems.

The STL file, conceived by the 3D Systems, USA, is created from the CAD database via an interface on the CAD system. This file consists of an unordered list of triangular facets representing the outside skin of an object. There are two formats to the STL file. One is the ASCII format and the other os the binary format. The size of the ASCII STL file is larger than that of the binary format but is human readable. In a STL file, triangular facets are described by a set of X, Y and Z coordinates for each of the three vertices and a unit normal vector with X, Y and Z to indicate which side of facet is an object. [...]

Because the STL file is a facet model derived from precise CAD models, it is, therefore, an approximate model of a part. Besides, many commercial CAD models are not robust enough to generate the facet model (STL file) and frequently have problems.

Nevertheless, there are several advantages of the STL file. First, it provides a simple method of representing 3D CAD data. Second, it is already a de facto standard and has been used by most CAD systems and rapid prototyping systems. Finally, it can provide small and accurate files for data transfer for certain shapes.

On the other hand, several disadvantages of the STL file exist. First, the STL file is many times larger than the original CAD data file for a given accuracy parameter. The STL file carries much redundancy information such as duplicate vertices and edges [...]. Second, the geometry flaws exist in the STL file because many commercial tessellation algorithms used by CAD vendor today are not robust. This gives rise to the need for a "repair software" which slows the production cycle time. Finally, the subsequent slicing of large STL files can take many hours. However, some rapid prototyping processes can slice while they are building the previous layer and this will alleviate this disadvantage.» (Chua, Leong & Lim, 2003, p. 237-238)

According to Gibson, Rosen and Stucker (2010, p. 342), «STL files can be output as either binary or ASCII (text) format. The ASCII format is less common but easier to understand and is generally used for illustration and teaching. Most additive manufacturing systems run on PCs using Windows. The STL file is normally labeled with a ".STL" extension that is case insensitive, although some additive manufacturing systems may require a different or more specific file definition. These files only show approximation of the surface or solid entities and so any information concerning the color, material, build layers, or history is ignored during the construction of the surface or solid, and not explicitly used in that solid or surface, will also be ignored.

An STL file consists of lists of triangular facets. Each triangular facet is uniquely identified by a unit normal vector and three vertices or corners. The unit normal vector is a line that is perpendicular to the triangle and has a length equal to 1.0. This length could be in mm or inches and is stored using 3 numbers. The STL file itself holds no dimensions, so the additive manufacturing machine operator must know whether the dimensions are mm, inches, or some other unit. Since watch vertex has also 3 numbers, there are a total of 12 numbers to describe each triangle.» (Ibid.)

Computer-aided-engineering (CAE)

«3D CAD is an extremely valuable resource for product design and development. One major benefit to using software-based design is the ability to implement change easily and cheaply. If we are able to keep the design primarily in a software format for a larger proportion of the product development cycle, we can ensure that any design changes are performed virtually on the software description rather than physically on the product itself. The more we know about how the product is going to perform before it is built, the more effective that product is going to be. This is also the most cost-effective way to deal with product development. If problems are only noticed after parts are physically manufactured, this can be very costly. 3D CAD can make use of additive manufacturing to help visualize and perform basic tests on candidate designs prior to full-scale commitment to manufacturing. However, the more complex and performance-related the design, the less likely we are to gain sufficient insight using these methods. However, 3D CAD is also commonly linked to other software packages [...] collectively known as Computer-Aided Engineering (CAE) software. Forces, dynamics, stresses, flow, and other properties can be calculated to determine how well a design will perform under certain conditions. While such software cannot easily predict the exact behavior of a part, for analysis of critical parts a combination of CAE, backed up with additive manufacturing-based experimental analysis, may be a useful solution.» (Gibson, Rosen & Stucker, 2010, p. 13-14)

«It is clear that additive manufacturing would not exist without computers and would not have developed so far if it were not for the development of 3D solid modeling CAD. The quality, reliability, and ease of use of 3D CAD have meant that virtually any geometry can be modeled, and it has enhanced our ability to design. Some of the most impressive models made using additive manufacturing are those that demonstrate the capacity to fabricate complex forms in a single stage without the need to assemble or to use secondary tooling. [...]

Virtually every commercial solid modeling CAD system has the ability to output to an additive manufacturing machine. This is because the only information that an additive manufacturing machine requires from the CAD system is the external geometric form. There is no requirement for the machine to know how the part was modeled, any of the features or any functional elements. So long as the external geometry can be defined, the part can be built.» (Ibid., p.341)

3D CAD modeling and analysis

«Since the 1990s, the dominant mode of representing designs has shifted dramatically from drawings, often created using a computer, to 3D computer-aided design models, known as 3D CAD models. 3D CAD models represents designs as collections of 3D solid entities, each usually constructed from geometric primitives, such as cylinders, blocks and holes.

The advantages of 3D CAD modeling include the ability to easily visualize the three-dimensional form of the design; the ability to create photo-realistic images for assessment of product appearance; the ability to automatically compute physical properties such as mass and volume; and the efficiency arising from the creation of one and only one canonical description of the design, from which other, more focused descriptions, such as cross-sectional views and fabrication drawings, can be created. Through the use of computer-aided engineering (CAE) tools, 3D CAD models have begun to serve as analytical prototypes. In some settings this can eliminate one or more physical prototypes. When 3D CAD models are used to carefully plan the final, integrated assembly of the product and to detect geometric interference amongst parts, this may indeed eliminate the need for a full scale prototype. For example, in the development of the Boeing 777 and 787 jets, the development teams were able to avoid building full-scale wooden prototype models of the planes, which had historically been used to detect geometric interferences among structural elements and the component of various other systems, such as hydraulic lines. Using a 3D CAD model of an entire product in this manner is known, depending on the industry setting, as a digital mock-up, digital prototype, or virtual prototype.

3D CAD models are also the underlying representation for many types of computer-based analysis. Forms of CAE include finite-element analysis of thermal flow or stress distribution, virtual crash testing of automobiles, kinematic and dynamic motion of complex mechanisms, all of which have become more sophisticated every year.» (ibid., p. 301)

Creating STL files from a CAD system

«Nearly all geometric solid modeling CAD systems can generate STL files from a valid, fully enclosed solid model. Most CAD systems can quickly tell the user if a model is not a solid. This test is particularly necessary for systems that use surface model techniques, where it can be possible to create an object that is not fully closed off. Such systems would be used for graphics applications where there is a need for powerful manipulation of surface detail [...] rather than for engineering detailing. [...]

Most CAD systems use a "Save as" function to convert the native format into an STL file. There is typically some control over the size of the triangles to be used in the model. Since STL uses planar surfaces to approximate curved surfaces, then obviously the larger the triangles, the looser that approximation becomes. Most CAD systems do not directly limit the size of the triangles since it is also obvious that the smaller the triangle, the larger the resulting file for a given object. An effective approach would be to minimize the offset between the triangle and the surface that it is supposed to represent. A perfect cube with perfectly sharp edges and points can be represented by 12 triangles, all with an offset of 0 between the STL file and the original CAD model. However, few designs would be that convenient and it is important to ensure a good balance between surface approximation and excessively large file. [...] The exact value of the required offset is smaller than the basic resolution of the process, then making it smaller will have no effect on the precision of the resulting model. Since many additive manufacturing processes operate around the 0.1 mm layer resolution, then a triangle offset of 0.05 mm or slightly lower will be acceptable for most additive manufacturing technologies.» (Gibson, Rosen & Stucker, 2010, p. 343-344)

Reverse engineering technology

According to Gibson, Rosen and Stucker (2010, p. 12-13): «More and more models are being built from data generated using reverse engineering (RE) 3D equipment and software. In this context, RE is the process of capturing geometric data from another object. This data is usually initially available in what is termed "point cloud" form, meaning an unconnected set of points representing the object surfaces. These points need to be connected together using RE software [...], which may also be used to combine point clouds from different scans and to perform other functions like hole-fitting and smoothing. [...] Engineered objects would normally be scanned using laser-scanning or touch-probe technology. Objects that have complex internal features or anatomical models may make use of Computerized Tomography (CT), which was initially developed for medical imaging but is also available for scanning industrially produced objects. This technique essentially works in a similar way to additive manufacturing, by scanning layer by layer and using software to join these layers and identify the surface boundaries. Boundaries from adjacent layers are then connected together to form surfaces. [...]" In other words: "Additive manufacturing can be used to reproduced the articles that were scanned, which essentially would form a kind of 3D facsimile (3D Fax) process. More likely, however, the data will be modified and/or combined with other data to form complex, freeform artifacts that are taking advantage of the "complexity for free" feature of the technology. An example may be where individual patient data is combined with an engineering design to form a customized medical implant. This is something that will be discussed in much more detail later [...].» (Ibid.)

The use of multiple materials in additive manufacturing

According to Gibson, Rosen and Stucker (2010, p. 423): «Almost since the very beginning, experimenters have tried to use more than one material in additive manufacturing machines. In fact, multiple materials are a fundamental benefit to how some additive manufacturing work. The laminated object manufacturing (LOM) process, for example, was one of the earliest additive manufacturing technologies developed and required that sheet material (paper) be combined with a resin to bond the sheets together to form a composite object of paper and resin.

Many vendors and researchers have added further materials to the single-material additive manufacturing technologies in order to enhance the basic process, either to optimize the process or to improve the properties of the final part in some way. [...]»

The authors state that multiple materials can actually be introduced to the additive manufacturing process, and this can happen in several ways:

- «Two or more discrete materials can be placed nest to each other. The interface between the materials can be such that they are either simply in contact with each other or where they are bonded together in some way. Two discrete materials are often used when generating supports, such as in the FDM process, where supports may be of a different material to the part and can, therefore, be easily removed once the build has been completed.
- A material can be processed in such a way that there is porosity in some segments or throughout the whole of the resulting part. It is quite common for powder based systems to display such porosity. This porosity can allow the use of a liquefied secondary material for infiltration. In some processes, the porosity may be varied in different regions (for example, by varying the laser power in the SLS powder bed fusion process) so that the ratio of parent material to infiltrate can also be varied throughout the part. Furthermore, infiltration may occur during the additive manufacturing process at the layer level rather than merely as a post-additive manufacturing process. The binders used in the 3D printing processes are an example of this approach. 3D printers parts often require an additional post-build infiltration to further strengthen the part, adding a third material component into the structure.
- Feed material can be presented to the additive manufacturing process as a blend of two or more different materials. In some cases, it may be possible to vary the ratio of each material to permit the fabrication of functionality graded components. In other cases, the entire batch of feedstock material will have the same blend; e.g., SLA resins can have ceramic or other particles mixed in with them to produce a composite, as can some SLS powders.» (Ibid., 423-424)

According to the authors, achieving a multiple material strategy would be crucial, as this can:

- «Improve the mechanical properties of the resulting parts: additional materials may increase the hardness, heat deflection properties or tensile behavior for example.
- Provide additional functionality in the resulting part: parts may have different colors, varying electrical conductivity, or variable mechanical properties (as opposed to globally improving the mechanical properties). In such cases, additional materials with differing properties would be placed in strategic locations around the parts.
- Improve the performance of the of the additive manufacturing process: in these cases, additional material may be used to help in part fabrication, such as a barrier material that separates two regions that, after removal of the secondary material, enables relative motion between the regions.

In some cases, the above-mentioned purposes can be achieved merely by presenting new materials or build strategies (e.g., software modifications) to the system. In other instances, the additive manufacturing process machinery (e.g., the material delivery system) must be modified to include the new material.» (Ibid., p. 424)

In conclusion, «the use of multiple materials can be viewed as a way of overlapping conventional manufacturing with additive manufacturing. Additive manufacturing currently suffers in comparison to conventional manufacturing when comparing part quality and part performance. Part quality is being dealt with in other areas relating to machine control and application of newer, high precision technologies. Part performance can however be enhanced application of multiple material systems. The use of composites can target functional regions within a part; applying the most appropriate materials in the most appropriate areas. The advantage of additive manufacturing is that this can be done in a single process and applied to a monolithic structure. It has always been said that additive manufacturing technology is a process where you get to complexity for free. Perhaps, by making additive manufacturing technology a little more complex, we can start to build parts that we have yet to even dream of.» (Ibid., p. 435-436)

II.5. A distinction between additive manufacturing and CNC machining

In the first paragraph of this chapter I explained the difference between additive, subtractive and formative manufacturing. CNC machining falls into the second category, that is, conventional manufacturing. However this manufacturing system shares many features with additive manufacturing techniques, and in some cases its applications are very similar to the ones of additive manufacturing. Hence, I consider crucial to point out the difference between those two manufacturing techniques. According to Gibson, Rosen and Stucker (2010, p. 9), «additive manufacturing shares some of its DNA with Computer Numerical Controlled machining technology. CNC is also computer-based technology that is used to manufacture products. CNC differs mainly in that it is primarily a subtractive rather than additive process, requiring a block of material that must be at least as big as the part that is to be made. [...]»

A range of topics is discussed by the authors:

- «Material: additive manufacturing technology was originally developed around polymeric materials, waxes and paper laminates. Subsequently, there has been introduction of composites, metals, and ceramics. CNC machining can be used for soft materials, like medium-density fiberboard (MDF), machinable foams, machinable waxes, and even some polymers. However, use of CNC to shape softer materials is focused on preparing these parts for use in a multistage process like casting. When using CNC machining to make final products, it works particularly well for hard, relatively brittle materials like steels and other metal alloys to produce high accuracy parts with well-defined properties. Some additive manufacturing parts, in contrast, may have voids or anisotropy that are a function of part orientation, process parameters or how the design was input to the machine, whereas CNC parts will normally be more homogeneous and predictable in quality.
- Speed: high speed CNC machining can generally remove material much faster than additive manufacturing machines can add a similar volume of material. However, this is only part of the picture, as additive manufacturing technology can be used to produce a part in a single stage. CNC machines require considerable setup and process planning, particularly as parts become more complex in their geometry. Speed must therefore be considered in terms of the whole process rather than just the physical interaction of the part material. CNC is likely to be a multistage manufacturing process, requiring repositioning or relocation of parts within one machine or use of more than one machine. To make a part in an additive manufacturing machine, it may only take a few hours; and in fact multiple parts are often batched together inside a single additive manufacturing build. Finishing may take a few days if the requirement is for high quality. Using CNC machining, this same process may take weeks.
- Complexity: as mentioned above, the higher the geometric complexity, the greater the advantage additive manufacturing has over CNC. If CNC is being used to create a part directly in a single piece, then there are some geometric features that cannot be fabricated. Since a machining tool must be carried in a spindle, there may be certain accessibility constraints or clashes preventing

the tool from being located on the machining surface of a part. Additive manufacturing processes are not constrained in the same way and undercuts and internal features can be easily built without specific process planning. Certain parts cannot be fabricated by CNC unless they are broken up into components and reassembled at a later stage. Consider, for example, the possibility f machining a ship inside a bottle. How would you machine the ship while it is still inside the bottle? Most likely you would machine both elements separately and work out a way to combine them together as an assembly process. With additive manufacturing you can build the ship and the bottle all at once. An expert in machining must therefore analyze each part prior to it being built to ensure that it indeed can be built and to determine what methods need to be used. While it is still possible that some parts cannot be built with additive manufacturing, the likelihood is much lower and there are generally ways in which this may be overcome without too much difficulty.

- Accuracy: additive manufacturing machines generally operate with a resolution of a few tens of microns. It is common for additive manufacturing machines to also have variable resolution along different orthogonal axes. Typically, the vertical build axis corresponds to layer thickness and this would be of a lower resolution compared with the two axes in the build plane. Accuracy in the build plane is determined by the positioning of the build mechanism, which will normally involve gearboxes and motors of some kind. This mechanism may also determine the minimum feature size as well. For example, SL uses a laser as part of the build mechanism that will normally be positioned using galvanometric mirror drives. The resolution of the galvanometers would determine the minimum wall thickness. The accuracy of CNC machines on the other hand is mainly determined by a similar positioning resolution along all three orthogonal axes and by the diameter of the rotary cutting tools. There are factors that are defined by the tool geometry, like the radius of internal corners, but wall thickness can be thinner than the tool diameter since it is a subtractive process. In both cases very fine detail will also be a function of the properties of the build material.
- Geometry: additive manufacturing machines essentially break up a complex, 3D problem into a series of simple 2D cross-sections with a nominal thickness. In this way, the connection of surfaces in 3D is removed and continuity is determined by how close the proximity of one cross-section is with an adjacent one. Since this cannot be easily done in CNC, machining of surfaces must normally be generated in 3D space. With simple geometries, like cylinders, cuboids, cones, etc., this is a relatively easy process defined by joining points along a path; these points being quite far apart and the tool orientation being fixed. In cases of freeform surfaces, these points can become very close together with many changes in orientation. Such geometry can become

extremely difficult to produce with CNC, even with 5-axis control or greater. Undercuts, enclosures, sharp internal corners and other features can all fail if these features are beyond a certain limit. [...]

- Programming: determining the program sequence for a CNC machine can be very involved, including tool selection, machine speed settings, approach position, and angle, etc. many additive manufacturing machines also have options that must be selected, but the range, complexity and implications surrounding their choices are minimal in comparison. The worst that is likely to happen in most additive manufacturing machines is that the part will not be built very well if the programming in not done properly. Incorrect programming of a CNC machine could result in severe damage to the machine and may even be a safety risk.» (ibid., p. 9-12)

Lennings (2000) compares advantages of additive manufacturing and CNC machining. The advantages of additive manufacturing are:

- «Design freedom;
- Complex geometry;
- Ease of use.»

On the other hand, advantage of CNC are:

- «Price of the system;
- In-house system possible;
- Trouble-free operation;
- Capable of handling incorrect STL files;
- Choice of materials;
- Large prototypes;
- Free choice of accuracy;
- Easy transfer to production tooling.»

Chapter 3

Additive manufacturing applications

In order to better understand the applications of the additive manufacturing techniques, it is necessary to look at the whole new product development process and think how this has changed because of the new technology. In the first paragraph, I will recall the mainstream notion of new product development. In the following paragraphs, I will attempt to show how additive manufacturing becomes crucial in the different stages of the new product development process.

III.1. New product development

Considering a product as the end result of the manufacturing process that is offered to the marketplace to satisfy a certain need, product development can be defined as «the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product.» (Ulrich & Eppinger, 2012, p. 2).

According to the authors (ibid., p. 3), «product development is an interdisciplinary activity requiring contributions from nearly all the functions of a firm; however, three functions are almost always central to a product development project:

- Marketing: the marketing function mediates the interaction between the firm and its customers. Marketing often facilitates the identification of product opportunities, the definition of market segments, and the identification of customer needs. Marketing also typically arranges for communication between the firm and its customers, sets target prices, and oversees the launch and promotion of the product.
- Design: the design function plays the lead role in defining the physical form of the product to best meet customer needs. In this context, the design function includes engineering design (mechanical, electrical, software, etc.) and industrial design (aesthetics, ergonomics, user interfaces).
- Manufacturing: the manufacturing function is primarily responsible for designing, operating, and/or coordinating the production system in order to produce the product. Broadly defined, the

manufacturing function also often includes purchasing, distribution, and installation. This collection of activities is sometimes called the supply chain.»

They define the generic product development process[2] as a «sequence of steps that transforms a set of inputs into a set of outputs. [...] the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product.» (ibid., p. 12)

The divide the product development process into six phases (ibid., p. 12-16):

5. «Planning: it is the link to advanced research and technology development activities. The output of the planning phase is the project's mission statement, which is the input required to begin the concept development phase and which serves as a guide to the development team. The planning activities is often referred to as "phase zero" because it precedes the project approval and launch of the actual product development process. This phase begins with opportunity identification guided by corporate strategy and includes assessment of technology development and market objectives. The output of the planning phase is the project mission statement, which specifies the target market for the product, business goals, key assumptions, and constraints.
6. Concept development: in the concept development phase, the needs of the target market are identified, alternative product concepts are generated and evaluated, and one or more concepts are selected for further development and testing. A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification of the project.
7. System-level design: the system-level design phase includes the definition of the product architecture, decomposition of the product into subsystems and components, and preliminary design of key components. Initial plans for the production system and final assembly are usually defined during this phase as well. The output of this phase usually includes a geometric layout of the product, a functional specification of each of the product's subsystems, and a preliminary process flow diagram for the final assembly process.
8. Detail design: the detail design phase includes the complete specification of the geometry, materials, and tolerance of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part to be fabricated within the production system. The output of this phase is

[2] The so-called "generic product development process" refers to the process used in a market-pull situation: "a firm begins the product development process with the discovery of a market opportunity and then uses the technologies available to satisfy the market need. In other words, the market pulls the product development decisions." (ibid., p. 18)

the control documentation for the product, the drawings of computer files describing the geometry of each part and its production tooling, the specification of the purchased parts, and the process plans for the fabrication and assembly of the product. Three critical issues that are best considered throughout the product development process, but are finalized in the detail design phase, are: materials selection, production cost, and robust performance.

9. Testing and refinement: the testing and refinement phase involves the construction and evaluation of multiple preproduction versions of the product. Early (alpha) prototypes are usually built with production-intent parts (parts with the same geometry and material properties as intended for the production version of the product but not necessarily fabricated with the actual processes to be used in production. Alpha prototypes are tested to determine whether the product will work as designed and whether the product satisfies the key customer needs. Later (beta) prototypes are usually built with parts supplied by the intended production processes but may not be assembled using the intended final assembly process. Beta prototypes are extensively evaluated internally and are also typically tested by customers in their own use environment. The goal for beta prototypes is usually to answers questions about performance and reliability in order to identify necessary engineering changes for the final product.
10. Production ramp-up: in the production ramp-up phase, the product is made using the intended production system. The purpose of the ramp-up is to train the workforce and to work out any remaining problems in the production process. Products produced during production ramp-up are sometimes supplied to preferred customers and are carefully evaluated to identify any remaining flaws. The transition from production ramp-up to ongoing production is usually gradual. At some point in this transition, the product is launched and becomes available for widespread distribution. A post-launch project review may occur shortly after the launch. This review includes an assessment of the project from both commercial and technical perspective and is intended to identify ways to improve the development process for future projects.»

The "concept development" phase, the one where the needs of the target market become crucial, is relevant to the main topic of this chapter, likewise the testing and refinement phase. In fact, Ulrich and Eppinger (2012, p. 16-18) divide the concept development phase into the following sub-phases:

- «Identifying customers needs;
- Establishing target specifications;
- Concept generation;

- Concept selection;
- Concept testing;
- Setting final specification;
- Project planning;
- Economic analysis;
- Benchmarking of competitive products;
- Modeling and prototyping.»

In particular, as for the "modeling and prototyping" phase, «every stage of the concept development process involves various forms of models and prototypes. These may include, among others: early "proof-of-concept" models, which help the development team to demonstrate feasibility; "form-only" models, which can be shown to customers to evaluate ergonomics and style; spreadsheet models of technical trade-offs; and experimental test models, which can be used to set design parameters for robust performance.» (ibid., p. 17,18) Methods for prototyping will be discussed in the following chapter.

In addition to the so-called market-pull situation, associated to the generic product development process, the authors outline some other situations where the product development process deviate from the generic one mentioned above.

- «Technology-push products: the team begins with a new technology, then finds an appropriate market.
- Platform products: the team assumes that the new product will be built around an established technological subsystem.
- Process-intensive products: characteristics of the product are highly constrained by the production process.
- Customized products: new products are slight variations of existing configurations.
- High-risk products: technical or market uncertainties create high risks of failure.
- Quick-build products: rapid modeling and prototyping enables many design-build-test cycles.
- Complex systems: system must be decomposed into several subsystems and many components.» (ibid., p. 18)

In the following paragraph, I will focus on the so-called "testing and refinement" phase, that is the one relevant to the main topic of this chapter: prototyping.

Prototyping

According to the Oxford Advanced Learner's Dictionary of Current English, «a prototype is the first or original example of something that has been or will be copied or developed; it is a model or preliminary version.»

According to Hilton and Jacobs (2000, p. 9), «the purpose of prototyping a product during development is to give the various interested parties (including engineering, sales and marketing, manufacturing, parts suppliers, and subcontractors) a better sense of the product. The prototype can serve to demonstrate functional attributes of the product, to exhibit its appearance, or point out manufacturing issues or requirements.»

According to Chua, Leong and Lim (2003, p. 2-4), «the general definition of the prototype contains three aspects of interests:

1. the implementation of the prototype; from the entire product (or system) itself to its sub-assembled and components,
2. the form of the prototype; from a virtual prototype to a physical prototype, and
3. the degree of the approximation of the prototype; from a very rough representation to an exact replication of the product.

The implementation aspect of the prototype covers the range of prototyping the complete product (or system) to prototyping part of, or a sub-assembly or a component of the product. The complete prototype, as its name suggests, models most, if not all, the characteristics of the product. It is usually implemented full-scale as well as being fully functional. One example of such prototype is one that is given to a group of carefully selected people with special interest, often called a focus group, to examine and identify outstanding problems before the product is committed to its final design. On the other hand, there are prototypes that are needed to study or investigate special problems associated with one component, sub-assemblies or simply a particular concept of the product that requires close attention. An example of such a prototype is a test platform that is used to find the comfortable rest angles of an office chair that will reduce the risk of spinal injuries after prolonged sitting on such a chair. Most of the time, sub-assemblies and components are tested in conjunction with some kind of test rigs or experimental platform.

The second aspect of the form of the prototype take into account how the prototype is being implemented. On one end, virtual prototypes that refers to prototypes that are non-tangible, usually represented in some form other than physical, e.g. mathematical model of a control system. Such prototypes are usually studied and analyzed. The conclusions drawn are purely based upon the assumed principles or science that has been understood up to that point in time. An example is the visualization of airflow over an aircraft wing to ascertain lift and drag on the wing during supersonic flight. Such prototype is often used when either the physical prototype is too large and therefore takes too long to build, or the building of such a prototype is exorbitantly expensive. The main drawback of these kinds of prototypes is that they are based on current understanding and thus they will not be able to predict any unexpected phenomenon. It is very poor or totally unsuitable for solving unanticipated problems. The physical model, on the other hand, is the tangible manifestation of the product, usually built for testing and experimentation. Examples of such prototypes include a mock-up of a cellular telephone that looks and feels very much like the real product but without its intended functions. Such a prototype may be used purely for aesthetic and human factors evaluation.

The third aspect covers the degree on approximation or representativeness of the prototype. One one hand, the model can be a very rough representation of the intended product, like a foam model, used primarily to study the general form and enveloping dimensions of the product in its initial stage of development. Some rough prototypes may not even look like the final product, but are used to test and study certain problems of the product development. An example of this is the building of catches with different material to find the right “clicking” sound for a cassette player door. On the other hand, the prototype can be an exact full scale replication of the product that models every aspects of the product, e.g. the pre-production prototype that is used not only to satisfy customer needs evaluation but also addressing manufacturing issues and concerns. Such “exact” prototypes are especially important towards the end-stage of the product development process.»

Ulrich and Eppinger (2012, p. 291) define a prototype as «an approximation of the product along one or more dimensions of interest. Under this definition, any entity exhibiting at least one aspect of the product that is of interest to the development team can be viewed as prototype. This definition deviates from standard usage in that it includes such diverse forms of prototypes as concept sketches, mathematical models, simulations, test components, and fully functional preproduction versions of the product. Prototyping is the process of developing such an approximation of the product.»

They classify types of prototypes according to the degree to which they are:

- Physical as opposed to analytical: «Physical prototypes are tangible artifacts created to approximate the product. Aspects of the product of interest to the development team are actually built into an artifact for testing and experimentation. Examples of physical prototypes include models that look and feel like the product, proof-of-concept prototypes used to test an idea quickly, and experimental hardware used to validate the functionality of a product. [...] Analytical prototypes represent the product in a non-tangible, usually mathematical or visual, manner. Interesting aspects of the product are analyzed, rather than built.» (Ibid.)
- Comprehensive as opposed to focused: «Comprehensive prototypes implement most, if not all, of the attributes of a product. A comprehensive prototype corresponds closely to the everyday use of the word prototype, in that it is a full-scale, fully operational version of the product. An example of comprehensive prototype is one given to customers in order to identify any remaining design flaws before committing to production. In contrast to comprehensive prototypes, focused prototypes implement one, or a few, of the attributes of a product. Examples of focused prototypes include foam models to explore the form of a product and hand-built circuit boards to investigate the electronic performance of a product design. A common practice is to use two or more focused prototypes together to investigate the overall performance of a product. One of these prototypes is often a "looks-like" prototype, and the other is a "works-like" prototype. By building two separate focused prototypes, the team may be able to answer its question much earlier than if it had to create one integrated, comprehensive prototype.» (Ibid.)

Ulrich and Eppinger also identify four purposes for the use of a prototype, that are:

- «Learning: prototypes are often used to answer two types of questions: "Will it work?" and "How well does it meet the customer needs?" When used to answer such questions, prototypes serve as learning tools.
- Communication: prototypes enrich communication with top management, vendors, partners, extended team members, customers, and investors. This is particularly true of physical prototypes: a visual, tactile, three-dimensional representation of a product is much easier to understand than a verbal description or even a sketch of the product.
- Integration: prototypes are used to ensure that components and subsystems of the product work together as expected. Comprehensive physical prototypes are most effective as integration tools in

product development projects because they require the assembly and physical interconnection of all the parts and subassemblies that make up a product. In doing so, the prototype forces coordination between different members of the product development team. If the combination of any of the components of the product interferes with the overall function of the product, the problem may be detected through physical integration in a comprehensive prototype. Common names for these comprehensive physical prototypes are testbed, alpha, beta, or preproduction prototypes.

- Milestone: particularly in the later stages of product development, prototypes are used to demonstrate that the product has achieved a desired level of functionality. Milestone prototypes provide tangible goals, demonstrate progress, and serve to enforce the schedule. Senior management (and sometimes the customer) often required a prototype that demonstrates certain functions before allowing the project to proceed.» (ibid., p. 294-297)

Similarly, Chua, Leong and Lim identify five roles that prototypes play in the product development process:

1. «Experimentation and learning;
2. Testing and proofing;
3. Communication and interaction;
4. Synthesis and integration;
5. Scheduling and markers.

To the product development team, prototypes can be used to help the thinking, planning, experimenting and learning processes whilst designing the product. Questions and doubts regarding certain issues of the design can be addressed by building and studying the prototype. For example, in designing the appropriate elbow-support of an office chair, several physical prototypes of such elbow supports can be built to learn about the "feel" of the elbow support when performing typical tasks on the office chair.

Prototypes can also be used for testing and proofing of ideas and concepts relating to the development of the product. For example, in the early design of folding reading glasses for the elderly, concepts and ideas of folding mechanism can be tested by building rough physical prototypes to test and prove these ideas to see if they work as intended.

The prototype also serves the purpose of communicating information and demonstrating ideas, not just within the product development team, but also to management and client (whether in-house or external). Nothing is clearer for explanation or communication of an idea than a physical prototype where the intended audience can have the full experience of the visual and tactile feel of the product. A three-dimensional representation is often more superior than that of a two-dimensional sketch of the product. For example, a physical prototype of a cellular phone can be presented to carefully selected customers. Customers can handle and experiment with the phone and give feedback to the development team on the features of and interactions with the phone, thus providing valuable information for the team to improve its design.

A prototype can also be used to synthesize the entire product concept by bringing the various components and sub-assemblies together to ensure that they will work together. This will greatly help in the integration of the product and surface any problems that are related to putting the product together. An example is a complete or comprehensive functional prototype of personal digital assistant (PDA). When putting the prototype together, all aspects of the design, including manufacturing and assembly issues will have to be addressed, thus enabling the different functional members of the product development team to understand the various problems associated with putting the product together.

Prototyping also serves to help in the scheduling of the product development process and is usually used as markers for the end or start of the various phases of the development effort. Each prototype usually marks a completion of a particular development phase, and with proper planning, the development schedule can be enforced. Typically in many companies, the continuation of a development project often hinges on the success of the prototypes to provide impetus to management to forge ahead with it.

It should be noted that in many companies, prototypes do not necessary serve all these roles concurrently, but they are certainly a necessity in any product development project.» (Chua, Leong, Lim, 2003, p. 5-7)

«Prototyping or model making in the traditional sense is an age-old practice. The intention of having a physical prototype is to realize the conceptualization of a design. Thus, a prototype is usually required before the start of the full production of the product. The fabrication of prototypes is experimented in many forms (material removal, casting, moulds, joining with adhesives, etc.) and with many material types (aluminum, zinc, urethanes, wood, etc.).

Prototyping processes have gone through three phases of development, the last two of which have emerged only in the last 20 years. Like the modeling process in computer graphics, the prototyping of physical models is growing through its third phase. Parallels between the computer modeling process and prototyping process can be drawn. The three phases are described as follows.» (Chua, Leong & Lim, 2003, p. 8-11)

First phase: manual prototyping

«Prototyping had begun as early as humans began to develop tools to help them live. However, prototyping as applied to products in what is considered to be the first phase of prototype development began several centuries ago. In this early phase, prototypes typically are not very sophisticated and fabrication of prototypes takes on average about four weeks, depending on the level of complexity and representativeness. The techniques used in making these prototypes tend to be craft-based and are usually extremely labor intensive.» (Ibid.)

Second phase: soft or virtual prototypes

«As application of CAD/CAE/CAM become more widespread, the early 1980s saw the evolution of the second phase of prototyping, that is the so-called “soft or virtual prototyping”. Virtual prototyping takes on a new meaning as more computer tools become available: computer models can now be stressed, tested, analyzed and modified as if they were physical prototypes. For example, analysis of stress and strain can be accurately predicted on the product because of the ability to specify exact material attributes and properties. With such tools on the computer, several iterations of design can easily carried out by changing the parameters of the computer models.

Also, products and as such prototypes tend to become relatively more complex, about twice the complexity as before. Correspondingly, the time required to make the physical model tends to increase tremendously to about that of sixteen weeks as building of physical prototypes is still dependent on craft-based methods though introduction of better precision machines like CNC machines helps.

Even with the advent of rapid prototyping in the third phase, there is still strong support for virtual prototyping. Lee argues that there are still unavoidable limitations (either because of expense or through the use of materials dissimilar to that of the intended part), the inability to perform endless what-if scenarios and the likelihood that little or no reliable data can be gathered from the rapid prototype to perform finite element analysis (FEA). Specifically in the application of kinematic/dynamic analysis, he described a program which can assign physical properties of many different materials, such as steel, ice, plastic, clay or any custom material imaginable and perform kinematic and motion analysis as if a working prototype existed. Despite such strengths of virtual prototyping, there is one inherent weakness that such soft prototypes cannot be tested for phenomena that is not anticipated or accounted for in the computer program. As such there is no guarantee that the virtual prototype is really problem free.» (Ibid.)

Third phase: rapid prototyping

«Rapid prototyping of physical parts [...] represents the third phase in the evolution of prototyping. The invention of this series of rapid prototyping methodologies is described as a "watershed event" because of the tremendous time savings, especially for complicated models. Though the parts (individual components) are relatively three times as complex as parts made in 1970s, the time required to make such a part now averages only three weeks.» (Ibid.)

The importance of prototyping

According to Todd Zaki Warfel (2009, p. 2-18), prototyping is:

- "Generative", meaning that «as you work through the prototyping process, you're going to generate hundreds, if not thousands, of ideas. Some of them are brilliant and some are less brilliant. I've found that even those less brilliant ideas can be a catalyst for brilliant solutions. As a generative process, prototyping often leads to innovation and a significant savings in time, effort, and costs. prototyping helps you get ideas out of your head and into something more tangible, something you can feel, experience, work through, play with, and test.»
- Has the «power of show, tell, and experience: if a picture is worth thousand words, then a prototype is worth 10,000. Prototypes go beyond the power of show and tell, they let you experience the design.»
- «Reduces misinterpretation: take a 60-pages requirements document. Bring 15 people into a room. Hand it out. Let them all read it. Now ask them what you're building. You're going to get 15 different answers. Imagine trying the same thing with a 200-page requirement document, it

gets even worse. Prototypes are a more concrete and tactile representation of the system you're building. They provide tangible experiences.»

- «Saves time, effort and money. [...] Prototyping isn't free, but the benefits of prototyping far outweigh the cost of prototyping, or most importantly, not prototyping. Talk to anyone who has made the transition from a design and development process that didn't include prototyping to one that does, and they'll tell you it has saved them a ton of time and headaches. Not only does prototyping let you realize and experience the design faster but ultimately it also reduces the amount of waste created by other design and development processes.»
- «Reduces waste: in a typical design and development process, requirements are written and handed off to a designer or developer. The designer or developer then interprets these requirements and builds something based on his/her interpretation. Theoretically, a requirements-driven design process should reduce waste. The overall goal is to get everyone on the same page. if we're all on the same page, ultimately, we'll have less waste. Sound fantastic. Theoretically, it's a very sound idea. As experience will show, however, theory and reality are often very different. There are a number of shortcomings in a traditional requirements-driven design and development process that create waste, and they include the following: written by the wrong person (designers and developers are rarely included in the requirements writing process. Instead, the requirements are often written by a business analyst or his equivalent. This person lacks the technical and design knowledge of their counterparts, which often results in any number of requirements being rewritten several times), significant time and effort (the amount of time invested in writing, reviewing, and revising these detailed requirements is significant. For complex systems, I've seen it takes 3-9 to finish something, sometimes more. During that time, things change), non-final final (theoretically, the requirements are the final documentation. In reality, requirements are constantly changing, even after they're "complete"), misinterpretation (the amount of misinterpretation of the 60-200-page requirements is often significant. Misinterpretation leads to weeks or months of rework and a delayed product launch), nonessential features (requirements are often filled with features that provide little, if any, value. Those features take time and effort to build and test. This results in wasted time in writing requirements, building, and testing features that provide little, if any, value and often go unused), catching mistakes too late (requirements-driven processes typically won't catch a mistake until it's in production. The later you catch a mistake in the development process, the more costly it is to fix). Any one of these items alone creates wasted time and effort. Typically, a requirements-driven process is plagued with several of these issues, creating a great deal of inefficiency and waste. On the other hand, including prototyping in the

process can help reduce the amount of waste and result in these benefits: decisions by the right people (designers and developers can flex their experience and knowledge, contribute to the process, and ultimately ensure that the right people make the design decisions), survival of the fittest (multiple ideas are created and tested to ensure that the strongest solutions survive), adaptive (prototypes can be quickly updated, compensating for the ever-changing nature of software development), reduced misinterpretation (the prototype is a visual, or sometimes physical, representation of the system. Visual and physical representation leave less room for misinterpretation than a 60-200-page written document. By reducing misinterpretation, you reduce the amount of rework. Less rework means lower costs and faster time to market), focus (prototyping produces more focused products. More focused products produce less waste in design, development, and rework), catch mistakes early (prototyping helps you catch mistakes early in the design and development process. The earlier you catch a mistake, the lower the cost to fix it will be), reduce risk (prototyping reduces risk, by reducing misinterpretation and catching problems earlier in the design and development cycle). While prototyping can't solve all the problems that plague requirements-driven processes, it can definitely help reduce many of the more common inefficiencies and waste.»

- «Provides real-world value: Jonathan Baker-Bates is someone who has seen a measurable benefit from prototyping firsthand. Jonathan works for a consulting company in the UK with a very typical design and development story. His team of developers regularly receive a 200-page specification document to quote against and build to. Well, that was what they used to do. Jonathan's company recently made a shift toward a prototyping-oriented process. Instead of giving developers a 200-page document, they now receive a high-fidelity prototype with a 16-page supporting document. Since the change, his company as noticed a number of significant improvements: time and effort required to produce the prototype and 16-page supplemental document is less than half required for the 200-page specification document, estimates for build time and cost have become 50 percent more accurate, request for clarification by the development team has been reduced by 80 percent, the amount of rework and bug fixes post-launch has been reduced to 25 percent of similar previous projects, all team members agree that executing the design with the prototyping process is easier than the old process.»

According to entrepreneur Tamara Monosoff (2012), creating a prototype is a crucial step in product development. In particular, a prototype allows to:

- «test and refine the functionality of your design”: Sure, your idea works perfectly in theory. It's not until you start physically creating it that you'll encounter flaws in your thinking. That's why another great reason to develop a prototype is to test the functionality of your idea. You'll never know the design issues and challenges until you begin actually taking your idea from theory to reality.»
- «test the performance of various materials”: For example, your heart may be set on using metal--until you test it and realize that, say, plastic performs better at a lower cost for your particular application. The prototype stage will help you determine the best materials.»
- «describe your product more effectively” with your team, including your attorney, packaging or marketing expert, engineers and potential business partners.»
- «encourage others to take you more seriously”: When you arrive with a prototype in hand to meet any professional--from your own attorney to a potential licensing company--you separate yourself from the dozens of others who've approached them with only vague ideas in mind. Instead, you'll be viewed as a professional with a purpose, as opposed to just an inventor with a potentially good idea.»

III.2. The first step: rapid prototyping

«The competition in the world market for manufactured products has intensified tremendously in recent years. It has become important, if not vital, for new products to reach the market as early as possible, before the competitors. To bring products to the market swiftly, many of the processes involved in the design, test, manufacture and market of the products have been squeezed, both in terms of time and material resources. The efficient use of such valuable resources calls for new tools and approaches in dealing with them, and many of these tools and approaches have evolved. They are mainly technology-driven, usually involving the computer. This is mainly a result of the rapid development and advancement in such technologies over the last few decades.

In product development, time pressure has been a major factor in determining the direction of the development and success of new methodologies and technologies for enhancing its performance. These also have a direct impact on the age-old practice of prototyping in the product development process.» (Chua, Leon & Lim, 2003, p. 1)

According to Hilton and Jacobs (2000, p. 3), «the rise of rapid prototyping stems from a more broad directional change in industry toward more rapid product development. There are numerous reasons for wanting to develop products more rapidly and a great deal of pressure to do so. [...] The shorter the development time, the more effectively the developer can respond to current consumer trends.»

The aim of this paragraph is to introduce and examine one such development, that is rapid prototyping.

«The development of rapid prototyping is closely tied in with the development of applications of computers in the industry. The declining cost of computers, especially of personal and mini computers, has changed the way a factory works. The increase in the use of computers has spurred the advancement in many computer-related areas including computer-aided design (CAD), computer-aided manufacturing (CAM) and computer numerical control (CNC) machine tools. In particular, the emergence of rapid prototyping systems could not have been possible without the existence of CAD. However, from careful examinations of the numerous rapid prototyping systems in existence today, it can be easily deduced that other than CAD, many other technologies and advancement in other fields such as manufacturing systems and materials have been also crucial in the development of RP systems.» (Chua, Leong & Lim, 2003, p. 7)

According to Chua, Leong and Lim (2003, p. 11-14), «common to all the different techniques of rapid prototyping is the basic approach they adopt, which can be described as follows:

1. A model or component is modeled on a computer-aided design/computer-aided manufacturing (CAD/CAM) system. The model which represents the physical part to be built must be represented as closed surfaces which unambiguously define an enclosed volume. This means that the data must specify the inside, outside and boundary of the model. This requirement will become redundant if the modeling technique used is solid modeling. This is by virtue of the technique used, as a valid solid model will automatically be an enclosed volume. This requirement ensures that all horizontal cross sections that are essential to rapid prototyping are closed curves to create the solid object.
2. The solid or surface model to be built is next converted into a format dubbed the STL file format which originates from 3D Systems. The STL file format approximates the surfaces of the model by polygons. Highly curved surfaces must employ many polygons, which means that

STL files for curved parts can be very large. However, there are some rapid prototyping systems which also accept IGES data, provided it is of the correct “flavor”.

3. A computer program analyzes a STL file that defines the model to be fabricated and “slices” the model into cross sections. The cross sections are systematically recreated through the solidification of either liquids or powders and then combined to form a 3D model. Another possibility is that the cross sections are already thin, solid laminations and these thin laminations are glued together with adhesives to form a 3D model. Other similar methods may also be employed to build the model.»

Chua, Leong and Lim (2003) see the development of rapid prototyping in four areas and created a “wheel” that depicts these four key aspects of rapid prototyping. The four key aspects, according to the authors, are:

- «Input: input refers to the electronic information required to describe the physical object with 3D data. There are two possible starting points: a computer model or a physical model. The computer model created by a CAD system can be either a surface model or a solid model. On the other hand, 3D data from the physical model is not at all straightforward. It requires data acquisition through a method known as reverse engineering. In reverse engineering, a wide range of equipment can be used, such as CMM (coordinate measuring machine) or a laser digitizer, to capture data points of the physical model and “reconstruct” it in a CAD system.
- Method: while they are currently more than twenty vendors for rapid prototyping systems, the method employed by each vendor can be generally classified into the following categories: photo-curing, cutting and glueing/joining, melting and solidifying/fusing and joining/binding. Photo-curing can be further divided into categories of single laser beam, double laser beams and masked lamp.
- Material: the initial state of material can come in either solid, liquid or powder state. In solid state, it can come in various forms such as pellets, wire or laminates. The current range materials include paper, nylon, wax, resins and ceramics.
- Application: most of the rapid prototyping parts are finished or touched up before they are used for their intended applications. Applications can be grouped into: design, engineering, analysis, planning, tooling and manufacturing. A wide range of industries can benefit from rapid prototyping and these include, but are not limited to, aerospace, automotive, biomedical, consumer, electrical and electronics product.» (ibid., p. 13,14)

According to eFunda, rapid prototyping can be defined as «a group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data.»

According to eFunda, main reasons for a manufacturing company to employ rapid prototyping techniques are:

- «to increase effective communication by enabling better communication in a concurrent engineering environment;
- to decrease development time, by allowing corrections to a product to be made early in the process;
- to decrease costly mistakes, by giving engineering, manufacturing, marketing, and purchasing a look at the product early in the design process, mistakes can be corrected and changes can be made while they are still inexpensive;
- to minimize sustaining engineering changes;
- to extend product lifetime by adding necessary features and eliminating redundant features early in the design."

In addition, "the trends in manufacturing industries continue to emphasize the following:

- increasing number of variants of products;
- increasing product complexity;
- decreasing product lifetime before obsolescence;
- decreasing delivery time.»

According to Chua, Leong and Lim (2010, p. 1), «the competition in the world market for manufactured products has intensified tremendously in recent years. It has become important, if not vital, for new products to reach the market as early as possible, before the competitors. To bring products to the market swiftly, many of the processes involved in the design, test, manufacture and market of the product have been squeezed, both in terms of time and material resources. The efficient use of such valuable resources calls for new tools and approaches in dealing with them and many of these tools and approaches have evolved. They are mainly technology-driven, usually involving the computer. This is mainly a result of the rapid development and advancement in such technologies over the last few decades. In product development, time pressure has been a major factor in determining the direction and success of developing new methods and advanced technologies. These also have a direct impact on the age old practice of prototyping in the product development process.»

Benefits of rapid prototyping

«Today’s automated, tool-less, patternless rapid prototyping systems can directly produce functional parts in small production quantities. Parts produced in this way usually have an accuracy and surface finish inferior to those made by machining. However, some advanced systems are able to produce near tooling quality parts that are close to or are the final shape. The parts produced, with appropriate post processing, will have material qualities and properties close to the final product. More fundamentally, the time to produce any part, once the design data are available, will be fast, and can be in matter of hours.» (Chua, Leong & Lim, 2003, p. 14)

Chua, Leon and Lim categorize the benefits of rapid prototyping systems into direct and indirect benefits: one direct benefit would be «the ability to experiment with physical objects of any complexity in a relatively short period of time. It is observed that over the last 25 years, products realized to the market place have increased in complexity in shape and form. For instance, compare the aesthetically beautiful car body of today with that of the 1970s. [...] More interestingly and ironically, the relative project completion times have not been drastically increased. Initially, from a base of about 4 weeks’ project completion time in 1970, it increased to 16 weeks in 1980. However, with the use of CAD/CAM and CNC technologies, project completion time reduces to 8 weeks. Eventually, RP systems allowed the project manager to further cut the completion time to 3 weeks in 1995. To the individual in the company, the benefits can be varied and have different impacts. It depends on the role in which they play in the company.» (ibid., p. 14-15)

- «Benefits to product designers: the product designers can increase part complexity with little significant effect on lead time and cost. More organic, sculptured shapes for functional or aesthetic reasons can be accommodated. They can optimize part design to meet customer requirements, with little restrictions by manufacturing. In addition, they can reduce parts count by combining features in single-piece parts that are previously made from several because of poor tool accessibility or the need to minimize machining and waste. With fewer parts, time spent on tolerance analysis, selecting fasteners, detailing screw holes and assembly drawings is greatly reduced. There will also be fewer constraints in the form of parts design without regard to draft angles, parting lines or other such constraints. Parts which cannot easily be set up for machining, or have accurate, large thin walls, or do not use stock shapes to minimize machining and waste can now be designed. They can minimize material and optimize strength/weight ratios without regard to the cost of machining. Finally, they can minimize time-consuming discussions and evaluations of manufacturing possibilities.

- Benefits to the tooling and manufacturing engineer: the main savings savings are in costs. The manufacturing engineer can minimize design, manufacturing and verification of tooling. He can realize profits earlier on new products, since fixed costs are lower. He can also reduce parts count and, therefore, assembly, purchasing and inventory expenses. The manufacturer can reduce the labor content of manufacturing, since part-specific setting up and programming are eliminated, machining/casting labor is reduced, and inspection and assembly are also consequently reduced as well. Reducing material waste, waste disposal costs, material transportation costs, inventory cost for raw stock and finished parts (making only as many as required, therefore, reducing storage requirements) can contribute to low overheads. Less inventory is scrapped because of design changes or disappointing sales. In addition, the manufacturer can simplify purchasing since unit price is almost independent of quantity, therefore, only as many as are needed for the short-term need be ordered. Quotations vary little among supplies, since fabrication is automatic and standardized. One can purchase one general purpose machine rather than many special purpose machines and therefore, reduce capital equipment and maintenance expenses, need fewer specialized operators and less training. A smaller production facility will also result in less effort in scheduling production. Furthermore, one can reduce the inspection reject rate since the number of tight tolerances required when parts must mate can be reduced. One can avoid design misinterpretation (instead, “what you design is what you get”), quickly change design dimensions to deal with tighter tolerances and achieve higher part repeatability, since tool wear is eliminated. Lastly, one can reduce spare parts inventories (produce spare on demand, even for obsolete products).
- Benefits to marketing: to the market, it presents new capabilities and opportunities. It can greatly reduce time-to-market, resulting in reduced risk as there is no need to project customer needs and market dynamics several years into the future, products which fit customer needs much more closely, products offering the price/performance of the latest technology, new products being test-marketed economically. Marketing can also change production capacity according to market demand, possibly in real time and with little impact on manufacturing. One can increase the diversity of product offerings and pursue market niches currently too small to justify due to tooling cost (including custom and semi-custom production). One can easily expand distribution and quickly enter foreign markets.

- Benefits to the consumer: the consumer can buy products which meet more closely individual needs and wants. Firstly, there is a much wider diversity of offerings to choose from. Secondly, one can buy (and even contribute to the design of) affordable products built-to-order. Furthermore, the consumer can buy products at lower prices, since the manufacturers' savings will ultimately be passed on.» (ibid., p. 16-18)

According to Todd Grimm (2004), because rapid prototyping has demonstrated a great ability to reduce time and cost in the product development cycle along with an improvement in the product quality, «the industry's attention has turned to downstream processes that promise an even greater impact on time and cost. These applications are rapid tooling and rapid manufacturing. [...] For many, it may be premature to consider either rapid tooling or rapid manufacturing. There are limitations in both that prevent widespread use. Yet, as developments unfold, both will be very powerful in the future.»

III.3. From rapid prototyping to rapid tooling and manufacturing[3]

Rapid prototyping is the term used for processes that allow to make an accurate model from a CAD file without any additional tooling or machining. However, applications of additive manufacturing techniques goes far beyond the "show and tell" function of rapid prototyping. Additive manufacturing techniques are being used to make masters for cast tooling and sometimes to create the tooling or casting patterns directly. This is having a great impact on many industries.

«Rapid prototyping was termed because of the process of this technology was designed to enhance or replace. Manufacturers and product developers used to find prototyping a complex, tedious, and expensive process that often impeded the developmental and creative phases during the introduction of a new product. Rapid prototyping was found to significantly speed up this process and thus the term was adopted. However, users and developers of this technology now realize that additive manufacturing technology can be used for much more than just prototyping.

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[3] "Rapid manufacturing" is used with different meanings by different authors. Some mean all the manufacturing processes that, by employing the technologies described in the previous chapter, allow to accelerate the whole manufacturing process (hence, including rapid prototyping). While, some only mean the production of actual goods or components. Finally, as showed in this paragraph, others mean the production of actual goods/components and tools.
"Rapid manufacturing" and "direct digital manufacturing" are synonymous: both words have to do with the usage of additive manufacturing techniques for the production of end-use products.

Significant improvements in accuracy and material properties have seen this technology catapulted into testing, tooling, manufacturing, and other realms that are outside the “prototyping” definition. However, it can also be seen that most of the other terms described above are also flawed in some way. One possibility is that many will continue to use the term rapid prototyping without specifically restricting it to the manufacture of prototypes [...].»

According to Todd Grimm (2004, p. 267), «rapid prototyping has demonstrated its ability to reduce time and cost in the development cycle while improving product quality. With this success, the industry’s attention has turned to downstream processes that promise an even greater impact on time and cost. These applications are rapid tooling and rapid manufacturing. [...]

Today, rapid tooling can encompass prototype tooling, bridge-to-production tooling, and production tooling.

Close on the heels of rapid tooling developments, another effort arose: rapid manufacturing. Applying rapid prototyping technologies to the manufacturing process would eliminate the need for tooling of any kind. In doing so, cost and time could be slashed.

For many, it may be premature to consider either rapid tooling or rapid manufacturing. There are limitations in both that prevent widespread use. Yet, as developments unfold, both will be very powerful in the future.»

Rapid manufacturing can be defined as the usage of additive manufacturing for production or manufacturing of end-use components. «Although it may seem that rapid manufacturing is a natural extension of rapid prototyping, in practice this is not usually the case. Many additional considerations and requirements come into play for production manufacturing that are not important for prototyping.» (Gibson, Rosen & Stucker, 2010, p. 363)

According to Hilton and Jacobs (2000, p. 5), «rapid manufacturing actually refers to two functions, the rapid development of “tooling” for the conventional manufacturing process (e.g., molds for injection molding) and rapid manufacturing cycle times (e.g., conformal cooling of molds to reduce the injection-molding cycle time).»

«Rapid prototyping technologies are being used to create patterns for casting processes, for urethane casting and for investment casting of metals. In the case of urethane casting, the rapid prototyping piece is the pattern for producing a silicone rubber mold that, in turn, is used to cast a number of urethane parts (typically 1-to-50). Urethane casting is an effective process when one needs to create multiple prototypes for evaluation purposes. For investment casting, the rapid prototyping piece is used in a sacrificial manner in place of the traditional casting wax pattern. It is coated with a ceramic slurry that forms a shell. The rapid prototyping piece is melted or burned out. Molten metal is poured into the shell to form the part. This process is appropriate for very low-volume production or for prototyping a higher-volume casting process because a new rapid prototyping piece is required for each casting. [...] An important, emerging application for rapid prototyping technologies is in the toolmaking (or mold and die) area. Industry is driven by the goal of reducing the time and cost of product development while assuring that the product and the process for manufacturing it are of high quality. More rapid product development means getting to the market faster, enabling a stronger market position with premium pricing, and/or improved market share. The importance of product development speed varies among market sectors. [...] Molding, casting, or stamping tools typically require several months to produce and cost tens to hundreds of thousand of dollars. Therefore, the possibility of positively impacting the time and cost of tooling production is appealing.» (ibid., p. 10-13)

«Investment casting[4] can be traced back thousands years to the ancient Egyptians and has been a staple of industry since. The basic process is quite simple: you make a pattern of what you want the end product to look like, coat it with a heat-resistant material to form a shell, melt or burn out the pattern, and pour in molten metal. [...] If you want several dozen or several hundred metal parts and you want them identical, it becomes apparent that a process to mass produce patterns is necessary. The most common process is to make a mold -also referred to as wax pattern tooling- with the desired shape, and then inject wax into it to create wax patterns. [...]

We have all heard the saying “garbage in, garbage out”. The basic premise here is, of course, that what you get out of a process is never going to be any better than what you put into it. The same holds true for investment casting: if you want to produce great-looking, accurate metal parts, then you need great-looking accurate patterns. If you want to have great-looking, accurate patterns, you need great-looking, accurate tooling. Unfortunately, if you want to have great-looking, accurate tooling, you must understand that a very large percentage of the up-front cost, in both time and money, to get a casting program rolling will be to generate the pattern tooling. [...]

[4] “Investment casting: solid metals are melted, poured into a ceramic mold, allowed to cool, solidify, and are removed from the mold.” (Hilton & Jacobs, 2000, p. 76)

So, if tooling is so costly to generate, why use investment casting? Well, there are basically four areas that must be considered:

- Quantity: if you have to produce a large number of parts, then investment casting is often a very cost-effective mass-production method. The up-front cost of the wax pattern tooling is nicely amortized. However, if only a small number of parts are needed, it generally is not good business to dump a large amount of money into tooling; your per-piece cost will probably be disproportionately high.
- Design: generally speaking, the more complex the design, the more machine and/or assembly time will be required to produce the product. [...] Investment casting can often be a cost-effective method to produce complex parts, even for a relatively low number of parts, if, of course, the up-front cost of the tooling can be offset relative to the cost of the alternative. Again, if the product is complex, the tooling will usually be complex, and expensive.
- Material: some materials are much more difficult to machine than others. [...] Again, investment casting can provide some relief, if you can design castings such that there is little finishing work required to produce the end product.
- Speed: simply put, sometimes you can live with the lead times required to develop wax patterns tooling, and other times you cannot.

Most manufacturing situations require a combination of these factors to reach a satisfactory production decision. However, sometimes, many products that are made via investment casting consist of geometric shapes that would require extensive material removal if machined. But the quantity vary. Sometimes, we need a smaller number of products, or we may need just one.» (Anderson, 2000, p. 227)

According to Hilton and Jacobs (2000, p. 257-264), «there continues to be strong driving forces in industry to compete more effectively by reducing time and cost while assuring high-quality products and services. Some of these forces which will drive technology development and implementation in the area of rapid manufacturing are as follows:

1. Reducing the time and cost of new product development;
2. Reducing the manufacturing cycle time;
3. Reducing the cost of tooling to enable smaller economical lot sizes and, thus, product customization for niche markets or mass customization.

Several industries participate in annual cycles normally associated with seasonal sales around the Christmas holiday. [...] New generation products are needed annually. The faster the product development time, the later product development can be initiated and the closer to the market entry time the customer trends can be gathered and included into product design. [...] Manufacturing cycle time relates directly to costs. By reducing the cycle time, one is able to produce more product with the same capital, as well as reducing labor costs per production unit. Injection molders compete directly on unit costs, and leading firms are very adapt at minimizing the cycle time (injection-molding machine time is often the largest component of the unit cost). They may use process simulation to assist in cycle time minimization (e.g., by performing design-of-experiment tests on the computer and thereby developing an analysis tool for process optimization). A major portion of the injection-molding cycle time is the time required to cool the part sufficiently so it can be removed from the mold without distortion. Approaches to enhancing mold cooling are included in efforts to reduce molding cycle time. One such approach is to incorporate conformal cooling channels into the mold. We predict substantial use of process simulation and conformal cooling to reduce injection-molding cycle time.

A major component of the cost of injection-molded parts is that for tool amortization. Obviously, the cost per unit goes up as the number of units to be produced in a tool decreases. This analysis has set minimum limits on the economical use of injection molding as well as other near-net-shape processes such as die casting. For smaller volumes, manufacturers have typically selected forming operations with lower tool cost and higher labor or other costs (e.g., machine capital). If tooling costs can be reduced, the equation shifts the minimum economic lot size for molding processes. This enables more customization for niche markets, shorter runs (and more product refreshment cycles), more product models, and so forth. Although reducing tooling costs is always of strong importance, the specific possibility of lower-cost tooling for shorter runs is technologically feasible. One is able to trade-off tool performance against costs. Fortunately, it is likely that these lower-cost, lower-volume tools will also be able to be produced in less time. We anticipate an accelerating trend toward the development and use of lower-cost/shorter-life tools.

In 1993, we suggested a conceptual model as the target to strive toward. The model "Mold-less Forming: An Advanced Manufacturing Process" was presented at an executive workshop with the same name, sponsored by Arthur D. Little, Inc. The idea was to envision designing products on a computer-aided design (CAD) system and producing them directly on some computer-controlled equipment without the use of any molds or special purpose fixtures. The team of industry leaders pondered the impact of such capabilities on their businesses. Today, we are getting a bit closer to achieving this paradigm, although we still have a long way to go. The concept is helpful for guiding the direction of research even while its full realization still eludes us.

An intermediate conceptual model "the disposal tool", is closer to reality. Imagine that the time and cost to produce tooling can be dramatically decreased. Then, one can consider use of the tooling to produce a lot of product and disposal of the tooling at the completion of the lot production. At another time, one could produce new tooling to produce more parts, and at that time, one might choose to update the product design at nominal cost. This approach would enable the user to avoid issues concerning different revisions of a product and concern about whether the tooling revision was consistent with the product revision to be produced.

We are very close to achieving this intermediate paradigm today. The direct use of stereolithography (SLA) produced mold cavity inserts in conjunction with standard molds frames has enabled the molding of severely limited (typically 5-50 parts) production runs. The run capability of the plastic molds is impacted by the material to be molded (filled and composite materials typically decrease mold life) and by the molding conditions (pressure and temperature). It is reasonable to predict continuing improvement in stereolithography material as well as modification of other rapid prototyping techniques to more closely achieve disposable tooling. On the other hand, some firms are working to reduce the severity of the molding conditions so that current SL mold inserts will be able to produce longer runs. [...]

More broadly, the desire on the part of product-development teams to have real prototypes (i.e. prototypes made from the production material by the production process) will drive continuing improvement of rapid tooling (or prototype tooling) technologies.

This desire is not frivolous; rather, it is based on the goal of easing the transition from design to manufacturing by verifying early in the product-development process that the parts can be produced by the anticipated manufacturing process. Further, this enables the development team to judge the tolerance capabilities of the fabrication process as well as to identify aspects of the design that may be difficult to produce. They can then make modifications to the product design or the processing to achieve robust manufacturing (the ability to produce parts within the required tolerances with a high degree of certainty). Robust manufacturing avoids high initial reject rates as well as early field problems. This conceptual approach to reducing quality problems is formalized through the use of statistics by setting allowable failure rates and designing the combination of the part and manufacturing process to assure that they are achieved. [...]

We believe that the development of computer software tools to support product development will continue and result in decreased need for paper or prototypes. Such CAD/CAE/CAM tools will continue to become more accurate and efficient as the power of desktop computers continues to increase. The result will be very fast responses for very complex calculations (e.g., simulation of the coupled fluid flow and heat transfer during the filling of a mold). The approach to product development will increasingly include CAD design, CAE analysis of performance, simulation (and optimization) of the manufacturing processes, and CAM, all using a single database and closely coupled. A bit further in the future, computing systems will be fast enough to enable real-time intelligent manufacturing process control (i.e., the process parameters will be monitored and compared to the optimal values as determined by the earlier analysis). The process will then be continuously adjusted to minimized the difference between actual conditions and optimal conditions. Alternatively, the processes may be managed by neural networks that enable learning and process improvement over time. Eventually, integrated computer-aided design, simulation, and control will enable combined optimization of product design and processing conditions, followed by actual processing at these conditions. The result should include product performance improvement, product-manufacturing cost reduction, low (or zero) manufacturing reject rate, and high product quality.

One specific area in which computer-aided process analysis will support process improvement is mold temperature control. One generally wants the mold cavity active surface to maintain nearly uniform temperature, independent of the particular process (injection molding, investment casting, etc.) so as to minimize part distortion and residual stress buildup during forming. Further, rapid transfer of heat from the part causes rapid part cooling and allows shorter processing cycles, saving capital and variable costs. Computer-based heat-transfer analyses can provide guidance on mold surface temperatures in terms of processing conditions and cooling systems. This information can guide the tool design for the location of cooling channels and the coolant flow rates to set for each channel. [...] The use of some advanced mold-making processes in conjunction with advanced analysis tools enables the creation of molds optimized to cause uniform part surface temperature during the processing cycle and rapid part cooling to reduce the cycle time.

Ideally, molds have active surfaces which are hard and abrasion resistant as well as able to withstand high temperatures and dramatic temperature cycles (just watch a die-casting operation in which molten metal and cold water sequentially contact the mold surface). On the other hand, the interior mold material should have high thermal conductivity to transfer the heat from the part and good fracture toughness to withstand the fatigue cycles to which it is subjected. This is traditionally accomplished through heat treatments and/or surface coatings. An advanced approach to achieving improved tools is to create “gradient” materials, that is, to somehow form a part with varying material composition (e.g., with a hard ceramic or cermet mold surface and a tough metal interior and a continuous transition between the ceramic or cermet and the metal composition). Gradient materials have been developed and formed by various deposition processes. Japan has been a leader in this area. The challenge that several rapid prototyping technology developers are taking on is to produce gradient materials within rapid prototyping environment and, therefore, to enable the production of rapid tooling with gradient material compositions. [...]

Although these various technology advances may occur at different rates and having different degrees of success, we can predict with a high level of certainty the overall trend to increased use of near-net-shape-forming processes and decreased use of machining. Net shape processes are more energy efficient and result in less material scrap. They can also be faster and less costly than the machining processes they substitute. Net shape process utilization is limited by the cost and fabrication time for the associated tooling. [...] The tooling will be further enhanced to contribute to process optimization through such factors as conformal cooling. The net shape (molding) processes themselves will also become more efficient through the use of computer-aided tools for process optimization, including process modeling and potentially neural-net or related techniques for continually learning and process fine-tuning.»

«Many people have described this technology as revolutionizing product development and manufacturing. Some have even gone on to say that manufacturing, as we know it today, may not exist if we follow additive manufacturing to its ultimate conclusion. We might, therefore, like to ask "why is this the case?" What is about additive manufacturing that enthuses and inspires some to make these kinds of statements?

First, let's consider the "rapid" character of this technology. The speed advantage is not just in terms of the time it takes to build parts. The speeding up for the whole product development process relies much on the fact that we are using computers throughout. Since 3D CAD is being used as the starting point and the transfer to additive manufacturing is relatively seamless, there is much less concern over data conversion or interpretation of the design intent. Just as 3D CAD is becoming What You See Is What You Get (WYSWYG), so it is the same with additive manufacturing and we might just as easily say that What You See Is What You Build (WYSIWYB).

The seamlessness can also be seen in terms of the reduction in process steps. Regardless of the complexity of parts to be built, building within an additive manufacturing machine is generally performed in a single step. Most other manufacturing process would require multiple and iterative stages to be carried out. As you include more features in a design, the number of these stages may increase dramatically. Even a relatively simple change in the design may result in a significant increase in the time required to build using conventional methods. Additive manufacturing can, therefore, be seen as a way to more effectively predict the amount of time to fabricate models, regardless of what changes may be implemented during this formative stage of the product development.

Similarly, the number of processes and resources required can be significantly reduced when using additive manufacturing. If a skilled craftsman was requested to build a prototype according to a set of CAD drawings, he may find that he must manufacture the part in a number of stages. This may be because he must employ a variety of construction methods, ranging from hand carving, through molding and forming techniques, to CNC machining. Hand carving and similar operations are tedious, difficult, and prone to error. Molding technology can be messy and obviously requires careful planning and a sequential approach that may also require construction of fixtures before the part itself can be made. All this presupposes that these technologies are within the repertoire of the craftsman and readily available.

Additive manufacturing can be used to remove or at least simplify many of these multi-stage processes. With the addition of some supporting technologies like silicon-rubber molding, drills, polishers, grinders, etc. it can be possible to manufacture a vast range of different parts with different characteristics. Workshops which adopt additive manufacturing technology can be much cleaner, more streamlined and more versatile than before.» (Gibson, Rosen & Stucker, 2010, p. 8-9)

Benefits or rapid manufacturing

Tuck, Hague and Burns (2007) look at the supply chain of a manufacturing company as a whole and identify the benefits that emerge along it. They define the supply chain as «the network of suppliers that are involved in providing products or services. This may include raw material suppliers, sub-assembly, information systems, logistics, retailers and finally the customer.»

In the development of supply chain practices, they identify the following ones:

- Lean;
- Agile;
- Mass customization.

According to the authors, these concepts have been used as basis for arguments and they now become relevant with the discussion of rapid prototyping.

III.4. Additive manufacturing as a challenge to conventional paradigms

The lean paradigm

«The lean paradigm of supply chain management encompasses the idea of reducing waste throughout the supply chain.» They summarize the lean paradigm into eight characteristics:

- «Perfection in delivering value to customers;
- Produce only when necessary and concentrate on the creation of value;
- Eliminate waste in all operational processes, both internal and external;
- All members of the supply chain must be able to appropriate value;
- Trusting relationships are necessary rather than adversarial ones;
- Co-operate with suppliers to create lean and demand driven logistics processes;
- Reduce the number of suppliers to those preferred for long-term relationships;
- Create a supplier network that understands the waste reducing principles of the lean paradigm.»

The authors take these points in turn and identify the effect of rapid manufacturing.

- «Produce only when necessary, through just-in-time: the application of rapid manufacturing techniques will hold a number of advantages for just-in-time manufacture, which include:
  - Dematerialized supply chain: the overriding requirement for rapid manufacturing is to have suitable 3D CAD data from which to produce the part or product. This will have consequences upon the supply chain as it will be said that the supply chain is becoming dematerialized.
  - True just-in-time: as the rapid manufacturing machine require only 3D CAD data and raw material in order to produce the part, the application of rapid manufacturing in the manufacturing environment will result in a reduction of material distribution and stock holding or warehousing costs for work in progress. The ability to amalgamate rapid manufacturing with Internet technology and other manufacturing systems (MRP, etc.) will lead to just-in-time manufacture at the factory, rather than the traditional concept of just-in-time to the firm;
  - Reduced set-up, change over time and number of assemblies: it must be stressed that the production of parts through rapid manufacturing will change the manufacturing paradigm from that of skilled labor operating machinery and forming a large portion of part cost, to one where the burden of cost is transferred to the technology or specifically the rapid manufacturing and

materials. A further driver for the reduction of costs is in the product design. For example, rapid manufacturing processes may make traditional designs obsolete, by reducing the need for assemblies and thus the production processes may provide cost savings for parts and components. [...]

- Elimination of waste: a principle driver for the lean paradigm is to reduce waste wherever possible in the supply chain. The effect that rapid manufacturing will have on this area will be especially significant, if arguments about the digital supply chain are taken into account. Integration with Internet technology will result in the fast exchange of data between designers and manufacturers, where in the case of rapid manufacturing, this data can be sent directly to the rapid manufacturing system for build. [...] The factors discussed above will result in the elimination of waste in terms of: material, time, costs and distribution.»

The agile paradigm

According to Tuck, Hague and Burns, «agility focuses on lead time compression, rather than the elimination of waste. The use of flexible production methods allows fast reconfiguration of processes to cope with consumer demand. For this reason, the agile paradigm is suited to products that have a short life cycle, such as fashionable goods, compared with lean's focus on commodity production. Therefore, the market order winner for agile supply chains is no longer cost but availability. [...] It could be said that the advent of the agile supply chain has been necessary because of the increased demands of the customer being placed on the produces. The sophistication of customer desires and tastes has led to goods becoming increasingly fashion oriented with styles and colors becoming a market order winner rather than production function. One methodology for enabling this "value-adding" activity has been the concept of mass customization. The ability to define a customer's needs and wants relies on the availability of suitable information on customer preferences and the ability within the agile organization to provide these services in a timely manner. Thus, the emphasis on production has changed from one based on costs of production to knowledge and information availability and hence, the skills and knowledge of the organization are now paramount.»

The authors also argue: «The agile supply chain works better for volatile products, such as those that are fashionable or have a short product life cycle. The advent or rapid manufacturing will mean that lean production in a responsive manner will become a reality without the need for a “leagile” concept.

In effect rapid manufacturing would become the de-coupling point with orders only pulled off at the request of the customer. With this concept, there would be no stock outs, as all products can be produced to order, plus the threat of obsolescent stock would be negated as the only stock necessary to hold would be raw material and design data. [...]

In summary, rapid manufacturing will offer:

- Truly “leagile” supply chain;
- Low cost products with fast re-configurability and fast response;
- Reduction in stock levels;
- Reduced waste;
- Increased value;
- Reduced logistics cost;
- Reduction in part count;
- Increased flexibility.

[...] The application of rapid manufacturing for suitable parts and components especially those that are low volume but high value can result in a significant reduction in stock costs and inventory levels. The ability to produce components to order is an inherent quality associated with rapid manufacturing. As such the parts or products required can be stored as low value raw materials and the stock value is reduced to that of the raw material and any obsolescence risks associated with the part or product design are eliminated.

As rapid manufacturing has a low labor requirement, implications on the manufacturing location will occur. The ability to produce rapid manufacturing parts locally will also have implications on the current globalization culture of manufacturing business. [...] The overriding cost for rapid manufacturing production is not labor, but the machines and materials necessary for production. [...] For this reason, the migration of manufacturing operations to low-wage countries can be challenged especially for low volume and customized products and with the advent of more capable machinery, high volume products in the long term.»

Mass customization

«All your, mass customization transforms manufacturing in the 21st century» wrote The Economist in a 2001 feature article.

According to Fralix (2001): «With the advent of the industrial revolution and interchangeable parts, manufacturing moved from the craft era to the mass production era. Today there is a new era emerging and it is called Mass Customization. Mass Customization takes the best of the craft era, when customers had products built to their specifications but only the elite could afford them, with the best of the mass production era, when everybody could get the same product because it was affordable. This presentation will highlight the development of Mass Customization and how the sewn products industry is positioned to capitalize on it. As progressive companies trade their traditional production concepts and practices for powerful mass customization techniques, this presentation will provide insight into the integration of information technology, mechanization, and team-based flexible manufacturing.»

«Enterprises in all branches of industry are being required to become more customer centric, yet, at the same time, increasing competitive pressure dictates that costs must also continue to decrease. Mass customization and personalization are strategies developed to address this challenge by producing goods and services meeting individual customer's needs with near mass production efficiency.» (Tseng & Piller, 2003)

«Prior to the industrial revolution, manufacturing was considered a craft. Products were typically custom made to meet the needs of a particular individual. No two products were exactly alike and parts from one product could not necessarily be interchanged with the similar parts on another product. Since products tended to be relatively expensive, access was limited primarily to the upper class or aristocracy. With the advent of the industrial revolution and the concept of interchangeable parts, like products began to be produced in large quantities and were made available to the middle class. Because of the large production quantities of like products, the costs were low enough that they became affordable for most people.

Mass customization has emerged as a practice that combines the best of the craft era with the best of the mass production era. Not to be confused with custom-made, mass customized products may still be manufactured is relatively large quantities; however, each item might be slightly different based on the needs and desires of the individual end customer. [...]

The ability for manufacturers to offer mass customization is limited by their ability to get consumer information to the "workplace" doing the customization. Mass customization is also limited by the extent to which production workers have been cross-trained and empowered to accept responsibility for the manufacturing and "customization" process, so that they can accurately respond to those needs. In addition, manufacturers are constrained by the lack of available technology that can be reconfigured quickly, easily, and cost effectively to meet customer needs.

During the era of mass customization, product development cycles will be extremely short and product life cycles will also be extremely short relative to the era of mass production. Large homogeneous markets will be replaced by heterogeneous niches and with fragmented demand. Large numbers of similar products will continue to be manufactured; however, each consumer will be able to alter products based on their individual needs and the capabilities of the producer.

On the other hand, mass customization, does not mean that everything about a product is customizable. This may have been true in the craft era, and may still be true for some products, but it is not true for mass customization. [...] Customizable features must include only those things the customer determines are important and the customized products should not necessarily cost any more, other than the initial investment in the technology required to provide those features.

Information technology and automation play a key role in mass customization in that they create the linkage between a customer's preferences and the ability of a manufacturing team to construct products based on those preferences. Customization will be limited by the availability of technology to make the customization seamless. It will also be limited by the ability of business systems to provide information about products features and customer requirements to the individuals who are able to respond to those requests. It is expected that the order-to-delivery process will be less than one week, including the manufacturing.» (Fralix, 2001, p. 3-4)

According to Tseng and Piller (2003, p. 5-6): «There is a wide variety of understandings and meetings of mass customization and personalization: "Extant literature has not established good conceptual boundaries for mass customization" state Duray et al. after literature review. The same is true for managers and practitioners who use the term mass customization for many forms of being more customers centric. Davis, who coined the phrase in 1987, refers to mass customization when "the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously they can be treated individually as in the customized markets of pre-industrial economies." In order to address the implementation issues of mass customization, a working definition of mass customization was adopted as "the technologies and systems to deliver goods and services that meet individual customers' needs with near mass production efficiency." This definition implies that the goal is to detect customers needs first and then to fulfill these needs with efficiency that almost equals that of mass production. Often this definition is supplemented by the requirement that the individualized goods do not carry the price premiums connected traditionally with (craft) customization. However, mass customization practice shows that consumers are frequently willing to pay a price premium for customization to reflect the added value of customer satisfaction due to individualized solutions, i.e. the increment of utility customers gain from a product that better fits to their needs than the best standard product attainable. We consider the value of a solution for the individual customer as the defining element of mass customization. A customer centric enterprise recognizes that customers have alternatives of choice which are reflected through their purchase decisions: customers can either choose mass customized goods which provide better fit, compromise and buy a standard product of lesser fit (and price), or purchase a truly customized product with excess features but also at a higher price. Thus, value reflects the price customers are willing to pay for the increase in satisfaction resulting from the better fit of a (customized) solution for their requirements. Mass customization is only applicable to those products for which the value of customization, to the extent that customers are willing to pay for it, exceeds the cost of customizing.

The competitive advantage of mass customization is based on combining the efficiency of mass production with the differentiation possibilities of customization. Mass customization is performed on four levels. While the differentiation level of mass customization is based on on the additional utility customers gain from a product or service that corresponds better to their needs, the cost level demands that this can be done at total costs that will not lead to such a price increase that the customization process implies a switch of market segments. The information collected in the course of individualization serves to build up a lasting individual relationship with each customer and, thus, to increase customer loyalty (relationship level). While the first three levels have a customer centric perspective, a fourth level takes an internal view and relates to the fulfillment system of a mass customizing company: mass customization operations are performed in a fixed solution space that represents "the pre-existing capability and degrees of freedom built into a given manufacturer's production system." Correspondingly, a successful mass customization system is characterized by stable but still flexible and responsive processes that provide a dynamic flow of products. While a traditional (craft) customizer re-invents not only its products but also its processes for each individual customer, a mass customizer uses stable processes to deliver high variety goods. A main enabler of stable processes is to modularize goods and services. This provides the capability to efficiently deliver individual modules of customer value within the structure of the modular architecture. Setting the solution space becomes one of the foremost competitive challenges of a mass customization company, as this space determines what universe of benefits an offer is intended to provide to customers, and then within that universe what specific permutations of functionality can be provided.»

Moreover, Tseng and Piller (2003, p. 7) claims: «Personalization must not be mixed up with customization. While customization relates to changing, assembling or modifying product or service components according to customers' needs and desires, personalization involves intense communication and interaction between two parties, namely customer and supplier. Personalization in general is about selecting or filtering information objects for an individual by using information about the individual (the customer profile) and then negotiating the selection with the individual. Thus, personalization compares strongly to recommendation: from a large set of possibilities, customer specific recommendations are selected. From a technical point of view, automatic personalization or recommendation mean matching meta-information of products or information objects against meta-information of customers (stored in the customer profile). Personalization is increasingly considered to be an important ingredient of web applications. In most cases personalization techniques are used for tailoring information services to personal user needs. In marketing, personalization supports one-to-one marketing which should increase the customer share over a lifetime.»

Tuck, Hague and Burns define customization as «to make or change something according to the buyer's or user's need". The concept of customization created a new paradigm in manufacturing that the authors describe as follows: "the impact of mass customization on the production environment has been profound. [...] Mass customization could be thought of as a key driver for the agile supply chain paradigm's prominence in manufacturing business thinking worldwide. The use of mass customization can be seen in many of today's products.» In this sense, rapid manufacturing can offer true core customization by allowing a certain degree of involvement to the customer.

Hague, Campbell and Dickens (2003) identify the following scenarios:

1. «Restrict the design input of the user to selection from a predetermined set of alternatives. [...] Using parametric CAD and assembly modeling is possible to create applications that are existing CAD models to create new product designs. The models are created by experiencing

designers and satisfy all the constraints of rapid manufacturing. Each model could represent a component within a particular product. An application can then be written that will allow the customer to select component options they wish to include in their “new design”. Furthermore, some of the dimensions of the components can be varied within set limits to modify the design to meet customer requirements. This makes use of knowledge relationships within the CAD model(s).»

2. «Use an innovative user interface that requires little training and no construction strategy. [...] It may be feasible to give customers access to three-dimensional design through innovative interfaces where little or no training is required. [...] Such methods have been designed to be intuitive to the user and reduces any computational or engineering skills necessary to operate the system to an absolute minimum. This approach ensures that not only are new users “up and running” and therefore productive within a very short period of time but they also feel far less inhibited and constrained by the technology. It can be easily envisaged that a customer could be allowed to generate new shapes, or at least modify existing designs produced using this technology.»
3. «Enable the customer to work as part of the design team, e.g. in real-time collaboration with a designer. [...] The third technique for involving customers in the design process is through partnership with a designer. This can be readily done when the customer is brought into direct contact with the designer, e.g. in a design studio. However, if the goal is to allow the customer to stay at home then an alternative strategy must be used. Using the Internet, it is possible to connect the customer and designer using virtual conferencing, real-time imaging software and collaborative CAD software. However, designers are not always available and international time zones can cause serious difficulties. An alternative is to couple the user with a knowledge-based system that simulate an experiences designer. [...]»

«Bringing the customer further into the design process is a desirable part of rapid product development that could lead to truly customized products. The unique characteristics or rapid manufacturing make it particularly suitable for this strategy. A number of alternative techniques offer this capability and the optimum solution will vary from one product to the next. Indeed, the optimum solution may well be a combination of those discussed.» (Hague, Campbell & Dickens, 2003)

«The geography of supply chains will change. An engineer working in the middle of a desert who finds he lacks a certain tool no longer has to have it delivered from the nearest city. He can simply download the design and print it. The days when projects ground to a halt for want of a piece of kit, or when customers complained that they could no longer find spare parts for things they had bought, will one day seem quaint.» (The Economist, 2012) The revolution will affect not only how things are made, but where. Off-shoring production is moving back to rich countries not because Chinese wages are rising, but because companies now want to be closer to their customers so that they can respond more quickly to changes in demand. And some products are so sophisticated that it helps to have the people who design them and the people who make them in the same place.

«Advantages of additive manufacturing lie in the ability to produce highly complex parts that require no tooling and thus reduce the costs of manufacture, especially for low volumes. As high volumes do not need to be manufactured to offset the cost of tooling then the possibilities for affordable, highly complex, custom parts becomes apparent. In theory, each part that is produced could be a custom part.» (Tuck, Hague & Burns, 2007)

Chapter IV

Additive manufacturing in the biomedical industry

The biomedical industry, where customization becomes crucial, is considered one of the key industries driving innovation in additive manufacturing. According to Gibson, Rosen and Stucker (2010, p. 386), «additive manufacturing models have been used for medical applications almost from the very start, when this technology was first commercialized. Additive manufacturing could not have existed before 3D CAD since the technology is digitally driven. Computerized tomography was also a technology that developed alongside 3D representation techniques. [...] Computerized tomography is an X-ray based technique that moves the sensors in 3D spaces relative to the X-ray source so that a correlation can be made between the position and the absorption profile. By combining multiple images in this way, a 3D image can be built up. [...] While originally used just for imaging and diagnostic purposes, 3D medical imaging data quickly found its way into CAD/CAM systems, with additive manufacturing technology being the most effective means of realizing these models due to the complex, organic nature of the inputs forms. Medical data generated from patients is essentially unique to an individual. The automated and de-skilled form of production that additive manufacturing makes it an obvious route for generating products from patient data.» (Gibson, Rosen & Stucker, 2010, p. 386-387)

This chapter discusses the use of additive manufacturing for medical applications which has consistently been one of the key industries driving innovation in additive manufacturing. The main benefit is related to the «ability to include patient-specific data from medical sources so that customized solutions to medical problems can be found.» (Gibson, Rosen & Tucker, 2010, p. 386)

«There is an excellent opportunity to use additive manufacturing in making models based on an individual person's medical data. The data can be incorporated into the system in a variety of different ways. Such data is based on 3D scanning obtained from systems like Computerized Tomography (CT), Magnetic Resonance Imaging (MRI), 3D ultrasound, etc. This data often needs considerable processing to extract the relevant sections before it can be built as a model or further incorporated into a product design. There are only a handful of software systems that can process the medical data in a suitable way, and a range of applications is starting to emerge.» (Ibid., p. 56-57)

«There is no question that we will see increasing utilization of additive manufacturing techniques is production manufacturing. In the near-term, it is likely that new applications will continue to take advantage of the shape complexity capabilities for economical low production volume manufacturing. Longer time-frames will see emergence of applications that take advantage of functional complexity capabilities (e.g., mechanisms, embedded components) and material complexities. [...]

In summary, the capability to process material in an additive manner will drastically change some industries and produce new devices that could not be manufactures using conventional techniques. This will have a lasting and profound impact upon the way the products are manufactures and distributed, and thus on society as a whole.» (Gibson, Rosen & Stucker, 2010, p. 382-382)

In the following paragraphs, I will show how rapid prototyping, rapid tooling and rapid manufacturing can affect the biomedical industry and I will also present the limitations that come with this technology.

I will go into two examples that, according to some authors, fit the mass customization paradigm: those are the hearing aid shells and the teeth aligners.

I will finally present a groundbreaking topic, that is the so-called "biofabrication".

IV.1. Rapid prototyping in the biomedical industry

Chua, Leong and Lim (2003, p. 327-335) identify the examples of how additive manufacturing techniques can play a valuable role in the biomedical industry:

- Operation planning for cancerous brain tumor surgery: «In one case, a patient had a cancerous bone tumor in his temple area and because of that the surgeon would have to access the growth via the front through the right eye socket. The operation was highly dangerous as damage to the brain was likely which would result in the impairment of some motor functions. [...] Before proceeding with the surgery, the surgeon wanted another examination of the tumor location, but this time using a three-dimensional plastic replica of the patient's skull.» (Ibid.) The plastic model used by the surgeon was fabricated by the SLA from a series of scans of the patient's skull.

- Planning reconstructive surgery: due to a serious bone fracture on the upper and lateral orbital rim in the skull, a patient might need surgery in order to transplant an artificial bone instead of, e.g. a shoulder bone, that might dissolve right after the surgery. «The conventional procedure of such a surgery would be for surgeons to manually carve the transplanted bones during the operation until it fitted properly. This operation would have required a lot of time, due to the difficulty in carving bone, let alone during the surgery.» (Ibid.) As a result, a SLA prototype of the patient's skull allowed to make an artificial bone that fitted the hole caused by the dissolution, reducing the time required and improving its accuracy.
- Cranofacial reconstructive surgery planning: «Restoration of facial anatomy is required in cases of congenital abnormalities, trauma or post cancer reconstruction. In one case, the patient had a deformed jaw by birth, and a surgical operation was necessary to amputate the shorter side of the jaw and change its position. the difficult part of the operation was the evasion of the nerve canal that runs inside the jawbone. Such as operation was impossible in the conventional procedure because there was no way to visualize the inner nerve canal. Using a CAD model reconstruction from the CT images, it clearly showed the position of the canal and simulation of the amputating process on workstations was a good support for surgeons to determine the actual amputation line. Furthermore, the use of a resin prototype of the jawbone allowed the visualization of the internal nerve canal. The semi-transparent prototype facilitated the determination of the amputation line and enabled an efficient surgery simulation with an actual tool.» (Ibid.)
- Biopsy needle housing: «Biomedical applications are extended beyond design and planning purposes. The prototypes can serve as a master for tooling such as a urethane mold.» (Ibid.) Designers of medical products companies use additive manufacturing techniques «to create master models from which they develop metal castings. The masters also serve as a basis for multiple sub-tooling processes. [...] The prototypes are then delivered to customer focus groups and medical conferences for professional feedback. Design changes are then incorporated into the master CAD database. Once the design is finalized, the master database is used to drive the machining of the part.» (Ibid.) Using this method, medical products companies make models of biopsy needle housing and many other products.
- Knee implants: «Suppliers of orthopedic implants have integrated CAD and rapid prototyping into their design environment, using it to analyze the potential fit of implants in a specific patient and

then modifying the implant design accurately. [...] The prototypes are also used as a master for casting patterns to launch a product or to do clinical releases of a product.» (Ibid.)

- Scaffolds for tissue engineering[5]
- Customized tracheobronchial stents: «Stents for maintaining the potency of the respiratory channel has been investigated for production using rapid prototyping techniques. Customization of these stents can be carried out to take into account compressive resistance with respect to stent wall thickness, as well as unique anatomical considerations.» (Ibid.)
- Inter-vertebral spacers: «Human spinal vertebras can disintegrate due to conditions such as osteoporosis or extreme forces acting on the spine. In the management of such situations, a spacer is usually required a part of the spinal fixation process. Rapid prototyping has been investigated for the production of such spacers as it is an ideal process to fabricate 3D structures with good interconnecting pores for the promotion of tissue in-growth. Other considerations for producing such as implant are that the material is biocompatible, and that the mechanical compressive strength of the spacer is able to withstand spinal load.» (Ibid.)
- Cranium implant: «A patient suffered from a large frontal cranium defect after complications from a previous meningioma tumor surgery. This left the patient with a missing cranial section, which caused the geometry of the head to look deformed. Conventionally, a titanium-mesh plate would be hand-formed during the operation by the surgeon. This often resulted in inaccuracies and time spent for trial and error. Using rapid prototyping, standard preparation of the patient were made and a computed tomography scan (CT) of the affected area and surrounding regions was taken during the pre-operation stage. The three-dimensional CT data file was transferred to a CAD system and the missing section of the cranium topography was generated. After some software repair and cleaning up were carried out on the newly generated section, an inverted mold was produced on CAD. This three-dimensional solid model of the mold was saved in STL format and transferred to the rapid prototyping system, such as the SLS, for building the mold. The SLS mold was produced and used to mechanically press the titanium-mesh plate to the required three-dimensional profile of the missing cranium section. During the operation, the surgeon cleared the scalp tissue of the defect area and fixated the perfectly pre-profiled plate onto the cranium using self-tapping screws. The scalp tissue was then replaced and sutured. At post-operation recovery, results observed showed improved surgical results, reduced operation time and a reduce probability of complications.» (Ibid.)

[5] See next paragraph

IV.2. Rapid tooling in the biomedical industry

Rapid prototyping is the term used for processes that allow to make an accurate model from a CAD file without any additional tooling or machining. However, applications of additive manufacturing techniques goes far beyond the “show and tell” function of rapid prototyping. Additive manufacturing techniques are being used to make masters for cast tooling and sometimes to create the tooling or casting patterns directly. This is having a great impact on many industries, including the biomedical industry.

«If tooling were substantially less expensive and faster, or if there were a way to produce accurate patterns quickly and cost-effectively without tooling, what would be the impact on industry?» (Anderson, 2000, p. 228) According to Anderson:

- «Low-quantity casting runs could be more readily utilized for custom implants, regional products, and clinical studies.
- Lower overall casting costs could increase profit margins, reduce the cost of the end product to the customer, or both.
- Functional first-article castings could be obtained much faster for debugging finishing operations and/or to speed up product launches.»

The first alternative, according to Anderson, is: «If we can make prototype parts with an SLA machine, why can’t we make wax pattern tooling?» In other words, a wax pattern can be designed on a CAD system and built with a SLA.

However, some problems might emerge with the approach of building wax pattern tooling on SLA: «The cured photopolymer was brittle and several three-piece tools ended up being “too-many-pieces-to-count” tools during the wax-injection process, and there was some “stair-stepping” on angled surfaces that was difficult to smooth out in the internal areas. We started looking at other possibilities and eventually reached the conclusion that we would be better off if we made an SL model, smoothed out the surfaces, and formed a material around it to produce the tooling. [...] We used this method for a few years for product launches and products where we would run several wax patterns. [...]»

The second alternative to conventional tooling, according to Anderson, is: "No tooling at all!" This is called "direct pattern generation" that consists of an additive manufacturing system «that produces parts (patterns) that can be used directly in the investment-casting process, being burned out of the ceramic shell, completely bypassing the need for wax pattern tooling.»

This has several advantages: «the most obvious, of course, being the fact that you will not incur any expenses related to tooling. Another advantage is the ability to tackle projects that are cost-prohibitive when considering traditional methods."

According to Anderson, there are basically two categories where "direct pattern generation" might be used:

- In the clinical product launches (the "hip stem" case study, according to Anderson) because of:
  - «Reduction cost;
  - Reduced lead time for tooling;
  - Changes from information obtained during the clinical period would probably result in modifications to the product.» (Ibid., p. 230)
- In custom implants (the "knee implant" case study, according to Anderson) because: «The major goal is to reduce both cost and time to a level where a custom knee implant can be generated cost-effectively and without negatively impacting other projects. If the only option were to create traditional machined wax pattern tooling, then the cost of the project would be prohibitive, as the level of complexity of the impact design would necessitate a four-piece wax pattern tool. [...] Direct pattern generation seems to be tailor-made for this type of scenario. There are no costs or lead times associated with generating wax pattern tooling and no machining is required to produce wax patterns or, even more costly, the implant itself. Also, in the event of a late design change, you can react more quickly than with conventional methods.» (Ibid., p. 235-236)

IV.3. Rapid manufacturing in the biomedical industry

Gibson, Rosen and Stucker identify the following categories of medical applications that have been involved in the additive manufacturing technology advances:

- Surgical and diagnostic aids: this is considered probably the first medical application of additive manufacturing. «Surgeons are often considered to be as much artist as they are technically proficient. Since many of their tasks involve working inside human bodies, much of their operating procedure is carried out using the sense of touch almost as much as by vision. As such, models that they can both see from any angle and feel with their hands are very useful to them. Surgeons work in teams with support from doctors and nurses during operations and from medical technicians prior to those operations. They use models in order to understand the complex surgical procedures for themselves as well as to communicate with others in the team. Complex surgical procedures also require patient understanding and compliance and so the surgeon can use these models to assist in this process too. Additive manufacturing models have been known to help reduce time in surgery (by having the model on hand to refer to within the operating theater). Machine vendors have, therefore, developed a range of materials that can allow sterilization of parts so that models can be brought inside the operating theater without contamination. [...]» (Gibson, Rosen & Stucker, 2010, p. 387-388)

- Prosthetics development: «Initially, computerized tomography generated 3D models combined with the low resolution of earlier additive manufacturing technology to create models that may have looked anatomically correct, but that were perhaps not very accurate when compared with the actual patient. As the technology improved in both areas, models have become more precise and it is now possible to use them in combination for fabrication of close-fitting prosthetic devices. [...] Support from CAD software can add to the process of model development by including fixtures for orientation, tooling guidance, and for screwing into bones. [...] Alternatively, many additive manufacturing processes can create parts that can be used as casting patterns or reference patterns for other manufacturing processes. Many prosthetics are comprised of components that have a range of sizes to fit a standard population distribution. However, this means that precise fitting is often not possible and so the patient may still experience some post-operative difficulties. These difficulties can further result in additional requirements for rehabilitation or even corrective surgery, thus adding to the cost of the entire treatment. Greater comfort and performance can be achieved where some of the components are customized, based on actual patient data. [...]» (Gibson, Rosen & Tucker, 2010, p. 389)
- Manufacturing of medically related products: «Some customized prosthetics became mainstream product manufacture and some of those are in-the-ear hearing aids and the orthodontic aligners. “Both of these applications involve taking precise data from an individual and applying this to the basic generic design of a product. The patient data is generated by a medical specialist who is familiar with the procedure and who is able to determine whether the treatment will be beneficial. Specialized software is used that allows the patient dat to be manipulated and incorporated into the medical device. One key success for customized prosthetics is the ability to perform the design process quickly and easily. The production process often involves additive manufacturing

plus numerous other conventional manufacturing tasks, and in some cases the parts may even be more expensive to produce; but the product will perform more effectively and can sell at a premium price because it has components which suit a specific user. This added value can make the prosthetic less intrusive and more comfortable for the user. [...]» (Gibson, Rosen & Stucker, 2010, p. 390)

- Tissue engineering and organ printing[6].

A case study: teeth aligners

The production of teeth aligners is a great example of how companies can benefit from the shape complexity capability of additive manufacturing techniques to economically achieve mass customization.

«Align Technology, in Santa Clara, California, is in the business of providing orthodontic treatment devices. Their Invisalign treatments are essentially clear braces, called aligners, that are worn on the teeth. Every one or two weeks, the orthodontic patient receives a new set aligners that are intended to continue moving their teeth. That is, every one or two weeks, new aligners that have slightly different shapes are fabricated and shipped to the patient's orthodontist for fitting. Over the total treatment time (several months to a year typically), the aligners cause the patient's teeth to move from their initial position to the position desired by the orthodontist. If both the upper and lower teeth must be adjusted for six months, then twenty-six different aligners are needed for one patient, assuming that aligners are shipped every two weeks.

The need for many different geometries in a short period of time requires a mass customization approach to aligner production. Align's manufacturing process has been extensively engineered.

I. The orthodontist takes an impression of the patient's mouth with a typical dental clay.
II. The impression is shipped to Align Technology where it is scanned using a laser digitizer.
III. The resulting point cloud is converted into a tessellation (set of triangles) that describes the geometry of the mouth. This tessellation is separated into gums and teeth, then each tooth is separated into its own sets of triangles. Since the data for each tooth can be manipulated separately, an Align Technology technician can perform treatment operations as prescribed by the patient's orthodontist. Each tooth can be positioned into its desired final position.

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[6] See next paragraph

IV. Then, the motion of each tooth can be divided into a series of treatments (represented by different aligners). For example, if 13 different upper aligners are needed over 6 months, the total motion of a tooth can be divided into 13 increments.

V. After manipulating the geometric information into specific treatments, aligner molds are built in one of Align's SLA-7000 stereolithography (SLA) machines. The aligners themselves are fabricated by thermal forming of a sheet of clear plastic over stereolithography molds in the shape of the patient's teeth.

The aligner development process is geographically distributed, as well as highly engineered. Obviously, the patient and orthodontist are separated from Align Technology headquarters in California. Their data processing for the aligners is performed in Costa Rica, translating customer-specific, doctor-prescribed tooth movements into a set of aligner models. Each completed data set is transferred electronically to Align's manufacturing facility in Juarez Mexico, where the data set is added into a build on one of their SL machines. After building the mold using SL from the data set, the molds are thermal formed. After thermal forming, they are shipped back to Align and, from there, shipped to the orthodontist or the patient.

Between its founding in 1997 and March, 1999, over 44 million aligners have been created. Align's stereolithography machines are able to operate 24 hours per day, producing approximately 100 aligner molds in one SLA-7000 build, with a total production of 40,000 unique aligners per day. As each aligner is unique, they are truly "customized". And by any measure, 40,000 components per day is mass production and not prototyping. Thus, Align Technology represents an excellent example of "mass customization" using DDM[7].

To achieve mass-customization, Align needed to overcome the time-consuming pre- and post-processing steps in stereolithography usage. A customized version of 3D Systems Lightyear control software was developed, called MakeTray; to automate most the build preparation. Aligner mold models are laid out, supports are generated, process variables are set, and the models are sliced automatically. Typical post-processing steps, including rinsing and post-curing can take hours. Instead, Align developed several of its own post-processing technologies. They developed a rinsing station that utilized only warm water, instead of hazardous solvents. After rinsing, conveyors transport the platform to the special UV post-cure an entire platform in 2 min., instead of the 30-60 min that are typical in a Post-Cure Apparatus unit. Platforms traverse the entire post-processing line in 20 min. Support structures are removed manually at present, although this step is targeted for

[7] "DDM" stands for "direct digital manufacturing" and is a synonyms of "additive manufacturing" as previously stated.

automation. The Align Technology example illustrated some of the growing pains experienced when trying to apply technologies developed for prototyping to production applications.» (Gibson, Rosen & Stucker, p. 363-365)

IV.4. Limitations of additive manufacturing in the biomedical industry

According to Gibson, Rosen and Stucker (2010), because additive manufacturing techniques were originally invented to solve a wide range of manufacturing problems other than medical problems, there are some issues connected with the use of such technology to solve medical and surgical problems. These issues are connected to:

- Speed: «Additive manufacturing models can often take a day or even longer to fabricate. Since medical data needs to be segmented and processed according to anatomical features, the data preparation can in fact take much longer than the additive manufacturing building time. [...] medical models can effectively only be included in surgical procedures that involve long-term planning and cannot be used, for example, as aids for rapid diagnosis and treatment in emergency operations.» (Gibson, Rosen & Stucker, 2010, p. 394)
- Cost: «For the medical product (mass customization) manufacturing applications mentioned earlier, machine cost is not as important as perhaps some other factors. In comparison, the purpose of medical models for diagnosis, surgical planning and prosthetic development is to optimize the surgeon's planning time and to improve quality, effectiveness and efficiency. These issues are more difficult to quantify in terms of cost, but it is clear that only the more complex cases can easily justify the expense of the models. The lower the machine, materials and operating costs, the more suitable it will be for more medical models.» (Ibid., p. 394-395)
- Accuracy: «Many additive manufacturing processes are being improved to create more accurate components. However, many medical applications currently do not require higher accuracy because the data from the 3D imaging systems are considerably less accurate than the additive manufacturing machines they feed into. However, this does not mean that users in the medical field should be complacent.» (Ibid., p. 395)
- Materials: «Only a few additive manufacturing polymer materials are classified as safe for transport into the operating theater and fewer still are capable of being placed inside the body. Those machines that provide the most suitable material properties are generally the most expensive machines. Powder-based systems are also somewhat difficult to implement due to

potential contamination issues. This limits the range of applications for medical models. Many additive manufacturing machine manufacturers now have a range of materials that are clinically approved for use in the operating theater. Metals systems, on the other hand, are being used regularly [...]. It appears that titanium is the preferred material, but cobalt chromium and stainless steel are both available candidates that have the necessary biocompatibility for certain applications.» (Ibid.)

- Ease of use: «Additive manufacturing machines generally require a degree of technical expertise in order to achieve good quality models. This is particularly true of the larger, more complex and more versatile machines. However, these larger machines are not particularly well suited to medical laboratory environments. Coupled with the software skills required for data preparation, this implies a significant training investment for any medical establishment wishing to use additive manufacturing. While software is a problem that all additive manufacturing techniques face, it doesn't help that the machines themselves often have complex setup options, materials handling, and general maintenance requirements.» (Ibid., p. 395-396)

IV.5. Future directions: biofabrication

«Biofabrication can be defined as the production of complex living and non-living biological products from raw materials such as living cells, molecules, extracellular matrices, and biomaterial. Cell and developmental biology, biomaterial science, and mechanical engineering are the main disciplines contributing to the emergence of biofabrication technology. The industrial potential of biofabrication technology is far beyond the traditional medically oriented tissue engineering and organ printing and, in the short term, it is essential for developing potentially high predictive toxicology assays, and complex in vitro models of human development diseases. In the long term, biofabrication can also contribute to the development of novel biotechnologies for sustainable energy production in the future biofuel industry and dramatically transform traditional animal-based agriculture by inventing "animal-free" food, leather, and fur products. Thus, the broad spectrum of potential applications and rapidly growing arsenal of biofabrication methods strongly suggests that biofabrication can become a dominant technological platform and new paradigm for 21st century manufacturing. The main objectives of this review are defining biofabrication, outlining the most essential disciplines critical for emergence of this field, analysis of the evolving arsenal of biofabrication technologies and their potential practical applications, as well as a discussion of the common challenges being faced by biofabrication technologies, and the necessary conditions for the development of a global biofabrication research community and commercially successful biofabrication industry.» (Mironov, Trusk, Kasyanov, Little, Swaja & Markwald, 2009, p. 1)

While, according to Gibson, Rosen and Stucker: «The ultimate in fabrication of medical implants would be the direct fabrication of replacement body parts. This can feasibly be done using additive manufacturing techniques, where the materials being deposited are living cells, proteins and other materials that assist in the generation of integrated tissue structures. However, although there is a great deal of active research in this are, practical applications are still quite a long way off. The most likely approach would be to use printing and extrusion-based[8] technique to undertake this deposition process. This is because droplet-based printing technology has the ability to precisely locate very small amounts of liquid material and extrusion-based techniques are well-suited to build soft-tissue scaffolding. However, ensuring that these materials are deposited under environmental conditions conducive to cell growth, differentiation and proliferation is not a trivial task. This methodology could eventually lead to the fabrication of complex, multicellular soft tissue structures like livers, kidneys and even hearts.

A slightly more indirect approach that is more appropriate to the regeneration of bony tissue would be to create a scaffold from a biocompatible material that represents the shape of the final tissue construct and then add living cells at a later juncture. Scaffold geometry normally requires a porous structure with pores of a few hundred microns across. The size permits goods introduction and ingrowth of cells. A micro-porosity is often also desirable to permit the cells to insert fibrils on order to attach firmly to the scaffold walls. Different materials and methods are currently under investigation, but normally such approaches use bioreactors to incubate the cells prior to implantation. [...]» (Gibson, Rosen & Stucker, 2010, p. 391)

Biofabrication can affect rapid prototyping and manufacturing as follow:

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[8] «This technique can be visualized as similar to cake icing, in that material contained in a reservoir is forced out through a nozzle when pressure is applied. If the pressure remains constant, then the resulting extruded material (commonly referred to as "roads") will flow at a constant rate and will remain a constant cross-sectional diameter. This diameter will remain constant if the travel of the nozzle across a depositing surface is also kept at a constant speed that corresponds to the flow rate. The material that is being extruded must be in a semi-solid state when it comes out of the nozzle. This material must fully solidify while remaining in that shape. Furthermore, the material must bond to material that has already been extruded so that a solid structure can result." (Gibson, Rosen & Stucker, 2010, p. 143) The most common extrusion-based additive manufacturing technique is Fused Deposition Modeling (FDM), which "uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure.» (Ibid., p. 157) This technique is produced and developed by Stratasys, USA. According to the classification in chapter two, this technique falls into the solid-based systems.

- Rapid prototyping: scaffolds for tissue engineering. «Tissue engineering has been used to replace failing or malfunctioning organs such as skin, liver, pancreas, heart valve leaflet, ligaments, cartilage and bone. This has given rise to the interests in applying rapid prototyping techniques to build scaffolds either to induce surrounding tissue and cell in-growth or serve as temporary scaffolds for transplanted cells to attach and grow onto. These scaffolds can be designed in three-dimensions on CAD taking into consideration the porosity and good interconnectivity for tissue induction to occur. The function of cells, such as in bones and cartilage regeneration, is dependent on the three-dimensional spatial relationship. As such, the geometry of these hard tissue are critical to its function. Rapid prototyping has been able to lends itself to producing complex geometry scaffolds.» (Chua, Leong & Lim, 2003, p. 332)
- Rapid manufacturing: tissue engineering and organ printing. «The ultimate in fabrication of medical implants would be the direct fabrication of replacement body parts. This can feasibly be done using additive manufacturing technology, where the materials being deposited are living cells, proteins and other materials that assist in the generation of integrated tissue structures. However, although there is a great deal of active research in this area, practical applications are still quite a long way off. The most likely approach would be to use printing and extrusion-based technology to undertake this deposition process. This is because droplet-based printing technology has the ability to precisely locate very small amounts of liquid material and extrusion-based techniques are well-suited to build soft-tissue scaffolding. However, ensuring that these materials are deposited under environmental conditions conducive to cell growth, differentiation and proliferation is not a trivial task. This methodology could eventually lead to the fabrication of complex, multi-cellular soft tissue structures like livers, kidneys and even hearts. A slightly more indirect approach that is more appropriate to the regeneration of bony tissue would be to create a scaffold from a biocompatible material that represents the shape of the final tissue construct and then add living cells at a later juncture.» (Ibid., p. 390-391)

Mironov, Trusk, Kasyanov, Little, Swaja, Markwald (2009, p. 3-6) identify the “arsenal” of biofabrication technologies, and this include:

- «Solid scaffold-based biofabrication;
- Embedding and molding technology;
- Cell sheet technology;
- Organ printing: directed tissue self-assembly;
- Digital bioprinting;

- Inkjet bioprinting;
- Centrifugal casting;
- Biospraying;
- Dielectrophoresis for biofabrication;
- Magnetic force-driven biofabrication;
- Electrospinning or nanostructuralized scaffold-based biofabrication;
- Continuous and digital microfluidic-based biofabrication.»

Some applications of biofabrication, according to Mironov, Trusk, Kasyanov, Little, Swaja, Markwald (2009, p. 9-11) include:

- «Biofuel production from algae;
- Animal-free meat biofabrication;
- Animal-free leather and fur production;
- Biofabrication of human tissue and organs for implantation;
- Biofabrication of extracorporeal living tissue including devices;
- Biofabrication of in vitro 3D tissue models of human diseases;
- Drug toxicity and discovery assays;
- Biosensors and bioreports in space research;
- Biofabrication and bioart;
- Biogames and bioentertainment.»

Conclusion

As showed in the previous chapters, additive manufacturing can allow mass customization in the biomedical industry. Moreover, through its crucial have an impact on into this industry, additive manufacturing can allow a whole improvement to human health. Other industries, such as the automotive and the aerospace industry, benefit this additive manufacturing, and even more industries are aligning their mechanical endowment in order to take advantage of this technology.

«The current approach for many manufacturing enterprises is to centralize product development, product production, and product distribution in a relative few physical locations. These locations can decrease even further when companies off-shore product development, production, and/or distribution to other countries/companies to take advantage of lower resources, labor or overhead costs. The resulting concentration of employment leads to regions of disproportionately high underemployment and/or unemployment. As a result, nations can have regions of underpopulation with consequent national problems such as infrastructure being underutilized, and long-term territorial integrity being compromised.

Because of recent developments in additive manufacturing, as described in this thesis, there is no fundamental reason for products to be brought to markets through centralized development, production, and distribution. Instead, products can be brought to markets through product conceptualization, product creation, and product propagation being carried out by individuals and communities in any geographical region.» (Gibson, Rosen & Stucker, p. 437)

Gibson, Rosen and Stucker define "conceptualization" as «the forming and relating of ideas, including the formation of digital versions of these ideas (e.g., CAD)" (ibid.), "creation" as the "bringing an idea into physical existence (e.g., by manufacturing a component)" (ibid.); and "propagation" as «multiplying by reproduction through a digital means (e.g., through digital social networks) or through physical means (e.g., by distributed additive manufacturing production).» (ibid.).

«Many companies already use the Internet to collect product ideas from ordinary people from diverse locations. However, these companies are feeding these ideas into the centralized physical locations of their existing business operations for detailed design and creation. Distributed conceptualization, creation, and propagation can supersede concentrated development, production, and distribution by combining additive manufacturing with novel human/digital interfaces which, for instance, enable non-experts to create and modify shapes. Additionally, body/place/part scanning can be used to collect data about physical features for input into digitally-enabled design software and onwards to additive manufacturing.

Web 2.0 is considered as the second generation of Internet, where users can interact with and transform web content. The advent of the Internet allowed any organization, such as a newspaper publisher, to deliver information and content to anyone in the world. More recently, however, social networking sites such as Facebook or auction websites such as eBay, enable customers of web content to also be content creators. These, and most new websites today, fall within the scope of Web 2.0.

Additive manufacturing makes it possible for digital designs to be transformed into physical products at that same location or any other location in the world (i.e., “design anywhere, build anywhere”). Moreover, the web tools associated with Web 2.0 are perfect for the propagation of product ideas and component designs that can be created through additive manufacturing. The combination of Web 2.0 with additive manufacturing can lead to new models of entrepreneurship.

Distributed conceptualization and propagation of digital content is known as digital entrepreneurship. However, the exploitation of additive manufacturing to enable distributed creation of physical products goes beyond just digital entrepreneurship. Accordingly, the term, “digiproneurship[9]” was coined to distinguish distributed conceptualization, propagation and creation of physical products from distributed conceptualization and propagation of just digital content. Thus digiproneurship is focused on transforming digital data into physical products using an entrepreneurship business model. [...]

Web 2.0 combined with additive manufacturing has the potential to generate distributed, sustainable employment that is not vulnerable to off-shoring. This form of employment is not vulnerable to off-shoring because it is based on distributed networks in which resource costs are not a major proportion of total costs. Employment that is generated is environmentally friendly because, for example, it involves much lower energy consumption than the established concentration of product development, production, and distribution, which often involves shipping of products worldwide from centralized locations.» (Ibid., p. 437-439)

[9] According to Gibson, Rosen and Stucker (2010), “digiproneurship” stands for “digital to physical product entrepreneurship”.

«There is no longer any fundamental reason for product to be brought to markets through centralized product development, production and distribution. Instead, products can be brought to markets through product conceptualization, creation and propagation in any geographical region. This form of digiproneurship is built around combinations of advanced information and communication technologies and advanced manufacturing technologies.

Digiproneurship offers many opportunities for a reduction in the consumption of non-value adding resources during the creation of physical goods. Further, the amount of factory equipment needed and, therefore, factory space is reduced. As a result, opportunities for smaller, distributed, and mobile production facilities will increase. Digiproneurship can eliminate the need for costly conventional market research, large warehouse, distribution centers, and large capital investments in infrastructure and tooling.

Creation of physical products at point-of-demand can make regional disadvantages unimportant. A wide range of people and businesses could offer digiproneurship products, including: artist, hobby, enthusiast; IT savvy programmers, underemployed and unemployed people who are reluctant to up-root to major cities to look for work, and others.

Novel combinations of ICT and AM have already made it possible for enterprises to be established based on digitally-driven conceptualization creation and/or propagation. The success of these existing enterprises is due to their recognition of market needs which can be fulfilled by imaginative, digitally enabled product offerings. As ICT and AM progress, and new creation networks are established, the opportunities for successful digiproneurship will expand and Factory 2.0 will come into being.

As digiproneurship expands and Factory 2.0 becomes a reality, AM could come to have a substantial impact on the way society is structured and interacts. In much the same way that the proliferation of digital content since the advent of the internet has affected the way that people work, recreate and communicate around the world, AM could one day affect the distribution of employment, resources, and opportunities worldwide.» (Ibid., p. 445-446)

References

Amatori F., Colli A. (2011), *Business History, Complexities and Comparisons*, Routledge, New York.

Anderson D. L. (2000), *Rapid Tooling in the Medical Device Industry*, in Hilton P. D., Jacobs P. F. (2000), *Rapid Tooling: Technologies and Industrial Applications*, Marcel Dekker, Inc.

Berg M. (1985), *The Age of Manufacturers: Industry, Innovation, and Work in Britain, 1700-1820*, Fontana Press, London.

Chua C. K., Leong K. F., Lim C. S. (2003), *Rapid Prototyping: Principles and Applications*, World Scientific.

Chua C. K., Leong K. F., Lim C. S. (2010), *Rapid Prototyping: Principles and Applications*, World Scientific.

Cipolla C. M. (1976), *Before the Industrial Revolution: European Society and Economy, 1000-1700*, Meuthen, London.

Coase R. H. (1939), *The Nature of the Firm, Economica*, New Series, Vol. 4, No. 16 (Nov. 1937), pp. 386-405, Blackwell Publishing.

Cormier D., Harrysson O., Mahale T. (2003), *Rapid Manufacturing in the 21st century*, Journal of the Chinese Institute of Industrial Engineers, Vol. 20, No. 3, pp. 193-202.

Cox A. (1999), *Power, Value and Supply Chain Management, Supply Chain Management: An International Journal*, Vol. 4, No 4, pp.167-175.

Fralix M. T. (2001), *From Mass Production to Mass Customization*, Journal of Textile and Apparel, Technology and Management, Volume 1, Issue 2, Winter 2001.

Gibson I., Rosen D. W., Stucker B. (2010), *Additive Manufacturing Technologies, Springer Science +Business Media*, LLC 2010.

Grimm T. (2004), *User's Guide to Rapid Prototyping*, Society of Manufacturing Engineers.

Hague R., Campbell I., Dickens P. (2003), *Implications on design of rapid manufacturing*, Journal of Mechanical Engineering, Vol. 217.

Hilton P. D., Jacobs P. F. (2000), *Rapid Tooling: Technologies and Industrial Applications*, Marcel Dekker, Inc.

Kelley, T. (2001), *Prototyping is the Shorthand of Design*, Design Management Journal Vol. 12, No. 3.

Landes D. (1969), *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*, Cambridge University Press, Cambridge.

Lennings L. (2000), *Selecting Either Layered Manufacturing or CNC Machining to build Your Prototype.*

McCloskey D. (1981), *The Industrial Revolution 1780-1860: A Survey*, Economic History of Britain Since 1700.

Mironov V., Trusk T., Kasyanov V., Little S., Swaja R., Markwald R. (2009), *Biofabrication: a 21st Century Manufacturing Paradigm*, IOP Publishing Limited.

Mokyr J. (1990), *The Lever of Riches: Technological Creativity and Economic Progress*, Oxford University Press, New York-Oxford.

Mokyr J. (2002), *The Gifts of Athena: Historical Origins of the Knowledge Economy*, Princeton University Press, Princeton.

Monosoff, T. (2012), *Creating a Product Prototype*, Entrepreneur http://www.entrepreneur.com/article/80678 (accessed on September 15, 2012).

Rhoades, L. J. (2005), *The Transformation of Manufacturing in the 21st Century*, The Bridge.

Rifkin J. (2011), *Leading the Way to the Third Industrial Revolution and a New Social Europe in the 21st Century*.

Rifkin J. (2012), *The Third Industrial Revolution: How the Internet, Green Electricity, and 3-D Printing are Ushering in a Sustainable Era of Distributed Capitalism*, World Financial Review (http://www.worldfinancialreview/?=1547 accessed on September 16th 2012).

Tseng M. M., Piller F. T. (2003), *The Customer Centric Enterprise*, Springer-Verlag Berlin.

Tuck C., Hague R. J. M., Burns N. D. (2007), *Rapid manufacturing – impact on supply chain methodologies*, Inderscience.

Ulrich K. T., Eppinger S. D. (2012), *Product Design and Development*, McGraw-Hill Higher Education.

Vance A. (2011), *The Wow Factor of 3-D Printing*, The New York Yimes, January 12, 2011.

Zaki Warfel T. (2009), *Prototyping: A Practitioner's Guide*, Rosenfeld Media.