From rapid prototyping to direct manufacturing: State-of-the-art and impacts on operational performance
The case of the automotive industry

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Abstract

Additive manufacturing is an industrial process, developed in the early 1980s and currently used in several industries such as the medical, aircraft and automotive industries.

In the first place, additive manufacturing was mostly used by manufacturing industries to produce prototypes, models and patterns. Nowadays, this technology can be used at any point in the lifecycle of a product from pre-production (rapid prototyping and rapid tooling) to production (direct manufacturing). This technology is especially adapted for the production of limited series of small and geometrically complex components.

The purpose of this study is to identify how additive manufacturing affects operational performance during the development and production phases, specifically in the case of the automotive industry.

With this purpose in mind, I have collected primary and secondary data through a qualitative study using both in-depth semi-structured interviews and archival records found on automotive companies’ websites. The objective of collecting multiple sources data was to gain a reliable and comprehensive perception of the situation and understand the effects of additive manufacturing on operational performance, and more precisely on the seven production wastes defined on lean practices, to be able to answer my research question. The data are analyzed using an inductive thematic analysis approach and test the presupposition that emerged from the empirical findings.

Through the analysis of the data collected, I came to the conclusion that additive manufacturing is mostly used during the prototyping phase and sometimes also used for rapid tooling. But it appears that this technology is only used for direct manufacturing in some specific niche markets such as luxury carmakers. Another interesting finding concerns the use of additive manufacturing for marketing purpose. Concerning operational performance, the impacts of additive manufacturing remain limited, and contrary to what some authors said, the use of this technology is still marginal in the automotive industry compared to traditional manufacturing.

Key Words: Additive manufacturing, rapid manufacturing, operational performance, lean manufacturing, lean practices, seven production wastes, automotive industry, rapid prototyping, rapid tooling, direct manufacturing
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1 INTRODUCTION

1.1 Background

Manufacturing industries have driven economic growth and increased living standards for nearly three centuries. And continue to do so. The role of manufacturing in the global economy has a promising future. Over the next fifteen years, it is forecasted that 1.8 billion people will enter into the global consuming class and general consumption at a global scale will nearly double (64$ trillion). (Atsmon et al., 2012)

In the highly competitive and dynamic environment that industries are facing today, the development of the next product generation is a daily struggle. A strong innovation pipeline in information technology, materials, production processes but also in manufacturing operations will give manufacturers the opportunity to build new products and reinvent existing ones. This trend will bring renewed dynamism to the sector. (Atsmon et al., 2012)

The high competition among products offered by industry and customers’ quickly changing needs are challenging issues faced by manufacturers. With these challenges, an increasing complexity comes in products and the supply chain management. Therefore, manufacturers have to find new processes and develop new technologies to stay competitive (Hashemi, Butcher and Chhetri, 2013, p. 151).

Global competition has increased pressure on manufacturing plants and pushed industries to improve multiple dimensions of operational performance. Accordingly, numerous studies have been conducted to identify the resources that can be utilized in order to help firms to excel in these operational dimensions. Based on past research on this topic (Swamidass and Kotha, 1998; Das, 2001), we can group manufacturing resources into two categories: lean practices and manufacturing technologies.

The lean practices concept was first designed for the automotive industry with the popular Toyota Production System (TPS) (Khanchanapong et al., 2014, p. 199). Lean practices was developed thirty years ago and its philosophy is based on performance in terms of productivity, quality, time and costs (Duncan and Ritter, 2014). The nature of this concept and the different schools of thought will be presented later. In this research, I adopt the more popular stated views of lean production: the elimination of production wastes (Hyer and Wemmerlov, 2002; Shingo, 1981). The main goal of lean production is to eliminate waste which does not add value to the product and increase the standardization of procedures, work practices, processes, designs and methods processes to end with a minimum amount of waste (Karlsson and Åhlström, 1996, p 27). Shingo (1981, p. 287-291) defined seven production wastes: Waste from overproduction, waiting time, transportation, over-processing, inventory, motion and producing defects.

In terms of manufacturing technologies, recent research has highlighted the high potential of additive manufacturing as a technology which can give rise to a new industrial revolution (The Economist, 2011 & 2012; Berman, 2012). Additive manufacturing started in 1980 with rapid prototyping. This technique is used to create
a rapid physical realization of products, well before they are manufactured. This technology uses computers to generate three-dimensional models which are quickly created from a digital drawing (Gibson, 2014, p.5). These digital drawings are created with hardware and computer programs such as computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), computer numerical control (CNC) machines, and enterprise resource planning systems (ERP) (Gibson, 2014, p.5). In this research, we focus on additive manufacturing technologies which use computer-aided design programs (CAD).

Additive manufacturing implementation in the automotive industry began thirty years ago with rapid prototyping. The automotive industry is an industry pioneer regarding the implementation of additive manufacturing processes. Companies such as Ford, Daimler, Toyota, and Chrysler have already extensive experience using this technology. In SmarTech Markets Publishing LLC (2014), researchers predicted that revenues from using this technology in the global industrial world will exceed $870 million in 2019 and will probably reach more than $1.8 billion in 2023. In 2014, revenues were estimated at approximately $265 million.

Some researchers (Cottelee et al., 2014) announce that additive manufacturing is not limited to rapid prototyping anymore and that the automotive sector is exploring new ways to use additive manufacturing. The main motivation for car manufacturers to use additive manufacturing is the ability to produce lower-weight, safer products and new products that are impossible to produce with traditional manufacturing processes. (Cottelee et al., 2014). Media and technology observers speculate that additive manufacturing will have a deep impact on the manufacturing sector and more generally on society as a whole (Koten, 2013, The Economist, 2013).

On one hand, some authors predict a great expansion of this technology, sometimes described as the potential triggering force for the 3rd industrial revolution (Kaivo-oja et al., 2014; Rayna & Striukova, 2014). But on the other hand, it has been proved by several studies that technological innovation significantly affects market structure and firms, complexifying the market and increasing the need for firms to be alert and adaptable (Mills and Schumann, 1985, Geroski and Pomroy, 1990; Khanna, 1995).

1.2 Problem statement

During my research, I found out that concrete returns concerning technology adoption are limited in the literature (Baumers et al., 2015, p. 33). In Umeå University’s library databases such as Emerald, ScienceDirect, EBSCOhost, Taylor & Francis, ELSEVIER, SAGE and others, some researches can be found regarding the technical aspects of additive manufacturing processes regarding the environment and the health and safety of additive manufacturing (e.g. the literature review of Huang et al., 2012 about Additive manufacturing and its societal impact) but also concerning the evolution of this technology (e.g. Campbell, Bourell and Gibson, 2012; Ratto and Ree, 2012).

In previous literature, I found information about additive manufacturing implementation in several industries such as the medical or automotive industry but this research was mostly from engineering literature focused on the analysis of additive manufacturing processes in the production of specific parts from a physical and
technical perspective (e.g. Cheah et al., 2004 for the medical industry and Arzanpour et al., 2006 for the automotive industry).

Despite the fact that the automotive industry is pioneer in term of lean practices and additive manufacturing, no research has yet been conducted adopting the perspective of lean practices and seven production wastes to analyze additive manufacturing impacts on operational performance.

In this situation, how does the implementation of additive manufacturing affect operational performance during the development and production phases, specifically in the case of the automotive industry?

RQ1  How does the automotive industry use additive manufacturing (rapid prototyping, rapid tooling and direct manufacturing)?

I believe it’s important to investigate how automotive companies’ use additive manufacturing as studies that can be found on the subject don’t precisely explain it. The findings link to this research question are the basis in order to be able to understand and answer the second research question which is…

RQ2  How does additive manufacturing affect the seven production wastes?

Specifically in the sector of the automotive industry where the concept of lean practices is extensively applied (Cooney, 2002, p. 1130-1047), it seems relevant to use this concept as a framework to analyze additive manufacturing impacts on operational performance.

Prove that additive manufacturing has positive or negative impacts on lean practices, and more precisely on the seven production wastes, is important for car makers to understand how this technology, during the production phase, can increase or decrease their operational performance in strategic production areas which are overproduction, waiting time, transportation, over-processing, inventory, motion and producing defects. Using the framework of the seven production wastes allows the focus to remain on strategic production characteristics which have a direct effect on operational performance during the production phases.

1.3  Purpose

The overriding purpose of this thesis is to identify the way automotive companies use additive manufacturing through their development and production phases and more importantly, to study how the use of additive manufacturing impacts the seven production wastes and so, the operational performance of these firms. Since previous researchers have solely focused on the analysis of additive manufacturing processes in the production of specific parts from a physical and technical perspective, I see an opportunity to increase knowledge in this research field. My aim is to make a study that will inspire an interest for future research in this area by offering a framework to
departure from. From a practical perspective, this thesis will serve as a guiding tool for businesses that are engaged in or will start using additive manufacturing in the automotive industry context to understand how they can use this technology and how this technology can impacts their operational performance.

1.4 Disposition

I start my research by a presentation of the reasons why I choose this thesis subject, explain the pre-understanding and the impartiality issues of the study and the sourcing of empirical data. Then, I explain the research strategy and design adopted and justify my choice to collect both primary and secondary data through a qualitative study. Finally, I present the ethical considerations that have been respected throughout the research process.

In the theoretical chapter, I present previous studies and theoretical perspectives concerning lean practices, operational performance and additive manufacturing. This part explains how lean practices are linked with operational performance through the reduction of production wastes. I also give an overview of additive manufacturing processes, the different uses of additive manufacturing during the production life cycle, and its implementation in automotive industry.

With this pre-understanding and theoretical basis in mind, I explain in chapter 4 the sampling and the research methods. I explain how I collected primary data through a qualitative study using in-depth semi-structured interviews and secondary data through the analysis of archival records founds on automotive companies’ websites. The contribution of the interviews combine with the archival records was to gain a reliable and comprehensive perception of the situation and understand the effects of additive manufacturing on operational performance. Then, I explain how I prepared interviews, selected companies within the car manufacturing industry, collected primary data and transcribed them. This part is ended by explaining how I collected secondary data, selected companies within the car manufacturing industry and transcribed these archival records.

The primary data collected during my interviews and the secondary data analyzed from the website of the companies are presented in chapters 5 and 6, using an inductive thematic analysis approach. Then, I discussed these findings in order to explain them and test the concepts and presupposition that emerged from the empirical findings.

I conclude my research and suggest several ways to conduct further investigations about the topic and present the truth criteria of my research.

This strategy allows me to cover all the aspects of my subject and publish relevant findings that can positively contribute to the research community.
2 METHODOLOGY

The purpose of the methodological section is to present the reasons why the subject of the research has been chosen, present the pre-understanding and the impartiality issues of the study, and the sourcing of empirical data. Then, I present the research strategy and design adopted as well as the nature of the research method used and data collection method. I end this methodological part by the presentation of ethical considerations that have been respected throughout the research process.

2.1 Choice of subject

I am a business development student from France, currently enrolled at Umeå School of Business. Since I started to study business development and innovation management have been two topics that captivate me. My desire was that this thesis makes a link between my current studies in business and my future studies in industrial design at Umeå Design School. In my future professional career, I would like to become a designer in the automotive industry. That is probably why this subject caught my attention and has fascinated me throughout the development of this thesis.

I believe that additive manufacturing is a fantastic technology even if it will probably take dozens of years before it becomes mature and fully exploited. I believe that additive technology, adopted with a central theme of creating value for customers, developing new products and increasing operational performance can bring changes and disrupt the manufacturing world.

The choice of concept to analyze additive manufacturing impacts in automotive operational performance was also very interesting to investigate. Lean practices related to operational performance is a concept that encourages industries to use their resources better and challenges them to rethink and constantly improve their processes.

2.2 Pre-understanding and impartiality

Pre-understanding is defined as a deliberate structure of sentiments and considerations, initiated when something is regarded as something (Nyström & Dahlberg, 2001, p. 339). Bryman and Bell (2011) study states that pre-understanding referred to prior encounters, experiences and understanding that researchers have attained concerning the subject they investigate (Bryman & Bell, 2011, p. 415). Nyström & Dahlberg (2001, p. 345) also state that a general presumption in research scientific philosophy is that research without previous knowledge can alter the understanding of the world.

My prior understanding of the subject within the social world allows me to clearly understand the research I want to carry out (Nyström & Dahlberg, 2001, p. 345). My choice to study additive manufacturing impacts on operational performance was driven by my pre-understanding, from my previous education and my working experience in the transportation industry. I believe that this topic perfectly fits my future education
and career ambitions. However, during the whole research process, I engaged in continuous discussions with other students, my supervisor and researchers in the field to ensure that my pre-understanding didn’t affect my perception of the topic. I remained as impartial as possible when I investigated this topic, transcribed interviews and analyzed previous researches that had been conducted on the topic. Nevertheless, I believe that my background and my pre-understandings concerning additive manufacturing, operational performance and lean practices were an advantage when carrying out this research.

2.3 The sourcing of empirical data

Empirical data are a very important aspect to ensure the credibility of a study. The sources of the research have to be reviewed in order to help the reader to understand how they supplement the thesis. The sources used in this thesis are a combination of archival interviews, books, peer-reviewed articles and journals. They were accessed via different sources on Umeå University’s library databases: Emerald, ScienceDirect, EBSCOhost, Taylor & Francis, ELSEVIER, SAGE and more. To complete these sources, I utilized academic articles in Google Scholar. Peer-reviewed scientific and academic articles are the main source of the literature in order to ensure information accuracy and relevance. I also believe that the use of several different sources gives more credibility to this thesis.

In order to ensure transparency in literature review, Saunders et al. (2011, p. 66) states that authors have to clarify precisely the way they searched and selected information use in the literature by selecting keywords and reference databases. Keywords are a central part and are simple terms that describe and define research questions and research goals (Saunders et al., 2011, p. 66). I used keywords such as: Additive manufacturing, rapid prototyping, rapid tooling, rapid manufacturing, direct manufacturing, design innovation, automotive industry, lean practices, production waste and operational performance. I chose articles after reading the summary, introduction and conclusion. Then, I read them completely and reviewed the bibliography and references of the articles I selected which led me to other articles. I further investigated the work of authors which appear to be pioneers regarding the field I study.

In this thesis, I used classical literature, new and old, to show how different researchers defined and supported the notion of additive manufacturing, lean practices and operational performance and how it has evolved through time.
2.4 Research strategy and design

2.4.1 Perspective of the researcher and the researched

This study starts from a pre-understanding of additive manufacturing technology, operational performance and a lean practices approach based on the theory of elimination of production waste developed by the Toyota production system. I explain in the theoretical framework how lean practices increase performance by identifying different wastes within the production process. To answer my research questions, I used the data collected to build a theoretical framework with a testable structure.

My analysis of empirical background on additive manufacturing highlighted the lack of research concerning the impacts of this technology on lean practices and operational performance. The global objective of my study is to highlight the impacts of additive manufacturing on the seven production wastes defined by lean practices.

First, I have adopted an ‘emic’ perspective as I describe additive manufacturing and lean practices as particular elements, and studied their internal functioning rather than studying any existing external scheme that could link these concepts together. As Ritchie and Lewis, (2003, p. 45) explained in their book, I have penetrated their frames of meaning.

Then, my view for this research was process oriented rather than statistic oriented as my aim was to highlight the processes and links between additive manufacturing and lean practices. My empirical background explained the context in which the study was conducted; therefore, providing a holistic perspective of the subject.

The last point concerns the empathic neutrality perspective I adopted to study this subject. I used my personal insight while taking a non-judgmental stance, making presuppositions about the results with my personal understanding of the subject and some empirical data.

All these points are defined by Ritchie and Lewis, (2003) as perspective stances associated with qualitative research.

2.4.2 Qualitative research

Quantitative research is concerned with the collection and the analysis of numerical data. Quantitative research tends to emphasize relatively representative and large-scale sets of data, and is often perceived as being about gathering facts.

On the other hand, qualitative research is concerned with collecting and analyzing different forms of data, mostly not numerical. Qualitative research tends to focus on exploring a specific area with as much detail as possible and aims to achieve ‘depth’ investigations rather than ‘breadth’. (Reynolds et al., 1997, p. 247). Qualitative research is descriptive and the meaning is the essential concern of qualitative approach. Qualitative researchers focus on process rather than outcomes and tend to analyze their data inductively (Bogdan & Biklen, 1992, p. 178).
The empirical data that have been collected for this study concerning additive manufacturing and lean practices are qualitative by nature as few numerical data on value added could be found. Furthermore, no links between additive manufacturing and operational performance have yet been made in empirical studies. Additive manufacturing is a relatively new concept, and studies conducted on this technology remain limited. Therefore, I believe that a qualitative study is more suitable to develop new knowledge around this topic.

2.4.3 Epistemology

Epistemology concerns the nature of knowledge and how the researcher perceives knowledge in the research. Kuhn (1991, p. 8-10) describes two different ways of reasoning in his book: inductive and deductive. Those two methods are different in terms of relationship between theory and empirical findings.

The deductive method goes from general to particular and uses existing theories to support empirical findings. Researchers start from theories and develop hypotheses with empirical generalizations. Then, hypotheses are accepted or rejected (Kuhn, 1991, p. 8-10).

On the other hand, the inductive method goes from particular to general. Inductive reasoning is commonly used in social sciences and is defined as the gathering of empirical findings in order to build a theoretical framework based on collected data with a testable structure (Kuhn, 1991, p. 38). The epistemological position adopted in research with an inductive orientation is described as interpretivism, meaning that, in contrast to the adoption of a natural scientific model in quantitative research, the highlight is on the understanding of the social world through an examination of the interpretation of that world by this participation (Bryman and Bell, 2007, p. 386).

Induction can be broadly understood in three ways: 1) as a direct empirical generalization (for example, the sun rises every morning); 2) as statistical induction which would result in a probability judgment (for example, men are twice as likely to die in a car accident than women); 3) as the reform of theories, hypotheses or intuitions in the light of experience and analysis (for example, our classroom observations make us think that there is a link between low student motivation and disruptive behavior). (Blais & Martineau, 2006, p.14)

It is the third inductive method which corresponds to my research design and strategy. As we have seen previously, the inductive method is defined as a type of reasoning that goes from particular to general; this means that from reported or observed facts (experiences, events, etc.), the researcher arrives at an idea or conclusion by a generalization rather than by the verification of a pre-established theoretical framework. As my strategy was to build an empirical background about additive manufacturing, operational performance and lean practices to understand the processes and links between these concepts through an automotive case study and then, conducted interviews and gathered secondary data from experts in the automotive industry to be able to generalize the finding to the automotive industry, the inductive method is best suited to my study.
2.4.4 Ontology

Ontology concerns the researcher’s view of reality. The ontological position in research with inductive orientation is described as constructionism, which implies that social properties are outcomes of the interactions between individuals, rather than phenomena “out there” and separate from those involved in its construction (Bryman and Bell, 2007, p. 386).

Again, as my strategy was to build an empirical background about additive manufacturing, operational performance and lean practices to understand the processes and links between these concepts through an automotive case study and then, conducted interviews and gathered secondary data from experts in the automotive industry to be able to generalize the finding to the automotive industry, the constructivism approach suit better to my study.

2.4.5 Choice of case study design

Aaker et al (2001, p. 495) defines research design as the “detailed blueprint used to guide a research study through its objectives and the process of designing a research study involves many interrelated decisions”. The research design can be an experimental design with a random assignment of subjects; a cross-sectional design with collection of data at a single point in time on more than one case; a longitudinal design, with a survey of the same sample but on more than one occasion; a case study design, which details and analyzes one case or a comparative design, which compares two or more contrasting cases (Bryman & Bell, 2007, p. 26).

The choice of using a case study design is related to both the purpose of my study and the properties of this particular research design.

According to Merriam (1998, p. 54), “a single case study is a particularly suitable design if you are interested in the process and it can be chosen for its uniqueness for what it can reveal, as regard to phenomenon, knowledge we wouldn’t otherwise have access to”. Yin (2014) adds to this definition the fact that the case study design is suitable when the main research question is a “How” or “Why” question, when researchers have little control over behavioral events and when the study focuses on a contemporary phenomenon (Yin 2014, p. 43).

I chose to focus on one specific industry, the automotive industry and analyze the impacts of a new and specific technology on operational performance. Within the industrial world, the automotive industry is in my opinion the most interesting to study as it is a pioneer in terms of both lean practices and additive manufacturing implementation.

I also thought about making a multiple case studies analysis and comparing the implementation of additive manufacturing within several industries. The automotive industry shares some features with other globalized industries such as apparel, electronics and consumer goods but this industry also has significant specificities (Sturgeon et al., 2009, p. 7). But Yin (2011) states that access to vital information is an important factor that researchers have to consider during case selection (Yin, 2011, p.
As I wasn’t sure to be able to have enough available data to compare the automotive industry to another one, I chose to focus on the automotive industry and conduct an in-depth investigation (instead of trying to give a superficial overview) to study the additive manufacturing phenomenon within the same market and regulations.

For these reasons, a single case study design seems to be the more suitable research design for this study.

2.5 Nature of the research method used and data collection method

2.5.1 Research method and triangulation

Bryman (2007, p. 36) suggests that a research method is a technique for data collection. When gathering evidence in a case study, several different research methods can be used. These include interviews, direct observations, participant-observations, documentation, archival records, and physical artefacts (Yin, 2011, p. 65). It is the possibility of using many different sources of empirical evidence that dictates the strength of a case study as a research design. Researchers are allowed to address a broad range of different behavioral and historical issues. Additionally, the findings of the study can be made more convincing and accurate by developing converging lines of inquiry through the process of triangulation (Yin, 2011, p. 65).

Triangulation is typically a strategy for improving the validity and reliability of research or evaluation of findings (Golafshani, 2003, p. 603). If the trustworthiness or validity can be tested or maximized then more “credible and defensible result” (Johnson, 1997, p. 283) may lead to the generalizability of the results, which is one of the concepts defined by Stenbacka (2001, p. 554) as the structure for both doing and documenting a high quality qualitative research. The ability to generalize the findings to a wider groups and circumstances is one of the common tests of validity for quantitative research. However, Patton (1990, p. 246) states that generalizability is one of the criteria for qualitative case studies too, depending on the case selected and studied by the researcher. My aim is to study very specific phenomenon to generate accurate results, therefore I have decided to follow Patton’s recommendation.

Patton (1990, p. 247) preconizes the use of triangulation to “strengthens a study by combining methods. This can mean using several kinds of methods or data, or using both quantitative and qualitative approaches”. Golafshani (2003, p 604) explains that when using triangulation of several data sources in quantitative research, any exception may lead to a disconfirmation of the hypothesis where exceptions in qualitative research are dealt to modify the theories and are fruitful. Moreover, Healy and Perry (2000, p. 121) explain that using triangulation of several data sources allows the research to relies on multiple perceptions about a single reality, making the results even more accurate and generalizable. Following this advice, I decided to use several data sources to maximize the validity, reliability and generalizability of my findings.

In my research, like in any qualitative research, the aim is to “engage in research that probes for deeper understanding rather than examining surface features” (Johnson, 1995,
Constructivism ontological orientation may facilitate toward that aim (Johnson, 1995, p.4). The constructivist notion explains that reality is changing, whether the observer wishes it or not (Hipp, 1993), this notion is an indication of various possible constructions of reality and multiple realities values that people have in their minds. Therefore, I believe that using triangulation of several data sources for my research allows me to acquire reliable and valid diverse and multiple realities. Using multiple methods of searching or gathering data, such as interviews and archival records is for me the best way to assure the validity, reliability and increase the generalization of my findings. It allows me to involve peer researchers’ interpretation and several investigators of the data at different location and time. This way of thinking is supporting by Johnson (1997, p. 284) when he explains that a qualitative researcher can “use investigator triangulation and consider the ideas and explanations generated by additional researchers studying the research participants”.

### 2.5.2 Data collected

There are two types of data that can be collected: primary and secondary data (Saunders et al., 2011, p. 140). A researcher may choose to collect primary or secondary or both kinds of data depending on the nature of the research (Saunders et al., 2011, p. 140). Primary data are data collected by the researcher conducting the study and data which have been collected by others are known as secondary data (Bryman & Bell, 2011, p. 37). There are various sources of secondary data, such as copies of letters and payroll details (Saunders et al., 2011, p. 140). Another advantage of secondary data is that they help the researcher to save enormous resources such as money and time (Saunders et al., 2011, p.140). However, secondary data have the disadvantage of having been collected for a specific purpose which can be completely different from the study the researcher intends to accomplish. Moreover, the data may also be irrelevant for the particular study (Bryman & Bell, 2011, p. 37; Saunders et al., 2011, p. 140). However, as I explained previously, I believe that gathering multiple sources data can strengthen my findings. Therefore, I believed it was necessary to collect both primary and secondary data as I felt it strengthen the reliability, generalizability and validity of my research.

Primary data can be collected using interviews. The interviews can be administered in different ways (Bryman & Bell, 2011, p. 40) and the type of the interview used depends on the research question, the research design and the research strategy (Saunders et al., 2011, p. 143). The qualitative data collection method can be highly structured and formalized or unstructured and informal depending on the types of question asked (Saunders et al., 2011, p. 143). Structured interviews refer to a standardized interview, where the interviewer asks precisely the same set of questions to all respondents (Bryman & Bell, 2011, p. 40). When the aim of an interview is to acquire findings generalized throughout a group of people, this kind of interview is more suitable in order to be able to compare answers (Bryman & Bell, 2011, p. 40). On the other hand, an unstructured interview is more suitable when the purpose of the research is to understand the point of view of the respondents (Bryman & Bell, 2011, p. 40). Another type of interview, called semi-structured interview, covers a broad set of examples. It refers to a setting in which the interviewer asks a sequence of questions that form an interview schedule which can vary regarding the sequence of questions. The questions are generally more general in their frame of reference compared to questions commonly found in a structured interview and the interviewer has the possibility of asking more questions in light of what the
respondents say to get a further understanding of certain points expressed by respondents (Bryman & Bell, 2011, p. 40).

After evaluating the various methods at my disposal, I concluded that a semi-structured interview is perfectly suitable for my research to allow respondents to express themselves freely. A semi-structured interview would allow me to ask the same questions to all of the respondents in order to distinguish conceivable patterns in their answers but it would also allow me to get the richness of open questions to be able to distinguish new perspectives I had not thought about before.

Concerning the collection of secondary data, I have selected four car manufacturing groups that fit my study purpose by representing different ways additive manufacturing have been implemented within these firms processes and supply chain. I gave preference to evidences that come directly from my studied companies’ websites to ensure the accuracy of information. I used the official websites of my studied companies, their official press releases and various interviews in text or video format where representatives of the studied companies are discussing their use of additive manufacturing technologies.

The success of research highly depends on considering access and ethics issues. The capacity to acquire data depends on acquiring access to proper sources. The relevance of sources is linked with the research questions and the research design strategy (Saunders et al., 2011, p. 139). For my primary data, gaining a physical access was difficult and challenging, probably because of the sensitivity and the nature of the research topic, as firms are protective regarding their privacy and their strategy. In this case, Saunders et al. (2011, p. 140) explained that the researcher’s reliability and capability are very important to convince them to participate. Bryman and Bell (2011, p. 42) emphasized the fact that it is difficult to gain access and schedule an appropriate time in order to interview managers. During the interviews I have conducted for this study, all managers that had accepted to answer my questions showed interest and were willing to dedicate time to answer my questions. Concerning my secondary data, it was easier to gain access but I had to make sure of the relevance of the information. I verify the identity of the participants and choose interviews where the researcher or journalist questions were available to verify the impartiality of the interviewer and the relevance of their questions.

2.5.3 Nature of outputs

Qualitative research produces a substantial amount of data (Bryman & Bell, 2011, p. 40) but there is no standardized way to analyze the data collected. The choice of the analysis method is connected to whether the research has an inductive or deductive approach (Saunders et al., 2011, p. 140). Bryman & Bell (2011) argue that thematic analysis is a general technique often used in qualitative research. It can be applied in most of the qualitative research types (Bryman & Bell, 2011, p. 45). Braun & Clarke (2006, p. 89) explain that this technique is used to identify, analyze and report patterns within data. It categorizes and arranges data in a set of rich details. For Roulston (2001, p. 288-290), thematic analysis is a common technique used by most researchers who conduct a qualitative study. I identified two main categories in my research: the way the automotive industry uses additive manufacturing and the impact of this technology on the seven production wastes and, therefore, on operational performance. The first category is
divided into 3 sub categories: rapid prototyping, rapid tooling and rapid manufacturing. The second category is divided into seven sub categories which are: over-production waste, waste of waiting, transportation waste, waste of over-processing, inventory waste, waste of motion and waste of defects. However, I kept a flexible framework and left my respondents free to complete this framework with their own knowledge and thoughts. Concerning the secondary data, it wasn’t relevant to organize the results the same way as I had no power on the questions asked by the interviewers and on the interviews orientation. Therefore, I decided to divide my secondary results in four categories: rapid prototyping, rapid tooling, rapid manufacturing and a fourth category to gather new findings or way to use additive manufacturing. I also made sure to collect all the secondary data available, in agreements with my research purpose, to stay as exhaustive as possible and let new potential perspectives of study emerged from my findings.

2.5.4 Ethical considerations for interviews

Theoretical considerations are important choices that usually govern the research orientation. Before getting involved in the research, the researcher has to consider the general ethical dilemma and how to access knowledge and data (Saunders et al., 2011, p. 147). In writing this thesis, I paid great attention to following the guidelines of ethics all along the research process. In this section, I discuss topics within ethics and argue how I have, as a researcher, attempted to consider ethical issues and follow the ethical guidelines. Bryman & Bell (2011, p. 127) described four ethical considerations that should be respected during the research process: “No harm should come to research participants, They should agree to participate and know what the research is about (informed consent), Their privacy should not be invaded (anonymity-confidence), They should not be lied to or cheated (no deception). Research participants must know that is what they are and what the research process is.”

2.5.4.1 Harm to participant

Harm to participants can occur in different situations and can affect the participant’s confidence as well as create tension. Bryman & Bell (2011, p. 128) explain that harm to participants can be physical and/or emotional harm which have an impact on participant development and self-esteem and produce a stressful situation for them. Harm to participants can also affect their current or future career. I paid great attention to the way I contacted participants. Prior to sending an interview request email, I asked some business students and relatives to read it in order to make sure that my letter gave a reliable and proper impression. I wanted to be sure that the letter clearly stated the purpose and objective of the research to ensure the respondents were aware of my intentions. According to Saunders et al. (2011, p. 168), a researcher may cause harm to participants by not considering the time at which he or she contacts his participants. I paid attention to send all my requests during working hours and not during the weekend. I also made sure to conduct the interviews at a proper time, convenient for participants. As some participants didn’t want me to divulge their identity and the name of their company, I choose to use pseudonyms in my research, to solve issues related to anonymity. I informed participants of this decision to make sure that they all agreed with it.
2.5.4.2 Lack of informed consent

According to Saunders et al. (2011, p. 190), the fact that participants agree to be interviewed doesn’t mean they show consent to how the data they provided the researcher are going to be used next. Before each interview, I informed participants that all the data collected during the interview would be used for academic purposes. Bryman & Bell (2011, p. 133) discussed the fact that it is hard and challenging to make potential participants fully aware of the data required to allow them to take a decision about their participation. Moreover, during the interviews, some lapses can disrupt the research, for example, miscalculation of the time required to conduct the interview.

During the period of requesting access, I made sure to include a short description of my research topic, purpose and objective in the request email. I also informed participants about the way I wanted to use data I gathered during the interviews. I made sure to be as transparent as possible and clear concerning the length of the interview. Participants knew beforehand approximately how long the interview would take. They also knew the interview questions beforehand.

2.5.4.3 Invasion of privacy

Maintaining anonymity and privacy is essential in order to achieve access to participants and companies. A researcher is responsible for the privacy of all the information gathered during the research process. These issues are also critical when it comes to personal data such as names (Saunders et al., 2011, p. 194). The problems of secrecy and privacy increase the difficulty of qualitative research design. Researchers must pay attention and avoid any probable identification or connections of companies or respondents (Bryman & Bell, 2011, p. 136). In certain situations, the researcher has to choose if it is suitable or not to record specific data that could be considered sensitive (Bryman & Bell, 2011, p. 136). Since revealing sensitive data could be considered by respondents as an invasion to company or individual privacy, I paid great attention to protect the identity of the respondents of this study. I did not disclose any of my participant’s names per to their request. I coded the content of the data gathered during the interviews so that participants’ identities remain confidential. Since I recorded the interviews to be able to use the information gathered from the participants in the result part of this research, I always asked their permission before the interviews and ensured respondents about the privacy and secrecy of the recordings. Overall, I followed the essential ethical guidelines and took respondents’ concerns and needs into consideration.

One important ethical consideration is that a researcher should not put pressure on respondents (Saunders et al., 2011, p. 188). Privacy is a right for everyone and no one should be pushed to take part in the research. If a researcher forces potential participants to take part in the research, he or she might be causing harm. Therefore, researchers should consider the rejection of participation (Saunders et al., 2011, p. 188). In my request letter and during interviews, I made sure that I was not pressuring participants. I gave them the freedom of choice to participate or not and to answer all of the questions or only the ones they chose to answer. I also sent a personal letter to all participants to thank them for their precious help and participation in my research.
Deception is linked to dishonesty about the main objective of the research. Dishonesty can for example come from the research connection with a company which will access the data and use them for a business advantage or private sponsorship (Saunders et al., 2011, p. 190). Moreover, once researchers have accessed data through interviews, they should not change the objective of their research without informing the research participants. It is considered a deception if the researcher does notinform participants that the research objective has changed (Saunders et al., 2011, p. 190). Even though my research would not benefit from using deception, I have carefully informed respondents about my intentions. I have been completely honest and open concerning my purpose. Respondents knew about my purpose from the beginning and I made sure to clearly communicate objectives during the collaboration with participants. The questions that I asked during the interview were the ones I analyzed.

Ethical considerations for secondary data

For Heaton (1998, p. 35), secondary analysis is “the use of existing data collected for the purposes of a prior study, in order to pursue a research interest which is distinct from that of the original work”.

When researchers interviews participants, they asked for consent in order to quote from their interviews and used information in any resulting publications. Informed consent is define as the “linchpin of ethical behavior” (Bulmer, 2008, p. 147). But how far the consent to use these information can be a matter of conjecture? Can I use quote and information from archival interviews without asking the consent of participants?

The British Sociological Association’s Statement of Ethical Practice (2004) establishes that researchers have to inform participants about how they will use their data and obtain consent for the future use of the information. However, the guidelines also state that in some research contexts it may be necessary to obtain a consent which is not as a one-and–for-all ultimate consent, but as a process that can be subject to renegotiation over time. (BSA, 2004) The guidelines do not state about the specific circumstances that may require further participant consents. Is it the case in this research as I use interviews of experts in the field I investigate? Do I need to return or not to participants to get their consent again?

Wiles et al (2005) states that On the one hand… “[it] ensures people know to what they are consenting as the focus and the direction of a study changes. Addresses participants tendency to disregard the information about participation that they are given.” On the other hand…”One off consent is adequate; seeking ongoing consent irritates participants and encourages them to withdraw from participation”. (Grinyer, 2009, p. 2)

These experts seems to state that ‘special consent considerations’ are left to the discretion and consideration of the researcher and argue that further consents are needed when the researcher perceived ‘vulnerability’ concerning data participants share with the researcher. I have decided that asking for further consent was not necessary for my research as I do not perceived any harm for the participants as their shared on their own websites the information I collected.
3 THEORETICAL FRAMEWORK OF THE STUDY

The aim of this part is to present previous studies and theoretical perspectives concerning lean practices, operational performance and additive technology. This part gives an overview of additive manufacturing processes and explains how lean practices are linked with operational performance through the reduction of production wastes.

3.1 Lean practices and operational performance

3.1.1 Lean practices and production waste elimination

Lean practices were first designed for the automotive industry with the popular Toyota production System (TPS). TPS was developed thirty years ago to produce better and more innovative products, faster and at lower costs (Khanchanapong et al., 2014, p. 199). The concept of Lean manufacturing can be resumed by doing more by doing less. According to Browning, (2000, p 168-172), who pointed out that lean doesn’t only mean reducing cycle time, minimizing costs or waste but can mean focusing on value maximization and enabling the right information to be available in the right place and at the right time. Nowadays, it is a common in automotive companies to use lean practices during the production process (Cooney, 2002, p. 1130-1147). Those companies embrace the general idea of lean production which is the elimination of production wastes and the production of the right number of items that are needed at the right time. Waste elimination is the key to increasing value added and supply chain performance. For Shah and Ward (2007, p. 793) it is possible to adopt different perspectives to define lean production. It can be a philosophy, bundles of practices and a set of principles. "Lean is not a set of tools. Instead, it is a philosophy of operation. Lean is about waste prevention whilst focusing on value for the customer in a flexible and responsive way to sustain and improve the business competitiveness" (Julien and Tjahjono, 2009, p 323).

Lean production is associated with the elimination of the seven production wastes defined by the Toyota production system (TPS). The lean production goal is to eliminate waste which does not add value to the product and increase the standardization of procedures, work practices, processes, designs and methods to end with a minimum amount of waste (Karlsson and Åhlström, 1996, p. 26; Shigo, 1981, p. 290). Those seven classic production wastes have been defined by Ōno (1988, p. 12) as: Waste from overproduction, waiting, transportation, over-processing, inventory, motion and production defects. They remain relevant as several recent studies have been conducted using the seven production wastes (e.g. Pampanelli et al. 2014)

According to Kippenberger (1997, p. 11), over-production relates to the production of goods which are not needed at the moment. Martins (2010, p. 84) went further and claimed that in a lean environment, practitioners have to produce only when it is necessary to match available capacity to actual demand. For Rother and Shook (2003, p.117), over-production is the most significant source of production waste as it increases lead-time and reduces your ability to be adaptable and flexible in your production process in order to respond to customer requirement.
The second type of waste in Kippenberger (1997, p. 12) is **waiting**. It is created when employees have to wait for materials, information or resources to continue their work. Delays are often due to movement of goods or delays concerning a process to be completed. When equipment is left idle, loss of process time (delay regarding production to downstream work operations) and production cost increases (Martins, 2010, p. 85). Hines and Rich (1997, p. 49) view is that waiting time should be used for maintenance activities, employee training, or Kaizen activities.

The third waste is **transportation**. When goods are moved from one point to another with an unnecessary amount of transportation cost, often due to an important number of useless intermediaries. When a good is transported between two locations within factories, value is not added to the product. The cost of this waste increases when unnecessary inspection, work, or storage locations are added to the production process (Kippenberger, 1997, p. 12).

**Over-processing** waste is the result of different circumstances. Adding unnecessary features and functions to a product leads to increased cycle time and costs which are associated with the design and production of that product (Martins, 2010, p. 87). Consequences of over-processing are excessive transport and poor communication since the more complex the production process is, the more difficult clear communication is.

The fifth type of production waste is **Inventory waste** forms. It occurs when a product is produced without being requested by a customer. The risk associated with this production waste is the build-up of a massive and costly inventory. This waste can be minimized if production matches demand. Regarding the waste of inventory, Karlsson and Ahlstrom (1996, p. 53) suggest that the reduction of lot size can have a positive impact on production flexibility and reduce inventory waste.

**Waste of motion** is defined as unnecessary movement from one point to another of employees (Kippenberger, 1997, p. 15). This waste occurs when specific activities or work within the production process is not performed efficiently. This waste impacts and increases cycle times and costs. It also tires employees more than necessary and might lead to poor productivity and eventually to quality problems (Hines and Rich, 1997, p. 55). To avoid this waste, the different processes involved in performing a task should be understood and devices should be well-organized to limit this waste (Martins, 2010, p. 90).

**Waste of defects** is related to mistakes in the production process that require rectification (Kippenberger, 1997, p. 16). When products do not meet customers’ needs and specifications, a rework is done. This rework increases cycle time and production costs. Minimizing this waste leads to an increase in customer satisfaction among other benefits (Martins, 2010, p. 90). Parts scrapping is identified as another source of defective waste.

### 3.1.2 Internal and external lean practices

This distinction is very interesting as it shows that industries and companies can be studied as an entity but also as an element of the environment in which they interact.
Internal lean practices are defined in the literature as a manufacturing system that covers manufacturing practices such as set-up time reduction, pull-production systems, JIT and quality management (Shah and Ward, 2003, p. 134).

Internal lean practices are characterized first by pull-production systems, which means that what companies produce is actually what customers’ demand, in terms of quantity and time (Sugimori et al., 1977, p. 557). Regarding quality management, internal lean practices foster mutual effort between a firm’s stakeholders to do their best to continuously improve production activities to tend to zero defects (Womack and Jones, 1994, p.78).

Another component of internal lean practices is set-up time reduction. According to Karlsson and Åhlström (1996, p.28), the most important source of waste in production is inventory waste, which can also be assimilated, for example, as work in progress. One way to reduce it is to increase lean practices concerning machine set-up time reduction and use machines that need less handling and which produce parts more quickly.

Internal lean practices are also associated with JIT, defined as the elimination of production waste through simplification of production processes (Karlsson and Åhlström, 1996, p. 28). JIT is closely associated with quality management and set-up time reduction as they are part of the global firm strategy to better utilize resources and reduce inventories. Pull-production systems are also highly supported by JIT techniques (Levy, 1997, p. 96) e.g. production of small lot sizes and controlled material flow allow manufacturers to synchronize their production with the demand rate (Kannan and Tan, 2005, p. 157).


The present study focuses on the internal perspective of lean strategy as we study the impacts of additive manufacturing on operational performance during the development and production phases. Therefore, we focus on one single industry, the automotive industry, and study the internal mechanisms that link this technology to lean practices and operational performance. Internal lean practices are conceptualized as an integrated management approach of internal manufacturing systems, which are characterized by JIT techniques, pull-production systems, quality management and reduced set-up time. The elimination of production waste is therefore the aim of this approach (Simpson and Power, 2005, p. 63).

3.1.3 Correlation between lean practices and operational performance

Several studies have shown the link between internal lean practices and operational performance (Flynn et al., 1995; Shah and Ward, 2003; Swink et al., 2005, Kannan and Tan, 2005). Operational performance is characterized by competitive priorities (Swink et
al. 2005, p. 441). Competitive priority was first defined by Hayes and Wheelwright (1984) as the strategic dimensions in which a firm chooses to compete. To be able to achieve a real competitive advantage, firms should build a strategic alignment between both competitive priorities and manufacturing capabilities (Hayes and Wheelwright, 1984, p. 254). Lean practices, and more precisely internal lean practices, are by definition a strategy to efficiently use manufacturing capabilities in order to focus on value maximization and enable to make available the right information in the right place and at the right time to answer customers’ demand (Browning, 2000, p. 171). For all these reasons, I believe that operational performance can be measured through lean practices, and more precisely through the seven production wastes framework, allowing me to clearly state where additive manufacturing impacts operational performance during the development and production phase.

3.2 The conceptual definition of Additive manufacturing

Additive manufacturing is “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM International, 2013; Cottelee et al., 2014, p. 5). Additive manufacturing technology has been developed for industrial use (see part below: 3.2.1. History of Additive manufacturing) and has in many sources been identified as the potential triggering force for the 3rd industrial revolution (Kaivo-oja et al., 2014, p. 34; Rayna & Štrikova, 2014, p. 132), that will disrupt the field of manufacturing and force different actors and industries to rethink their operations and competitive advantages.

There is often confusion between additive manufacturing technology and three dimensional printing. Through the reading of previous studies and articles, I have defined that three dimensional printing is associated with the machine itself and its domestic use whereas additive manufacturing technology encompasses additive processes used for industrial purposes.

3.2.1 History of additive manufacturing

Earlier additive manufacturing materials and equipment were developed in the 1980s in research laboratories in the United States, Japan and Europe for industrial use. Charles Hull, the American co-founder, executive vice president and chief technology officer of 3D Systems, is generally credited as the inventor. In 1984, he patented a “system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed” (Kaivo-oja et al., 2014, p. 7). It was the first commercially viable approach to this technology. Since then, additive manufacturing technologies have evolved and now include at least 13 different sub-technologies which can be grouped into seven different process types (see 3.2.2 Materials and processes). Additive manufacturing technology has grown, since 1990, from prototyping to end-part production, and has been deployed at a large-scale industrial level. This technological expansion has been driven by lowered system costs. (Cottelee et al., 2014, p. 11)
The 2000s marked another turning point for this technology, with the introduction of additive manufacturing applications in the production of aircraft and automobile parts, consumer products, as well as organ and tissue printing systems. (Cotteleer et al., 2014, p. 11)

Additive manufacturing technology is currently deployed in various industries. It can be used to fabricate end-use products in medical implants, aircraft (Dawes et al. 1996, p. 42), scaffolds in tissue engineering (Yeong et al., 2004, p. 647) and fashion products like jewelry (Ferreira et al., 2012, p. 188). In medical industry for example, the list of objects that have been successfully printed, such as tissues with blood vessels, bones, organs, low-cost prosthetic parts, medical equipment and drugs demonstrates the potential of this technology for the future of healthcare field (Meskó, 2015).

The available materials for additive manufacturing include plastics, ceramics, composites and metals, but there is a potential of combining nanotechnology, biotechnology and chemistry to create entirely new ways of production (Kaivo-oja et al., 2014, p. 12). If we take again the example of the medical industry, Organovo, a company specialized in medical research and practice, is able to print liver cells, which are currently used for pharmaceutical tests. But Organovo forecasts that, in a decade, they will be able to print a liver or even a heart. Nowadays, hundreds of thousands of people worldwide still wait for an organ donor. If Organovo succeeds in printing sustainable organs, bio printed organs will completely transform the lives of these people and the organ graft world (Meskó, 2015).

Nowadays, Additive manufacturing technology continues to be developed, with improvements concerning speed of processing, design complexity and multiple materials used. (Cotteleer et al., 2014, p. 16)

According to Marketsandmarkets research report, growth expectations for this market represent 13.5% of the Compound annual growth rate (CAGR) from 2012 to 2017 in order to reach $3,471.9 million by 2017. This growth involves various industries such as motor vehicles, academic, aerospace, medical industry, consumer products, business machines, government/military, architecture and others (Marketsandmarkets.com, 2015).

3.2.2 Materials and processes

With additive manufacturing technology, two primary types of materials are used: plastics and metals. Some other materials can also be used such as ceramics or composites but they are not as common. Wohlers (2012, p. 1096) defined eight categories of materials: Polymers and polymer blends, metals, composites, graded/hybrid metals, investment casting patterns, ceramics, sand molds and cores and paper.

In fact, there are a number of additive manufacturing processes and the categorization of these processes and materials have been clearly explained by ASTM International Standards and Wohlers (2012, p. 1096). The ASTM F2792 has developed standard
terminologies concerning additive manufacturing technologies. They divided them in seven group of rapid manufacturing processes (see Appendix 3)

3.2.3 From CAD file to the final piece

Even if additive manufacturing technology is divided into seven different process types, the design process is the same for all of them. Analogous to printing a document, additive manufacturing technologies can produce or reproduce structures in one piece (Appendix 1: 3D printed car). First, designers create a data file, a virtual ‘blueprint’ of the object manufacturers want to produce, which can be created either using computer aided design (CAD) software or by scanning the object and digitally recording the 3D image. The process happening inside the machine can be described in two stages. The first step is the transfer from the data file to printed structures. Then, the machine repeatedly positions the print head in all three spatial directions to print the whole object layer by layer (Zhang et al., 2008, p. 534). The final product is in fact a compilation of two dimensional slices (Appendix 2: additive manufacturing process flow). Using Computer Aided Design (CAD) software enables a completely integrated activity, from design to production, with the possibility of sharing technical aspects of the product in different places, with different machines (Berman 2012, p. 157).

3.2.4 Different uses of additive manufacturing during the production life cycle

3.2.4.1 Rapid prototyping

When rapid prototyping was introduced in the industrial world, this technique had only a marginal effect on the way industries carried out and planned their business. Moreover, the cost of 3D printers was also very high and therefore only affordable for large firms. (Rayna & Striukova, 2014, p. 120)

However, the introduction of rapid prototyping has led industries to significantly reduce the prototyping process. It became possible to produce a prototype in few days or even hours instead of a few weeks or sometimes months. Speeding up this production stage had impacts on companies’ efficiency as it allowed them to release new products more rapidly. At its early stage, rapid prototyping led to some cost reduction, as it takes more time to manually build a prototype than print it. (Rayna & Striukova, 2014, p. 122)

Brean (2013, p. 783) explained that automotive and aircraft industries were pioneers in the use of additive manufacturing to perform rapid prototyping. However, the high cost of using this new technology kept this practice from becoming mainstream until the 2000s. The situation changed in 2007 when the democratization of this technology made it possible to use it at a much lower cost. The decreasing-price of 3D printers has been the springboard for its expansion within many different industries (Rayna & Striukova, 2014, p. 122). We can give the example of FDM printers, which can now be purchased for less than $1000.
Rapid prototyping integrates 3 fundamental notions: time, cost, and complexity of shapes. Rapid prototyping focuses on saving time by quickly creating prototypes, for the purpose of reducing the design cycle time. The prototypes are made without the need for expensive tools, while ensuring the performance of the final product. Designers are thus able to explore different variants of the product being developed and then choose the most appropriate solution. This technique proceeds by adding materials and is capable of producing extremely complex shapes (inclusion, cavity ...). These complex designs are unachievable using traditional methods. (Hopkinson and Dickens, 2003, p. 33)

3.2.4.2 Rapid tooling

Rapid tooling refers to the production of tools using rapid prototyping, using additive manufacturing methods. Rapid tooling was the second stage of additive manufacturing development. Indeed, like rapid prototyping, rapid tooling does not radically change the production process but accelerates it (Noble et al. 2014, p. 252). Tooling remains an integral part of the traditional manufacturing process. Similar to rapid prototyping, rapid tooling lowers the cost of tooling. Even if this technique is not really economical for very small volumes, it nonetheless enables manufacturers to produce some limited elements of product customization, and so, makes it more affordable for firms to produce personalized and customized products (Rayna & Striukova, 2014, p. 124). For example, Zonder and Sella (2013, p. 48), calculated that it takes in general 30 days and $1400 to produce an aluminum mold enabling the manufacture of a set of six ice-cream spoons by injection molding. With additive manufacturing, the same mold can be printed in seven hours and for about half the cost ($785). Another example is that of U.S. nuclear submarines, where additive manufacturing enables the production of pump castings in 43 days at a reduced cost of approximately 60%. (Rayna & Striukova, 2014, p. 124)

Molds and casts that are 3D printed are faster to produce and significantly cheaper. Another point concerns the increased simplicity of modifying and customizing products for firms. This advantage means that they have the opportunity to serve new niche markets that had been left aside due to the high cost of customizing and personalizing products with traditional processes (Rayna & Striukova, 2014, p. 125). Campbell et al. (2007, p. 627) emphasized the fact that the lower cost of rapid tooling allows companies to develop in parallel several versions of the same product, thus making it possible to produce at the same time a range of the same product that can fit different market segments.

Concerning mold quality, a traditional mold can be used to produce 10,000 units, but the optimal quantity manufactured with a 3D printed mold is much lower, around 10 units (Zonder and Sella, 2013, p.48). The life of molds produced by additive manufacturing processes is therefore shorter than molds produced using traditional manufacturing processes. Noble et al. (2014, p. 253) explained that rapid tooling may serve as “bridge tooling” to begin production. Then, hardened steel molds are designed and machined through traditional processes. For Rayna & Striukova (2014, p. 125), rapid tooling is nowadays used in niche markets by firms who need intermediate tooling
to be able to produce a small number of functional test samples or prototypes for evaluation and to do tests on the market.

3.2.4.3 Rapid manufacturing/Direct manufacturing

Contrary to rapid tooling and rapid prototyping, additive manufacturing next stage of development, direct manufacturing, has the potential to deeply disrupt industrial processes (Rayna & Striukova, 2014, p. 127). Direct manufacturing can be defined as reducing the number of intermediaries between the production stage and the final selling stage as products are manufactured based on demand. The main reason is linked with the complete reconfiguration of the production process to implement direct manufacturing in industries. Another point concerns the potential of adoption. Whereas rapid tooling is limited in terms of adoption, as it is marginal for industries to order a 3D printed mold to manufacture products at a larger scale, direct manufacturing has far greater potential concerning the level of adoption. (Rayna & Striukova, 2014, p. 127)

Nowadays however, the cost of manufacturing with additive manufacturing processes remains more often higher than traditional processes. Industries that use additive processes do so to obtain the leverage of product uniqueness but not to replace traditional processes. One of the key aspects of the additive process is its ability to manufacture customized products at a large-scale (mass customization). As a result, industries can engage customers in a co-creation process and co-produce products, making sure that they answer the needs of customers. As a result, the value of the resulting product is more likely to be significantly higher than for mass-produced items (Rayna & Striukova, 2014, p. 127-128). Direct manufacturing enables the crowdsourcing paradigm to go one step further in industries. So far, crowdsourcing has been restricted to the ideation and design stages but now, with online 3D services such as MakeXYZ, companies can crowdsource the manufacturing of their products using various materials and finish qualities. (Calia et al., 2007, p. 428).

Direct manufacturing is a key technology that enables industries to serve any niche markets regardless of how small they are. It can also create new distribution channels. (Rayna & Striukova, 2014; Gibson et al., 2010). We can take the example of smartphone accessories. Companies can develop, in addition to their mass-manufactured products, a collaboration with online 3D printing services to produce accessories on-demand and directly sell them to their customers. In this case, no physical storage or transportation is involved until the consumer purchases the product.

With traditional manufacturing, fixed costs such as set-up costs, machinery, storage and transportation costs are significant while the marginal cost is often low. With additive manufacturing, fixed costs are lower and the marginal cost is higher. Besides the actual manufacturing cost, the cost structure has radically changed. In this respect, direct manufacturing enables companies to increase cash flow as they don’t have to pay upfront the production, storage and transport of a product, but can manufacture products on demand. Companies get the money upfront and then, pay for manufacturing and transportation. (Rayna & Striukova, 2014, p. 130)
3.3 Suppositions regarding Additive manufacturing impacts on lean practices

We know that additive manufacturing has never been studied with lean practices framework. But it is possible to find in some researches and articles information about its impact on production. In this part, I gathered these information and make some statements about additive manufacturing impacts on lean practices.

3.3.1 Overproduction waste

The ability to design and print objects based on demand has the potential to transform the codes inherited from the Industrial Revolution. We can illustrate it with one traditional industrial rule: economies of scale (Henderson, 2003, p. 5). With traditional manufacturing, if a customer wants to produce one single product, for example a screwdriver, the tool maker will ask for thousands of dollars. The screwdriver maker would have to first create a mold to produce the head and the plastic handle, machine it and assemble the parts. However, to be profitable, it is better to produce thousands of screwdrivers so the cost per unit will decrease (thanks to economies of scale). With additive manufacturing, economies of scale matter much less and production flexibility seems to increase. The cost of setting up the machine which produces a product is the same whether it produces one or many products (The Economist, 2011). Moreover, as additive manufacturing permits the production of small series, we can argue that this technology can reduce the production cost as no surplus of products are produced and stocked.

“Three-dimensional printing makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. It may have as profound an impact on the world as the coming of the factory did....Just as nobody could have predicted the impact of the steam engine in 1750—or the printing press in 1450, or the transistor in 1950—it is impossible to foresee the long-term impact of 3D printing. But the technology is coming, and it is likely to disrupt every field it touches.”

— The Economist, in a February 10, 2011 leader

3.3.2 Waste of waiting time

Delays are often due to the movement of goods or delays concerning a process to be completed. With additive manufacturing, process time is easier to evaluate as one machine can produce the final product. Therefore, employees don’t have to wait for additional materials and tools. Moreover, as additive manufacturing uses integrated systems (data file), information flow is easier to manage.
3.3.3 Waste of transportation

Xerfi (2014) research explained that automotive supplier activities are focused on design, manufacturing and assembly. Strategic parts such as vehicle engines, transmissions and bodies are mainly produced and assembled by the carmakers themselves. 60-75% of a vehicle's value lies in components outsourced to suppliers. With externalization of certain activities, industries often produce parts in multiple locations, which leads to companies creating several inventories in multiple geographical places. The parts are then moved to a facility where they are assembled into the final product. With additive manufacturing, some steps concerning some products can be replaced as this technology allows the production of multiple parts on the same machine, making it possible to produce an entire product (see 3.2 the conceptual definition of Additive manufacturing). These characteristics reduce the need for companies to maintain large and dispersed inventories. It would be easier for companies to manage geographically decentralized production and eliminate useless intermediaries to reduce both the transportation of parts produced at varying locations and the need for just-in-time delivery.

3.3.4 Waste of inventory

In 2011, $537 billion were stuck in inventories in the global manufacturing industry, which was the equivalent of 10% of the revenue (Xerfi, 2014). The resources which were used to produce and store these products could have been used differently if the need for industrial companies to have large inventories were reduced. Manufacturers often suffer from high distribution costs and large inventories. Additive manufacturing has the ability to manufacture parts based on demand. We can give the example of the spare parts industry. In this industry, specific parts are infrequently ordered but when one is needed, it should be produced rapidly because idle equipment and machinery that are waiting for parts are costly. With traditional technologies, it is too costly and time consuming to produce parts on demand. This results in a significant amount of inventory, full of infrequently ordered parts. This kind of inventory is costly and useless. These infrequently ordered parts occupy physical space, buildings or land that require rent, insurance, utility costs and taxes (Douglas et al., 2014, p. 214). Being able to produce parts on demand with additive manufacturing significantly reduces the need for keeping large inventories and it also eliminates the associated costs.

3.3.5 Waste of motion

As I said previously, additive manufacturing technology is able to produce multiple kinds of products on a single machine. Therefore, it considerably reduces the necessity for employees to move products from one machine to another. However, others issues regarding additive manufacturing use arise. From an environmental point of view, additive manufacturing is an energy hog. According to research done by Baumers et al (2011, p. 32), when 3D printers melt plastic with heat or lasers, the electrical energy consumed is about 50 to 100 times more important than the electrical energy used with an injection molding process in order to make a product of the same weight. 3D printers
may also cause a health risk because of emissions of ultrafine particles that occur during plastic heating (Stephens et al., 2013, p. 336). On one hand, additive manufacturing can have a positive impact on employees’ necessity to move but, on the other hand, these ultrafine particles may have a negative impact on employees’ health.

### 3.3.6 Waste of producing defects

The advantages of additive manufacturing allow manufacturers to rapidly redesign and rework a part in order to meet customers’ needs. However, some quality issues concerning the final product have been discussed in empirical literature. The quality of additive manufactured products varies largely between different printers. Other factors that impede the diffusion of additive manufacturing technology are the limits on materials that can be used, the durability of created objects, expensiveness of the technology, as well as lack of knowledge among different stakeholders (Dillow, 2013, p. 58).

### 3.4 Additive manufacturing in the automotive industry

Additive manufacturing implementation in the automotive industry began 30 years ago with rapid prototyping. Companies such as Ford, Daimler, Toyota, or Chrysler already have an extensive experience concerning this technology. In SmartTech Markets Publishing LLC (2014), researchers predicted that revenues from using this technology will exceed $870 million in 2019 and will probably reach more than $1.8 billion in 2023. In 2014, revenues were estimated at approximately $265 million. In Smartech Markets publishing LLC (2014), researchers seem very optimistic regarding the additive manufacturing evolution in the automotive industry. In Gausemeier et al. (2013), researchers are more doubtful and explained that in 2009, the automotive industry contributed 17.5% in volume to the total additive manufacturing market, which corresponds to about $190 million. SmartTech Markets publishing LLC (2014) emphasize the fact that the automotive industry is currently the major user of additive manufacturing processes, as this industry accounts the largest market volume, compared to all examined industries that are, in this research paper, aerospace, armament, automotive, dental, electronics, furniture, implants and prosthetics, jewelry, specialty food, sports, surgical devices and aids, textiles, tool and mold making, toys and collectibles industries. Gausemeier et al. (2013) are more circumspect as they explained that the additive manufacturing market remains marginal, even in the automotive industry, compared to the world market volume.

In some research, we can read that additive manufacturing is not limited to rapid prototyping anymore. The automotive sector is exploring new ways to use additive technology (Cotteleer at al., 2014, Rayna & Striukova, 2014). Car manufacturers’ main motivations for using additive manufacturing are the ability to produce lower-weight and safer products and new products impossible to produce with traditional manufacturing processes as well as to enable the reduction of lead time and improve supply chain performance. It also enhances an extensive product customization and lower-inventory (Cotteleer at al., 2014; Manyika et al., 2015; Rayna & Striukova, 2014).
Concerning the future trends for this industry, I found two different points of view. Xerfi (2014) and Manyika et al. (2015) studies both agree concerning the importance of the growth of innovation in the car manufacturing industry (such as fuel-efficient, safety, alternative engines and connectivity), the cost-cutting strategy and the globalization of car makers. For Cotteleer et al. (2014) and Manyika et al. (2015), additive manufacturing will play a crucial role in creating the vehicles of the future which answer those innovative issues. However, Xerfi (2014) states that standardization will become the norm, which means less variety in the parts required and increased volume. The Cotteleer et al. (2014) and Manyika et al. (2015) forecasts seem to favor the additive manufacturing expansion, contrary to Xerfi (2014) forecasts which tend to highlight the traditional industry. These trends are not completely opposed and emphasize the complementarity of these methods which can be and are used simultaneously within the current industrial process.

Traditional manufacturing is perfectly adapted for companies with high-volume production where specific tools are needed. Costs are amortized due to the large number of units produced. Additive manufacturing is often more competitive when a low or medium-volume of units are needed. Concerning materials, traditional manufacturing techniques are suited to a wide variety of materials, while additive manufacturing techniques can be used with a narrower range of materials. To manufacture large parts, traditional manufacturing is also more suitable (Cotteleer et al. 2014). Cotteleer et al. (2014) also highlight that additive manufacturing is a source of product innovation for the automotive industry. This technology can produce parts with fewer design restrictions compared to traditional manufacturing processes. Design flexibility is useful as it permits industries to produce parts with custom features, add functionalities such as complex geometries, integrate electrical wiring through hollow structures and lower weight through lattice structures. Furthermore, new additive manufacturing processes are able to produce multimaterial printed parts with specific properties such as variable electrical conductivity or variable strength (Ivanova et al., 2013). Cotteleer et al., (2014) research concluded that additive manufacturing processes play an important role in creating safer, faster, more efficient and lighter vehicles.

The idea of creating products with flexible and customized design is also found in Manyika et al. (2015). In Manyika et al. (2015), researchers explained that manufacturers sticking to business-as-usual approaches will be increasingly at risk and must develop a granular understanding of the world. Car manufacturers should understand trends to be able to seize new opportunities and exploit them. They have to develop a detailed, granular view of markets and customer segments to identify and tailor products and supply chain strategies to specific sub-segments of markets. Manyika et al. (2015) and Cotteleer et al. (2014) both discussed the fact that the automotive industry has to further develop their ‘build-to-order’ approach in which customers are able to choose some vehicle characteristics before the production stage. Currently, consumer choices for their future car are quite limited and superficial and lead time remains long. They both believed that additive manufacturing can be a relevant technology to increase the possibility of customers customizing their cars and so bring new opportunities to the car industry.

Cotteleer et al. (2014) has reviewed different applications of additive manufacturing in the car industry. We can see in Appendix 4 that additive manufacturing is already used to
produce different parts with different processes using both polymers and aluminum materials.

The last interesting point discussed in Cotteleer et al. (2014) concerns supply chain transformation drive by additive manufacturing implementation. By directly producing final parts and eliminating the need for new tooling, additive manufacturing cuts down lead time and so, improves market responsiveness. As additive manufacturing only uses the materials necessary to produce a component, this technology drastically reduces material usage and scrap. For Cotteleer et al. (2014), additive manufacturing can produce lightweight parts and thus, lower handling costs. On-demand and on-location production also have an impact on lower inventory costs and size. For Cotteleer et al., (2014), additive manufacturing offered the possibility to the automotive industry of driving significant changes to their supply chain and business model, and improving the ability to better serve specific customer needs without the need of an extensive capital deployment.
4 PRACTICAL METHOD

In this part, I explain the sampling and the research methods. Concerning the primary data, I explain how I have prepared interviews, selected companies within the car manufacturing industry, how I collected data and transcribed them. Concerning the secondary data, I explain how I have selected companies within car manufacturing industry and how I have accessed, collected and analyzed data. This part clarify the methods I have used to process and analyze data.

4.1 Sampling and research methods

The choice of sample is important for a research. The sample of population should be structured to ensure that participants can provide answers to the research question but the sample should also be diversified enough that each respondent can bring something new to the research (Bryman & Bell, 2011, p. 442). For Bryman & Bell (2011, p. 441), in a qualitative approach, probability sampling is almost never conducted because of the limitations of continuous research. On the other hand, purposive sampling is defined as a nonprobability sampling. Purposive sampling allows the researcher to choose participants in order to help him to achieve his research goals (Saunders et al., 2011, p. 273). But the purposive sampling is a non-probability sample method so this type of sampling does not permit the generalization of results, for example in my case, to generalize my results to another industry (Bryman & Bell, 2011, p. 442).

Since my goal is to study a very specific phenomenon to generate accurate results, I chose to use a purposive sampling technique for this thesis. First, in order to understand what type of companies and respondents I should target, I started the research process by developing my knowledge of the field through reading peer-reviewed material and newspaper articles, as well as by visiting Mats Falck at Umeå University External Relations who has conducted a project related to additive manufacturing in Sweden. Mats Falck gave me an overview of the project as well as a written pamphlet that was the outcome of the project. He also gave me contact information for the person who is knowledgeable about the use of additive manufacturing technologies at Volvo Trucks. I sent this person an email but unfortunately an interview in any form was not possible. I also tried to contact some additive manufacturing experts by LinkedIn but this attempt was unsuccessful. Therefore, I chose to use my network in France in order to find respondents. I listed companies and respondents, most of the time managers in senior positions who work closely with additive manufacturing technology. I also made research on automotive companies’ websites in order to find as much secondary information as possible. These kinds of data are important in research as they increase the objectivity of the research, explain reality in a relevant way contrary to primary data which are more subjective.

For the collection of both primary and secondary data, I chose to select companies regarding their global ranking concerning the production volume, manufacturing sites, country headquarters and the revenue in 2014. I selected companies which were in the Top 20 of the most important companies worldwide (concerning both the production volume and the revenue), to be able then to increase the generalization of my findings to
the whole automotive industry. I believe that these companies leading this oligopolistic industry and being technologically developed are representative of the trends within the automotive industry. I also include one case study of luxury car company, as these companies are technologically well develop too. For ethical reasons, I cannot divulge the names of the companies I interviewed. However, I share a table gathering information about the companies I used the websites information (secondary data) further in my research paper. The reader can also be sure that the nine case studies I use (four from interviews, five from secondary data) are nine different automotive companies.

4.2 Primary data collection

Before contacting each potential respondent, I researched the company on internet and looked up staff when they had a LinkedIn profile.

Due to the specific area I investigated and the shortage of resources and time, many potential respondents declined my invitation to collaborate. As I previously explained, I first tried to contact respondents at an international level through the resources available to me, LinkedIn and personal contacts. As this technique was unsuccessful, I decided to investigate in France through the network of my business school and my personal network. I was looking for respondents from the automotive industry, managers in international companies which had implemented additive manufacturing in their processes.

The first contact I had with these managers was an e-mail which summarized the purpose of my research. As suggested by Saunders et al. (2011, p. 329), my email also included the research objectives and explained how respondents were expected to participate. Another important point concerns the researcher knowledge about the company and staff they attempt to interview (Saunders et al., 2011, p. 329).

The number of interviews that should be conducted by the researcher are not set for any type of research. Saunders et al. (2011, p. 330) suggest continuing interviews until no more data to create new insights can be collected. For this research, I also had to consider the fact that the respondents I was looking for needed to be specific experts. It was not easy to contact them and several times, they were too busy to answer my questions. Therefore, I have done my best to deal with these two obstacles and found that the four interviews, combine with four case studies as the outcome of my secondary data research, were enough to answer my research questions.

4.2.1 Interview guide

The main objective when a researcher prepares an interview guide is to give indications to the respondents concerning the information the researcher expects to gather and the direction he desires for his research. Even if qualitative research is unstructured by nature, the interview guide helps the researcher to focus and concentrate on his research (Bryman & Bell, 2011, p. 475) to increase reliability and reach his objectives (Saunders et al., 2011, p. 330). The interview guide’s structure should help the researcher to answer his research questions, even though, at the same time, the respondents’ standpoint must be considered (Bryman & Bell, 2011, p. 475).
Questions in my interview guide are based on a theoretical framework and personal reflection aim to answer my research questions. However, as I did not wanted to be too directive with my participants to let them express their opinion, I tried to ask questions with a broad-spectrum of answers. Bryman & Bell (2011, p. 475) emphasize the fact that questions asked in the interview guide should not be leading questions. I tried to formulate simple questions and started my interviews by simple questions to gradually go deeper and deeper into the topic. The questions in the interview guide should be present in a consistent and rational order for participants and be formulated with an understandable language (Saunders et al., 2011, p. 330). I have divided my interview guide into three parts. First, I asked general questions regarding the background and the current position of my respondents. Then I asked them questions regarding how their company uses additive manufacturing and ended the interview by asking them questions regarding additive manufacturing impacts on production wastes. A full version of the interview guide can be found in appendix 5.

4.2.2 Companies and respondents description

The respondents are all experts in four different automotive companies. Through my empirical findings and analysis, I will refer to my respondents by codes presented in table 1 for ethical reasons. For example, answers from respondent 1 will be referred to by R1 etc.… As my respondents were French, I conducted the interviews in French and then translated everything into English.

4.2.2.1 Automotive company (C1)

My first interview was conducted with a senior prototype engineer based in Paris, France. He has been working in his current company, which is a German company, for 8 years and has 22 years of experience with product engineering and manufacturing. He is in charge of coordinating new products manufactured through the prototype processes. His job is not limited to the management of prototype fabrication; he also develops prototypes to production status and optimizes new products through part functionality and uses statistical capability to maximize prototype quality and manufacturability (cost estimation, document control, profit-loss tracking, and contribution to the existing quality system documentation). He also has some tasks related to project management (project time management and team management).

4.2.2.2 Automotive company (C2)

My second interview was with a rapid prototype fabricator also based in Paris. He has worked in an American car company for 5 years. With his team, he is engaged in different types of work that are done in the fabrication shops. Each member of the team has assigned tasks within the design organization and makes prototypes and parts in the plastic, metal, paint, trim and wood shops.
4.2.2.3 **Automotive company (C3)**

My third interviewee was a manufacturing engineer section supervisor. He works in a German company and his daily work is similar to R1. He has worked in 2 different automotive companies. He first worked in Japan but chose for personal reasons to come back to France and he has now been working for 13 years in his current company.

4.2.2.4 **Automotive company (C4)**

The last interview was conducted with a prototype engineer who is working in a French company. He started his career in the press industry and has now been working for the same automotive company since 2000. He was first a prototype preparer, then a prototype supervisor for workshops in Korea and Romania and is now manager of the upstream strategic functional team, which means that he is in charge of developing the international network of suppliers.

4.2.3 **Conducting the interviews**

As respondents were located in different geographic places, I conducted all interviews by phone. According to Fernández et al. (2012, p. 307), an interview conducted face-to-face and an interview conducted by phone have similar results. Moreover, phone interviews are cheaper for both the respondent and the researcher (Bryman & Bell, 2011, p. 489). Therefore, I believe phone interviews are suitable when it is hard to meet respondents due to distance. However, conducting an interview by phone carries some disadvantages. First, it is not easy to record participants; certain tools are required and even so, the audio recording might be unclear (Bryman & Bell, 2011, p. 489). To overcome this obstacle, I used a phone-recording application. During the interviews, I also used follow-up questions in order to push respondents to elaborate and explain in detail their answers (Bryman & Bell, 2011, p. 489). Thus, complex theoretical concepts and specific terminology were avoided in order to reduce confusion and misunderstanding between my respondents and me. To make sure that my respondents also understood my questions, I did not use complex and technical terms to formulate my questions. And at the end of each interview, I formulated a summary of the most important points we had discuss to make sure that I had fully understand them and that there was no bias in the answers. I also offered the opportunity to the participant to add extra information that could be relevant and important for them. This interview guide was very helpful for me in conducting interviews. As Bryman & Bell (2011, p. 490) explained, the length of time of each interview in qualitative research may vary. I believe that the interview guide helped me to have a certain homogeneity regarding the timing of each interview. Interviews I conducted were in general between half an hour and forty-five minutes long. In the following table, I summarize the characteristics of each interview I conducted, and mention the duration of each of them. Since some of my respondents asked me to not reveal both their name and the name of the company, I chose to keep the anonymity of all my respondents. Therefore, I provide limited information regarding their companies and only offer information regarding their position and years of experience.
<table>
<thead>
<tr>
<th>Company</th>
<th>Participant</th>
<th>Position</th>
<th>Country</th>
<th>Interview</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>R1</td>
<td>Senior prototype engineer</td>
<td>France</td>
<td>Phone</td>
<td>32 min</td>
</tr>
<tr>
<td>C2</td>
<td>R2</td>
<td>Manufacturing project coordinator</td>
<td>France</td>
<td>Phone</td>
<td>30 min</td>
</tr>
<tr>
<td>C3</td>
<td>R3</td>
<td>Manufacturing engineer section supervisor</td>
<td>France</td>
<td>Phone</td>
<td>34 min</td>
</tr>
<tr>
<td>C4</td>
<td>R4</td>
<td>prototype engineer</td>
<td>France</td>
<td>Phone</td>
<td>45 min</td>
</tr>
</tbody>
</table>

**Table 1. Respondents for my research and their characteristics**

### 4.2.4 Transcription

In qualitative research, it is a prerequisite to record interviews (Bryman & Bell, 2011, p. 482). Recording and transcribing interviews is therefore easier for the researcher who doesn’t lose any important information that has been said by participants. It also allows the researcher to focus on his discussion with the respondent as he can take superficial notes during the interviews. In the transcription, it is important that the researcher integrate some notes regarding the respondent’s attitude regarding questions, pauses, silences and all non-verbal signals that can bring additional information (Saunders et al., 2011, p. 333-334). Before each interview, I asked respondents about my intention to record our discussion and explained why it was important for me and my research (Bryman & Bell, 2011, p. 482). It is important to ensure the anonymity of participants to make them feel comfortable and able to talk freely about the research topic (Saunders et al., 201, p. 482). I checked that they were comfortable with this idea and explained that I would be the only person with access to these recordings. All my respondents accepted to be recorded under these conditions. I transcribed interviews right after the discussion I had by phone with my participants to be sure that I had completely understood their perspectives and eventually asked them for extra information, feedback or clarifications by e-mail a few days after the interview.

### 4.3 Secondary data collection

#### 4.3.1 The selection of companies, data collection and access

For my study, I selected five car manufacturing groups that fit to my study purpose by representing different ways additive manufacturing have been implemented within these firms processes and supply chain. The five car manufacturing groups that I investigated are Ford, Honda, Toyota, Volkswagen (Volkswagen Polo and Audi brands) and Koenigsegg.

Ford Motor Company is a global automotive industry leader based in Michigan. They have about 194,000 employees and 66 plants globally, and manufacture and distribute
automobiles across six continents. The company has two automobile brands: Ford and Lincoln. (Ford.fr)

Honda is a Japanese automaker that was established in 1946 by Soichiro Honda. In its early days Honda produced only motorcycles but has later become a global car manufacturer. (Honda.fr)

Toyota Motor Corporation is a Japanese automotive manufacturer. Toyota multinational corporation employs almost 340 000 employees worldwide and produce more than 10 million vehicles per year. (Toyota.fr)

Volkswagen group is one of the world’s leading automobile manufacturers and the largest carmaker in Europe. The group sell around 10 million vehicles per year. The group comprises twelve brands. In this study, I analyze Polo and Audi brands. Audi is a German car manufacturer. They have two car brands, Audi and Lamborghini, as well as the motorcycle brand Ducati. (Volkswagen Group.com)

Koenigsegg is a Swedish car manufacturer, specialized in high-performance sports cars. The company was founded in 1994 by Christian von Koenigsegg. Focused on performance, Koenigsegg develops and produces most of the components of their cars and have a large R&D department. At the end of 2015, the company had 97 employees including 25 engineers. (Koenigsegg.com, 2015)

I selected these companies on different criteria. First, I considered the global ranking concerning the production volume and their revenues. I chose automotive companies which are leading this oligopolistic industry and being technologically developed as I believe they are representative of the trends within the automotive industry. Then, I chose international companies as I think it’s important to have an accurate overview of additive manufacturing implementation at a world scale. The only exception is for Koenigsegg. I selected this company to represent the luxury car niche market. You can find a table below that resume the information in found about these companies:

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
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<td>worldwide</td>
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<td>Japan</td>
<td>worldwide</td>
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<td>Japan</td>
<td>worldwide</td>
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<td>215,298</td>
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<tr>
<td>Volkswagen</td>
<td>3</td>
<td>Germany</td>
<td>worldwide</td>
<td>1</td>
<td>220,290</td>
</tr>
<tr>
<td>Koenigsegg</td>
<td></td>
<td></td>
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</table>

Table 2. Information about the companies studied (information from Xerfi, 2014)
4.3.2 Data collection and access

As I said previously, I attempted to gather as much relevant empirical evidence from as various and relevant sources as possible. I used the official websites of my studied companies, their official press releases and various interviews in text or video format where representatives of the studied companies are discussing their use of additive manufacturing technologies. I have maximized the use of recent information and reports. I used public data which were accessible for everybody on the web. Thus, I have not taken any personal contact with companies or used other data accessing alternatives.

**Ford**
I gathered empirical evidence from Ford official news articles where Ford discussed the use of additive manufacturing technologies and forecasts for the future. I also used a video published on their website where three Ford representatives are discussing the characteristics and the benefits of their use of additive manufacturing technologies. (Media.ford.com; Gilpin, 2014)

**Honda**
The empirical evidence of the use of additive manufacturing technologies at Honda is collected from a Honda R&D research paper and the official website of Honda’s 3D printing related campaign. (Honda 3D Design Archives, 2015; Honda R&D Research Paper website, 2014)

**Toyota**
The empirical evidence of the use of additive manufacturing technologies at Toyota is collected from a Toyota press release where the “Mas Que Un Auto” – campaign is described as well as two newspaper articles providing an overview of the Toyota Motorsport GmbH (TGM). (Toyota.com; Corporatenews.pressroom.toyota.com; (TCT - 3D Printing, Additive Manufacturing and Product Development Technology)

**Volkswagen**
The empirical evidence of the use of additive manufacturing technologies at Volkswagen is collected from an official Volkswagen video from (Thepoloprinciple.com, 2014) that explains Volkswagen’s The Polo Principle campaign. I also collected information from Audi, a subsidiary of Volkswagen. Information about Audi are collected from an official Audi video where an Audi representative discusses how they are using additive manufacturing in their processes. (Audimedia.tv, 2015)

**Koenigsegg**
The empirical evidence of the use of additive manufacturing technologies at Koenigsegg is collected from the transcripts of two videos, possible to find on the company website, where the Koenigsegg CEO Christian von Koenigsegg explains how they have used additive technology in their One:1 car, both in the design phase as well as in the final production of various parts. (Koenigsegg.com, 2015)
4.3.3 Data processing and analyzing

I decided to analyze the results companies by companies. I chose to alternate some quotes from videos of experts talking about additive manufacturing implementation in their companies and information found in the press release of these companies. The interviews I transcribed have as main purpose the implementation of additive manufacturing without discussion about links with lean practices. Thereby, I don’t present the results the same way as primary data. However, some precious information about time and cost saving can be found throughout these data.
5 RESULTS OF INTERVIEWS I CONDUCTED

In this part, I gather the results of the four interviews I conducted: I first present how automotive companies use additive manufacturing and then present how additive manufacturing impacts the seven production wastes.

5.1 Additive manufacturing implementation

All respondents discussed why and how additive manufacturing technology has been implemented in their companies. For all of them, this technology has been used for a long time during the prototyping phase. As R4 said “additive manufacturing is massively used as a tool to help designers during car conception. We started to use this technology during the 80’s with stereolithographic. Nowadays, we use all types of additive processes […]. In our company, additive manufacturing is not massively used to produce end-parts directly used on final vehicles. However, I heard that some niche automotive companies use this technology to produce end-parts but only for small series (5-6 pieces) […]. One niche example is luxury car makers”.

R1 R2 and R3 also mentioned the fact that they used additive manufacturing during prototyping phase but they don’t commonly use it to produce end parts integrated into the final product.

R1 explained that their Rapid Technologies Centre fabricates nearly 100,000 parts annually by using 3D printing methods. These parts range from vehicle parts for functional tests to small plastic holders and design patterns. His company uses Fused Deposition to manufacture components that are made in small volumes: “this process can become an alternative to the conventional metal-cutting manufacturing methods such as milling, turning, and boring. We also use additive technology to produce complex bodies, which are too expensive to produce using conventional metal-cutting processes” (R1).

R2’s company used different additive manufacturing processes, including SLS and FDM. They used additive technology through rapid prototyping, which helps them to cut costs and time related to the process. They also used indirect additive manufacturing to produce tools, which refers to printing casts or molds that are used in the fabrication of end parts. R4 also mentioned the fact that rapid tooling was sometimes used to produce molds and casts but “most of the time, we use additive manufacturing for rapid prototyping” (R4).

Going deeper into additive manufacturing used during the prototyping phase, R3 stated that “we can divide the prototyping phase into two main processes: first, the numerical realization, which consists of the creation of the product prototype using numerical tools. The second one is the physical realization. During this phase, we use additive manufacturing to confirm numerical prototypes. We build a physical prototype to verify the global design and also check if the tools that will be used to build the future car can access narrow places in the car.” R3 also explained that “Currently, numerical tooling tends to replace physical realization”.

When I asked respondents about the reasons why they don’t use additive manufacturing to produce end-parts, R1 and R3 emphasized the fact that this technology is not mature
enough to produce end-parts. R1 added that “the physical aspects of parts that are produced layer-by-layer is not perfect, for example plastic parts have to be reworked to remove imperfections and give them a smooth appearance”. Another issue is linked to tender specifications. For every new vehicle, documents are created to specify the vehicle conception logic. « In our company, these documents are created 48 months before the vehicle commercialization. These documents are the result of an upstream documentation which includes the main orientations of the company (research, quality, design, purchasing, etc.). It aims to describe the product objectives of the said vehicle, within a framework set by internal profitability such as entry ticket, cost or asset utilization, and external market forecasts such as penetration, sales price, and geographical coverage. These specifications are a milestone in the development. Each part of the vehicle is also precisely described. The part quality is too uncertain in my opinion with additive manufacturing processes to fulfil all the quality requirements we have.” R4

All respondents recognized that even if the technology was more mature, it is very expensive to change their internal process, to switch from traditional industrial processes to additive processes. “The initial investment should be considered” (R1). R3 mentioned that “It is not only the technology itself that is expensive but also all related costs such as supply chain restructuration and experts with enough knowledge and skills to use machines”. R3 and R4 both agree with the fact that for them, this technology will never completely replace traditional manufacturing”. R4 added that “perhaps a hybrid automotive industry can emerge, using both traditional and additive techniques” but he remained sceptical about it.

I then asked for further information concerning the types of materials which are printed layer-by-layer during the prototyping phase. R4 explained that “The first vehicles we produce generally contain 3D printed plastic pieces. When some vehicle pieces are too small or too large, when the quality of junction between pieces is not good due to a conception problem, additive technology is very useful for designers as they can 3D print another piece and test it straight away. We also use it for metal parts but less often as this process is expensive.”

Concerning the parts that are 3D printed, respondents named wheels, exterior plastic parts, exterior headlights and some plastic buttons inside the car. These parts are 3D printed during the prototyping phase but then, produced in large batch with traditional manufacturing tools. As mentioned earlier, additive manufacturing processes are suitable for small batch and R4 again highlighted that “producing all these parts with additive manufacturing is not worth it for us as we produce thousands of pieces everyday”.

The last interesting point I discussed was with R4 concerning the use of additive manufacturing during early prototyping, when car makers create cars that are called technological demonstrators. These cars are secretly developed by car manufacturers and are very innovative. In that case, designers involved in such projects use the full range of additive processes to build prototypes at reduced size.
5.2 Additive manufacturing impacts on the seven production wastes

5.2.1 Over production

The respondents discussed the impacts of additive manufacturing on over production waste. It seems that additive manufacturing impacts on over production waste remain limited.

The experts all agree with the fact that, currently, additive manufacturing production cannot compete with conventional fabrication methods (traditional manufacturing) concerning the production of large size parts. R2 explains that “it is not possible to produce large parts with additive technology, it would perhaps be possible in the future but currently, it is not”. R1 explains that “for the moment, it is better to produce most of the parts we used with traditional machining, even if it means to have surpluses, losses and large stocks.”

R4 mentioned the fact that « […] parts we produced with additive technology are limited in terms of volume, compared to the parts we produce with traditional machining. They represent a tiny part of our production. As I said previously, additive technology is used to produce end-parts for luxury cars or race cars as this technology can produce parts with improved safety and weight factors in small series.” R4 continued “this technology is used in luxury cars, for example, to produce parts with complex designs that would be impossible to make with traditional manufacturing methods. But in our company, we produce thousands of vehicles per day, and pieces don’t differ a lot from one vehicle to another, for us, it is not worth it…”

Further evidence concerning the marginalization of additive manufacturing in the production process of commercial cars is the fact that “… the number of additive manufacturing parts represent probably less than 1% of the total number of parts we produce per year in volume!” (R3)

5.2.2 Waiting time

Concerning the waste of waiting time, the respondents agree that it is an important challenge for automotive companies to reduce this waste “the automotive supply chain is very complex as we have to deal with multiple suppliers to manufacture our products, manage multiple inventories and control points. The processes to develop a new product and commercialize it are very long (often several years) and costly […] New product development is critical for the automotive industry. It is common that we have to wait for tooling or parts in order to complete a batch” (R2). However, experts don’t really see how additive manufacturing can currently reduce this waste during the production phase “Currently, the use of additive manufacturing is too marginal to have a significant impact on the waste of waiting time.” (R1)
R4 mentioned the fact that “The benefit of additive manufacturing on waiting time can be seen during the prototyping phase, with the countermeasure pieces. Being able to produce countermeasure pieces in 3 days with additive manufacturing instead of 6 months with traditional manufacturing is an important benefit for us. And sometimes, with the new countermeasure piece, we realized that other pieces need to be reworked too. And we gain a lot of time when we see these flaws during the prototyping phase instead of during the machining stage”.

5.2.3 Transportation

Transportation is also an important issue for car manufacturers. As R2 explained “In traditional manufacturing, parts are produced in multiple locations and by different suppliers, and stocked in multiple inventories. The parts are then shipped to a facility that centralizes them. Then, they are assembled into a product and delivered to the client” (R3). R2 also mentioned the fact that 70% of parts are outsourced “only strategic parts such as the bodywork or the engine are produced in-house”.

R4 mentioned “it is true that if most of our parts were produced by additive processes, this waste could be reduced as we could produce an entire part, sometimes already assembled, at a single place. We can imagine that it could also reduce the need to maintain large inventories. But for all the reasons we have previously discussed, this scenario seems unrealistic”.

5.2.4 Over processing

The respondents discussed the impact of additive manufacturing on over processing waste. Again, R4 explained that “countermeasure pieces we can create rapidly with additive manufacturing are very useful for us as we can check the final design and make adjustments during the prototyping phase. This feature limits the number of necessary reworks which occur during the machining phase and so simplifies processes. Solving technical problems during the prototyping phase helps us to save a lot of time, energy and reduce costs.”

R1, R2 and R3 were again sceptical about the impact of additive manufacturing on over processing as the use of this technology remains marginal compared to traditional process.

5.2.5 Inventory

Concerning the inventory waste, all respondents agree that many raw materials and components are unused and stocked in large inventory. “Inventories are inert capital for companies” (R3). However, respondents agree that even if additive manufacturing could be a solution to produce small batches and so, reduce inventories, it is still better, for the moment, to continue to produce most of the parts with traditional manufacturing, even if it creates surpluses, losses and large stocks.
5.2.6 Motion

Concerning the waste of motion, respondents mentioned again that additive manufacturing use remains limited, therefore the impact of this technology on waste of motion remains limited too. Additive manufacturing allows manufacturers to produce one part with only one machine, therefore, R1 explained that “as additive manufacturing has the ability to produce fewer but more complex parts, contrary to traditional machining where a large number of simpler parts are produced and then assembled, it can reduce employees unneeded motion as the final piece can be created with only one machine. Therefore, employees don’t have to carry parts between different machines. But it is the only interesting point I can highlight concerning the impact of additive manufacturing on waste of motion”. This was also the opinion of R4.

5.2.7 Producing defects

R2 and R3 agree with the fact that it is possible to produce precise pieces with additive manufacturing processes but appearance and final quality issues should be considered “for sure, we can produce precise pieces with additive techniques and so, reduce the number of defective pieces. However, there is a problem concerning the appearance and the quality of final pieces due to the layer-by-layer technique.” (R2)

R4 goes further to say that “the fact that we don’t need to build molds when we use additive techniques is a positive point as it takes time and energy to create a mold. Moreover, a 3D printed mold can be used to produce a dozen pieces so we need to have many of them. When we need to rework some pieces, additive techniques are worth it compared to traditional machining”. But R4 also explained that “there is a problem concerning the quality of the final product with additive manufacturing. The fact that we lodge plastic layer-by-layer weakens the material. Therefore, pieces which are 3D printed cannot be used as key pieces in the vehicle; they can be used on the bodywork (after being reworked to give them a smooth appearance) but not in the engine for example. Moreover, we use different kinds of plastics, depending on if we want to use these raw materials with traditional machining or additive one. This characteristic is also an issue concerning the quality of pieces that are produced layer-by-layer.”
6 RESULTS OF INFORMATION I GATHERED ON AUTOMOTIVE COMPANIES’ WEBSITES

In this part, I present the results of the four companies I investigated concerning the use of additive manufacturing in their processes: These companies are Ford, Toyota, Honda and Volkswagen

6.1 Ford

According to Ford, they have been using additive manufacturing technologies for 25 years. They also claim to have been involved with the invention of additive manufacturing technique in the 1980s and that they purchased the third 3D printer ever made. Currently, Ford is using several additive manufacturing processes. They are also cooperating with suppliers to bring more additive manufacturing technologies to market. (Ford.com)

The following quotes are taken from the previously presented Ford webpage as well as a Ford promotional video where Paul Susalla, Rapid Manufacturing Section Supervisor, Roy Ramer, Rapid Manufacturing Project Coordinator, and Harold Sears, Technical Expert / Ford additive manufacturing specialist, describe Ford’s use of additive manufacturing technologies:

“Ford uses 3D printing because it gives us a lot of advantages and enables us to create something right away. We can do many iterations, all at the same time. We can come out, engineer come say “I’ve got some ideas, I’ve got five or six different parts, I don’t know which one I want”. We’ll make them all once. And we’ll make them all on a very short period of time. So then we’ll be able to put them on test and say “OK this gives me the direction, now I’m going to go and make three new parts, better, completely different than these, but they give me the information. And you can do that time and time again and come up with a really optimized part at the end of the day. And that’s all because of the speed that we can produce the prototype parts without tooling” (Paul Susalla, video, 0:27)

“So we are literally taking something that took 16 weeks and taking it down to just couple of days.” (Harold Sears, video, 1:05)

“So we can do the real life physical testing that holds up exactly to the way of production part we hauled up” (Harold Sears, video, 1:39)

“3D parts that we make for prototypes go on every part of the vehicle you can think of. We cover engine, transmission, we’ve done every program within Ford motor company in North America and abroad” (Roy Ramer, video, 1:09)

“Today, 3D printing is not fast enough for the high-volume direct production manufacturing we do, but it is ideal for test parts, or niche production applications, that go through frequent development changes.” (Harold Sears, webpage)

These illustrate the time savings related to the use of 3D printing technologies in rapid prototyping. It is also underlined that in terms of speed the current state of technology
does not support mass production, but is “ideal” for “test parts” or “niche production applications” that are being developed frequently.

“The 3D printed parts, out of saying, whereas we make the castings so that is basically identical to a production casting – you know, we are just using a different technology to make the mold, than you would in production” (Paul Susalla, video, 1:29)

This illustrates the use of rapid tooling.

In their website, Ford claims that “3D-printed auto parts save millions” and “boost quality”. They also list four key points of their use of additive manufacturing technologies:

1. Additive manufacturing technologies improve quality in Ford vehicles by providing engineers more time and freedom to optimize and test parts
2. Ford’s 500,000th printed auto part is a prototype engine cover for the all-new Ford Mustang
3. The next steps in Ford’s additive manufacturing strategy are auto industry firsts – mixed material applications, continuous 3D sand printing and direct metal printing.

Conclusively, this empirical evidence suggests that Ford is using additive manufacturing technologies in the production through rapid prototyping, which helps them cut costs and time related to the process. They are also using rapid tooling, which refers to printing casts or molds that are used in the fabrication of end parts. According to Ford, 3D-printed prototypes for auto parts have saved “millions” as well as boosted quality. Additionally, Ford expresses their intention to continue their use of the technologies in the future.

### 6.2 Toyota

Toyota’s main supplier of high-performance engineering services, Toyota Motorsports GmbH (TGM), is an experienced using of additive manufacturing technologies with 10 stereolithography machines and two large-frame laser sintering machines at their facilities in Cologne, Germany. Their history with the technology comes from the period when they were still competing in Formula 1. In 2013, TMG announced a partnership with 3D-Parts Ltd with an aim to serve companies in the UK with additive manufacturing services. (TCT - 3D Printing, Additive Manufacturing and Product Development Technology, 2013)

In their website, Toyota lists rapid manufacturing as one of the trends in the automotive industry that is currently being used. They state that “[i]nstead of taking weeks to design and make a part, it takes hours or days” with rapid prototyping. (Toyota.com)

Yet another different example of the use of additive manufacturing at Toyota is linked to their campaign “More than a Car”, or “Más Que Un Auto”, which aimed to engage the Latino community. Toyota had recognised that the Latino community often views their
cars as their family members and often even give them nicknames. Part of the campaign, as explained in Toyota’s press release, was that customers were given the opportunity to order customised, 3D printed nameplates from Toyota website that were then mailed to them for free. This would allow their customers to “demonstrate their love for their trusted companion and immortalise its place in the family”.

(Corporatenews.pressroom.toyota.com, 2014 ; Masqueunauto.com, 2014)

This is an example of customer engagement, enabled by additive manufacturing technologies. Doing such campaigns would be inherently difficult with conventional fabricating methods, as the demand and, for instance, the occurrence of a specific name would be nearly impossible, or at least time-consuming, to predict beforehand. With additive manufacturing the economies of scale are close to zero: in turn, customisation does not create any extra costs.

6.3 Honda

Honda is also identified as a user of additive manufacturing technologies. Honda R&D center research paper (Honda R&D Research Paper website, 2014) reveals stereolithography has been used to create “the master pattern of investment casting prototype parts of our gas turbine engine.” According to the article, the reason for using this particular rapid prototyping technique was that “decreased cost, reduced lead time and quick response to design changes are often required in the early stages of a project”. The article summarises the results as follows:

“[P]rototype parts which satisfied the design dimension and configuration requirements, could be produced. At the same time, the cost and lead-time were reduced to 1/15 and 1/8, respectively, of those for the conventional method.”

This is another illustrative example of the cost and time reductions enabled by rapid prototyping in the product development process.

However, Honda is not only using additive manufacturing technologies in the production process, but also in managing customer relations. The following is from (honda-3D.com) and illustrates how Honda is using 3D printing technologies in regards to this matter.

“At Honda, product development is driven from the bottom up, instead of from the top down. Why? Because we believe great inventions can spring from seemingly crazy ideas. That’s why we actively encourage our engineers to come up with the most radically innovative Concept Cars they can imagine.

Over the years, we’ve showcased many of these vehicles at motor shows around the world. Now, to share the fun with everyone, we’re making 3D design data for some of them available on the web. So you can download the designs, reimagine them according to your own personal vision, and share them with the world. Who knows? You may discover that you have what it takes to become the go-to car designer or engineer of tomorrow!”
Currently there are 3D models for five different Honda concepts, FSR, Fuya-Jo, Kiwami, NSX and Puyo, that can be downloaded, modified, and 3D printed, by anyone. This evidence is interesting because it empowers their customers (or anyone interested) to play with their concept designs and illustrate their ideas to others in a new way. It is also a step towards the future vision of e.g. Chris Anderson (2012), where manufacturing is moving back from low-cost countries to developed countries, even to peoples’ homes, thanks to additive manufacturing technologies. Such campaigns would have been extremely difficult to execute utilizing conventional manufacturing methods only, as the economies of scale could not be reached if, theoretically, every one of the customer-designed concept cars was unique.

Conclusively, Honda is, at least to some extent, using additive manufacturing technologies in the product development process which helps them to reduce time and costs. It is also (indirectly) utilizing the technology to better engage with their customer base.

6.4 Volkswagen

In 2014, Volkswagen Denmark launched a campaign called The Polo Principle. The following is transcribed from a video where the Polo Principle is explained: “We democratized one of the innovations that make the innovations at Volkswagen. The 3D printer was once a futuristic piece of high technology only within reach of trained engineers at large corporations. At Volkswagen, it is used to making prototypes of the cars. Now internet users could do that too. Through a 3D tool on our webpage, users could make their own Polo prototype in any style they wanted, or upload a photo or design from their computer. We printed the users’ designs, boxed them and sent them out to them. Now we hope people not only have a Polo on the drive, but on the mantelpiece too. The 40 best prototype designs were exhibited at the Danish Design Center to show the public what comes out of democratizing a 3D printer. The campaign was covered heavily in the media and blogs. By giving people access to technology that is otherwise out of their reach, we proved that we stand by our words when we say that we democratize innovations through The Polo Principle.”

This is yet another interesting application of additive manufacturing in customer commitment. This is also an example of value co-creation, where companies are closely collaborating with their customers to create better value. Again, the benefits of additive manufacturing technologies compared to conventional methods are visible as such a campaign involves production of miniature Polos in unpredictable volumes and varying designs. According to the video, which lists Volkswagen Denmark as the source, the campaign resulted in the buyer preference increasing by 16 per cent and Polo sales to increase by 17 per cent compared to last year.

Concerning Audi, The following quotations are from a video where Michael Breme, Head of Audi Tool Design, explains their use of 3D printing technologies:
“A brand new technology has made its way to tool-making, the 3D printer. It enables us to produce the parts faster and cost effectively. For example, with the 3D printer we don’t have any waste like we would with metal cutting, which means we are faster and more cost effective.”

This is an example of the use of rapid tooling. Michael Breme underlines the speed and cost improvements enabled by utilization of the technology, which has been a repeating theme among the studied case companies.

“Here we see a hot forming die with cooling channels that today is still bored in the conventional manner. In the future we want to print segments, we want to print these cooling channels, as can be seen so well in this sample. You can essentially bore cooling channels around corners, making the production of these dies much much more faster and much much more economical. I believe that this is just the beginning for this technology. In the future, we will have even bigger machines with which we can work even faster and produce larger work pieces. There definitely is going to be a major revolution in the next few years.”

According to Michael Breme, Audi is looking to further their use of additive manufacturing technologies in the future. He is also predicting a major revolution related to additive manufacturing, but this matter is not discussed further by him. Conclusively, the above presented empirical evidence displays the use of rapid tooling at Audi, which helps them cut costs and improve speed.

### 6.5 Koenigsegg

The following quotations are transcripts from two videos, possible to find on the company website, where the Koenigsegg CEO Christian von Koenigsegg explains how they have used additive technology in their One:1 car, both in the design phase as well as in the final production of various parts.

(3:10) “So many of the parts of course we first 3D print of CAD data to try in the car. This is a new One:1 brake pedal, this is a new One:1 throttle pedal. They are machined normally out of aluminum, they are adjustable for different angles and length of legs and so on. This way we could try them in a car. I wouldn’t want to go driving on a race track with these, but you can sit in the car and see how they feel, try spring loads, try positions, if needed modify them by hand until they are exactly how we want them, and then we laser scan them and throw them back into the computer again.”

Christian von Koenigsegg also indicates that these 3D printed plastic parts would not be ideal, or even appropriate, to be used in the final vehicle. This is most likely because the pedals have a critical role in controlling the vehicle and thus are bound to safer and more durable solutions than plastic, such as the aluminum he mentions. Nevertheless, Koenigsegg also uses plastic 3D printing in the end production, as seen in the following quote:

“We first CFD’d [a new wing mirror foot and housing] on a computer to check the aerodynamics and then tried it on our test Agera to see how it worked in reality with just
printed plastic. This is ABS plastic, it’s quite a good strong material to print out which is actually long lasting over time, and we, actually, since the last four five years, have been printing air ducts for track units and stuff like that, and some air guides for front wheel arches and a few bits and pieces, interior pieces in the wing mirror for production cars actually out of this material, so in low volume, it makes sense to print parts which are fairly arbitrary and not very highly loaded, like guides and things like that.”

As stated by Christian von Koenigsegg, the parts that are non-critical (“not very highly loaded”) can be printed with plastic. He also mentions their low production volume to support this choice.

(3:56) “So we printed out this piece, tried it in the car, it’s a footrest, two different positions for a comfort and spirited driving, and then we modified that by hand, laser scanned it, refined it in the computer, printed an aluminum tool with this shape, when we made this carbon piece for the first One:1 car. Also this happened in like 7-8 days period from first idea to finished product. So it can move really quickly.”

“So we just printed for the One:1 car one of the largest pieces in the world, printed out of titanium, the exhaust piece. It saves almost one kilo compared to our aluminum machined exhaust end piece. It’s much more expensive but very much lighter, and something very unique and cool to have on the car. As it’s also far back it’s important to save a lot of weight there.”

This illustrates the unique structures that can be fabricated using 3D printing technologies. It also helped Koenigsegg to decrease weight in the One:1 car to achieve the 1:1 power ratio. Christian von Koenigsegg, however, makes it clear that 3D printing metal parts is costly.

(6:12) “We are also printing our variable turbine housing for our turbos for the One:1. It has very intricate shapes that we found really difficult to cast. So we’ve had a great freedom of design when we 3D printed that’s totally unrestricted of draft angles and things like that. So for production we are actually 3D printing our turbine housings for our turbos to have the variable patented Koenigsegg solution.”

(other video) “And this [turbo housing] is actually 3D printed. It has quite complex shapes in here. So it’s difficult to cast when the chambers are kind of twisting around each other, so we tried to cast it at first, and I guess with a lot of trial and errors we could have made that work, but with the modern 3D printing methods, you can actually print at a relatively good price for low volume in stainless steel or titanium.”

“And we are printing the moving parts as well at the same time internally in the housing so we don’t need to fit them afterwards, they are already in there when we get the turbine housing. Also the threads to mount the turbine housing are 3D printed in the process so there is very little, almost nothing, in finish surfacing work. So all in all, it’s a very interesting unique solution that gives our engine a broader range and the unique capability for its size.”

This also illustrates the fabrication of unique structures that is enabled by 3D printing technologies. They can 3D print the “moving parts” inside the structure at once, as well as the threads to mount the turbine housing, which reduce the need for assembly.
“And we are going more and more into 3D metal printing because the low volumes we’re at, it’s very costly to make production tooling when only making ten, fifteen, twenty pieces per year out of them. So we can actually use that as an argument to pay a lot for 3D printed metal parts as we save tooling costs, we save tooling time, and we can make impossible... otherwise impossible shapes that are more efficient and lighter than our competitors can do, even if they are only at ... well, [with a] production volume [of] maybe hundred cars they can’t motivate the 3D printing cost because then they save so much money by making the tool. But at this volume we can motivate, not saving the money by making the tool because it doesn’t cost much more at this production level to 3D print and get the benefit of otherwise impossible shapes.”

Above Christian von Koenigsegg summarizes the reasons why they have chosen to use additive technology at Koenigsegg. They are manufacturing cars at low volumes, which firstly would make tooling very expensive, and secondly would not allow them the economies of scale that would follow the use of traditional manufacturing methods. Furthermore, the additive process allows creating complex shapes that would otherwise be impossible or difficult to fabricate. The choice to produce the exhaust end piece for the One:1 from titanium with the additive process enabled them to decrease the weight, which helped to achieve the 1:1 power ratio. Furthermore, the patented turbine housing of the One:1 turbo was designed free of the limitations that would have come with using traditional manufacturing methods. They are also using additive technology for some of the non-critical end parts, such as air guides or wind mirror feet, in plastic. Furthermore, it was addressed by Christian von Koenigsegg that the additive process makes their design-to-production process shorter, as they can easily try different design solutions through additive manufactured plastic models before casting the final parts in, for example aluminum.

It was also made clear that additive manufactured metal is costly. Christian von Koenigsegg says that they can motivate their use of additive manufacturing because of their low production volumes. This would not be the case if the production volume were at 100 cars; such a high volume would allow savings, through economies of scale, by using traditional tools. However, it was also stated that the use of additive manufacturing saves them time and enables creating complex structures that would otherwise be impossible.
7 DISCUSSION

In this part, I first discuss the results concerning the primary data and then the results of the secondary data I gathered

7.1 Analyze of primary data

7.1.1 Additive manufacturing uses in the automotive industry

The interviews I conducted show that my respondents mostly use additive manufacturing during the prototyping phase. One respondent (R4) also mentioned that his company sometimes uses additive manufacturing for rapid tooling to produce molds and casts but rapid prototyping remains the major way our respondents use this technology.

Respondents have emphasized the fact that the additive process is very useful during the prototyping phase, as it allows car manufacturers to develop parts, sometimes with complex shapes, rapidly. R4 mentioned the countermeasure parts that can be created quickly with additive manufacturing, reducing the risks of discovering flaws during the manufacturing phase. This highlights the indirect impact of additive manufacturing on the reduction of manufacturing lead-time and cost as the latter you discover the dysfunction, the more expensive it is to fix it.

Moreover, additive technology has been identified as an alternative to the conventional metal-cutting manufacturing methods by R1, as “producing certain metal parts with the additive process is less expensive than the traditional process.” But R4 had a different viewpoint, claiming that his company “also used it for metal parts but less often as this process is expensive.” These statements emphasize the fact that additive manufacturing can be employed as a complement of the traditional process but reaches its limits due to the cost of production of certain parts.

From these interviews, I noticed that the barriers to the expansion of additive manufacturing in the automotive industry can be classified in two categories: the technology maturity and the manufacturing process.

Concerning the technology maturity, it seems that the quality of parts that are produced through the additive process is lower than those produced with the traditional process: “The physical aspects of parts that are produced layer-by-layer is not perfect, for example plastic parts have to be reworked to remove imperfections and give them a smooth appearance” (R1). Another point is that the size of parts that are 3D printed remains limited due to technological limitations. The batch size is also important as it remains more profitable to produce large batches with traditional processes.

It seems that rapid prototyping and rapid tooling have been implemented in the automotive industry without requiring major changes in the manufacturing process as my respondents use this technology in parallel to traditional manufacturing processes. However, through the interviews, it appears to me that the implementation of direct manufacturing lead to significant changes in the manufacturing process. This has been evoked by my respondents as they told me that it is very expensive to change their internal
process, to switch from a traditional industrial process to an additive process. “The initial investment should be considered” (R1), “It is not only the technology itself that is expensive but also all related costs such as supply chain restructuration and experts with enough knowledge and skills to use machines” (R3). The importance of bureaucracy should also be considered because car makers have to scrupulously respect documents that specify the vehicle conception logic and the quality requirements.

The interviews that I conducted seem to indicate the opposite to what we can read in some research (e.g. Cotteleer et al., 2014, Manyika et al. report, 2015). In fact the additive manufacturing process is only marginally used in the automotive industry, especially for direct manufacturing, according to my research. Ivanova et al. (2013, p. 364) came to the same conclusion regarding additive manufacturing use in nanotechnology. It seems that the adoption of additive manufacturing to produce end-use components has been dampened by the narrow selection of available materials and the quality of parts produced layer-by-layer compared to parts produced with traditional process. Ivanova et al. (2013, p. 364) also explained that the application of the additive manufacturing process is usually limited to prototypes (form testing, presentation models, functional testing).

As we have seen previously, it appears that car manufacturers which produce an important volume of vehicles don’t use direct manufacturing. However, R4 discussed an interesting point concerning the luxury niche market. He mentioned the fact that luxury car makers use additive manufacturing to produce end-parts. I conducted further investigations in that direction and found that the famous Swedish luxury car manufacturer Koenigsegg currently use additive manufacturing to produce end parts.

In 2014, Koenigsegg introduced its One:1 model, a luxury car that uses many 3D printed components. This vehicle will be produced in limited series and has side-mirror internals, titanium exhaust components, air ducts, and a complete turbocharger assembly which have been 3D printed. Additive manufacturing technology play a key part in Koenigsegg both in product development and end production. They are utilizing additive manufacturing to find the ideal shape for various parts through rapid prototyping, and for some of the non-critical end parts in plastic. Additionally, Koenigsegg deploys additive manufactured metal to fabricate end parts with unique structures that, for instance, allowed them significant weight savings in the One:1 car. They are also expressing their intention to further their use of additive manufacturing technology. Overall, their ability to utilize this technology can be considered one of Koenigsegg’s core competencies and the 3D printer their key resource that has enabled them to improve product offerings and cost structures.

7.1.2 Additive manufacturing impacts on operational performance

To discuss findings related to additive manufacturing impacts on operational performance, I suggest to divide these findings in two categories: additive manufacturing impacts on operational performance during development phase and additive manufacturing impacts on operational performance during production phase. In the first category, I discussed about rapid prototyping and rapid tooling and in the second category, I discussed about rapid manufacturing.
Additive manufacturing seems to have a global positive impact on operational performance during development phase even if this impact remains limited as additive processes are less used than traditional processes. Additive manufacturing allows car manufacturers to reduce the prototyping time as parts can be produce more quickly with this process. R4 mentioned that this technology help his company “during prototyping phase to save a lot of time, energy and reduce costs”. This reflection is probably links with the possibility offered by additive manufacturing regarding countermeasure parts. Instead of waiting 6 months with traditional manufacturing process, it takes 3 days to build a new part with additive manufacturing. Time saving and design flexibility seems to be the most important impacts this technology has on operational performance. Waiting and over-processing wastes seems to be the two production wastes which are affected positively by this technology. However, additive manufacturing don’t seems to impact over-production, transportation, inventory and motion in an extreme way as the answers of my respondents were moderate and neutral concerning these production wastes. But concerning the last production waste, producing defects, it seems that additive manufacturing effects on operational performance is rather neutral, even negative. In one hand, parts that are produce with additive process can have a complex design and it is not necessary to create a mold to produce parts. But on the other hand, the final aspect of the part and its quality and durability are contested. The raw material used to produce these parts are limited and it seems that traditional processes produce significantly better results at this level. To resume, additive manufacturing impacts on operational performance during development phase is positive regarding the design flexibility and time savings aspects. It also allows manufacturers to reduce their costs as this technology can faster produce parts. However, the quality of final part is not convincing.

Concerning additive manufacturing impacts on operational performance during production phase, car manufacturers that produce an important volume of vehicle don’t used it to produce final parts, therefore operational performance impacts cannot be evaluate. I recommend to conduct further investigation, focusing on niche market in automotive industry to be able to gather interesting findings about it.

### 7.2 Analyze of secondary data

#### 7.2.1 Overview of results

In the following Table 3, I present evidence-based overview of the studied carmakers using additive manufacturing

<table>
<thead>
<tr>
<th></th>
<th>Rapid prototyping</th>
<th>End production</th>
<th>Tooling</th>
<th>Marketing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Toyota</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Honda</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Volkswagen</td>
<td>X</td>
<td></td>
<td>X (Audi)</td>
<td></td>
</tr>
<tr>
<td>Koenigsegg</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.2.2 Rapid prototyping

It is evident that carmakers are using additive manufacturing technologies (rapid prototyping) in product development. Rapid prototyping has enabled the studied companies to develop new models faster and more cost-efficiently, as they have been able to manufacture different designs effortlessly for test purposes to find the perfect fit for the end production.

The findings suggest that the use of additive manufacturing technologies in terms of rapid prototyping can enhance the product offerings of car manufacturing companies as they can develop new models and features faster.

The findings suggest that the use of rapid prototyping also improves the cost structures of car manufacturing companies through increased speed and reduced product development costs. To achieve the same number of prototype parts for testing in the product development process would be significantly more time consuming as well as more costly using conventional methods only. This is illustrated in the Honda research paper: “[a]t the same time, the cost and lead-time were reduced to 1/15 and 1/8, respectively, of those for the conventional method.”

7.2.3 Rapid tooling

Additive manufacturing is also used in fabricating the tools that are then used to make the end parts used in the vehicles. Fabricating molds or casts with additive processes is beneficial for three reasons: It is cheaper, faster and allows flexibility.

Direct evidence to support the speed benefits of indirect additive manufacturing in the studied case companies was found in Audi: “[i]t enables us to produce the parts more faster and cost effectively” and the additional case study Koenigsegg: “printed an aluminium tool with this shape .. this happened in like 7-8 days period from first idea to finished product.”

7.2.4 Rapid manufacturing

It was stated several times by the studied case companies that the current state of additive manufacturing technologies do not support manufacturing in high volumes. However, In the additional case study of Koenigsegg, The CEO Christian von Koenigsegg suggested that in small volumes even the metal 3D printed is economically viable. He also suggested that additive manufacturing allows fabricating structures that would otherwise be impossible, which has opened up possibilities in the end production of Koenigsegg hyper cars. Some concrete examples, e.g. the turbo housing and exhaust end piece, were given. These example parts helped Koenigsegg to achieve the high performance level of their One:1 car. Koenigsegg also printed some of the non-critical parts of the One:1 car in plastic.

Christian von Koenigsegg stated that the end production of metal parts with additive processes is economically viable if the production volumes are low. However, as it was
emphasised by Christian von Koenigsegg that 3D printing in metal is costly, we would not say it would be viable for other than hyper car manufacturers to integrate metal 3D printing in the end production.

Hyper cars seem like a natural area for the use of additive manufacturing in the end production, as they are performance driven and generally produced in low numbers. With higher production volumes the economies of scale benefits of conventional manufacturing methods would be given a higher value. By optimizing the structures of parts used in car manufacturing, lighter weights and therefore increased performance can be achieved. It is highly likely that additive manufacturing processes will be increasingly important manufacturing method for the performance driven vehicles as the technology develops and allows producing larger pieces with improved speed.

7.2.5 Use of additive manufacturing in marketing

It was very interesting to find that three of the studied companies were using additive manufacturing technologies in their marketing efforts.

**Honda** released 3D models for some of their concept vehicles online to let people modify and 3D print them. Such a campaign initially required the use of digital tools – 3D modelling – and fundamentally additive manufacturing technologies.

**Toyota** identified that their customers in the Latino community give an extraordinarily high value for their cars and often even give them nicknames. Therefore, Toyota launched a campaign which included a webpage where their customers could order a 3D printed nameplate. It is possible that such campaign could have been executed without the aid of additive manufacturing by e.g. ordering a bulk of different letters from low-cost manufacturers and then combining them according to customer orders, but it is likely this would have resulted in additional transport and inventory costs as well as increased handling time. With additive manufacturing, the fabrication would happen on-demand and would not incur extra costs regardless of the absolute number of unique nameplates. Nevertheless, this example is in line with the general feature of additive manufacturing: limitless customization with no extra costs.

**Volkswagen** launched a campaign called The Polo Principle in Denmark. Part of the campaign was to allow their customers to create their own Polo prototypes, which were then 3D printed and sent to the customers. The best designs were shown at an exhibition, and the winner design was turned into a real Polo. This is a strong example of value co-creation, where companies and customers are doing closer collaboration to create value together. According to Volkswagen Denmark, this campaign increased both the customer buyer preference and Polo sales. I argue that this type of campaign would not be feasible to execute without the aid of additive manufacturing technologies, as unpredictable demand and heavy customization are present in this case. Ordering a bulk of miniature Polos from a low-cost country and customizing them according to customer preferences would have incurred in extra transportation and inventory costs, as well as increased handling time. Again, 3D printed the customer-designed miniature Polos would happen on-demand and would not be sensitive to design variations, which is one of the main features of additive manufacturing.
8 CONCLUSION AND FURTHER RESEARCH

Additive manufacturing enables car manufacturing companies to improve their product offering through a faster product development process. Use of additive manufacturing technology in rapid prototyping seems to be a common practice among carmakers. Regarding end production, it seems that only automotive companies which target specific niche markets, and produce a low volume of vehicles, such as luxury car makers, use the additive process to produce end-use parts. The example of Koenigsegg suggests that metal end-parts produced with the additive process enables them to improve their product offering through unique, lightweight structures that lead to better performance in their vehicles. Moreover, I discovered that some car manufacturers use additive manufacturing as a marketing tool to increase customers’ fidelity and co-creation of value for their brand.

According to a Manyika et al. (2015), mass-customizations and reduced fuel consumption will be major trends in the future of the automotive industry. Both trends support the use of additive manufacturing technology, as it enables flexibility and creation of unique, lightweight structures. The current state of 3D printed metal does not support end production in other than low volumes, but this is likely to change in the future as the technology matures and becomes faster and more affordable.

Qualitative studies have been subject to criticism regarding their generalization to other situations than the studied specific context (Bryman & Bell, 2009, p. 78). This study is a good starting point and give an accurate views of additive manufacturing impacts in automotive industries. However, it can be relevant to conduct a quantitative study about the topic to complete the findings. It can also be possible to conduct researches regarding the impact of additive manufacturing implementation in others industries. To conclude, one interesting finding of this research concerns the use of additive manufacturing as a marketing tool. This findings can be related to other field of research such as marketing or co-creation and can be interesting to investigate.
9 TRUTH CRITERIA

The evaluation of the quality is an important stage in the research process. In this chapter, I explain how this research met the standards for quality. I first discuss and introduce the terms that determines the quality of a qualitative research and then evaluate the truth criteria of this paper.

According to Bryman & Bell (2011, p. 43), qualitative studies have to be judged and evaluate based on different standards from those used to assessed quantitative studies. Qualitative research is evaluate by two criteria: trustworthiness and authenticity. Bryman & Bell (2011, p. 395) explain that Trustworthiness can be divided into four sub-criteria: credibility, transferability, dependability, and confirmability.

9.1 Credibility

The capability and effort of the researcher are important factors that determines the credibility of the qualitative research (Golafshani, 2003, p. 600). Credibility criteria demands the assurance that the research which have been undertaken respect the principles of good practices. The researcher also have to submit research results to the respondents and individuals of the social world who have been studied in order to get the validation that the researcher has understood the social world (Bryman & Bell, 2011, p. 395).

The credibility of this study is high as I use triangulation to collect data. I conducted semi-structured interviews to collect data from experts, which allowed me to ask precise questions but also left the door open to some new ideas bring from the respondents. It also allowed me to ask for clarification when it was necessary. Furthermore, to increase credibility, I engaged in respondent validation and provided the result of my research to respondents in order to ensure that I fully understood them and correctly interpret what they said. I also verified my understanding at the end of each interview by summarizing what the respondents said to give them the opportunity to clarify and correct my understanding in order to avoid any partial interpretation or bias (Saunders et al., 2011, p. 334). Concerning the collection of secondary data, I pay attention to the information sourcing and carefully select the cases I wanted to study. I also followed ethical consideration for both primary and secondary data collection through the research process.

9.2 Transferability

Research ordinarily involves an investigation of a particular people or set of groups with similar attributes. Transferability is define as the degree to which the results of a research is applied to different sceneries and contexts (Krefting, 1991, p. 216). Qualitative research are oriented into the context of uniqueness of the social world being observed and findings are most of the time not generalized in other settings than the one studied (Bryman & Bell, 2011, p. 395).

In this case, the use of additive manufacturing in the production process slightly differs from one firm to another, even if the industrial field is the same. Even so, I believe that the findings are relevant within the automotive industry as I have use triangulation, to provide an objective view of this industry and transferable results. However, I am not sure that these results can
be fully apply to other industries such as defense or medical industries because of the different industrial structures and market rules which are proper to each industry

9.3 Dependability

Dependability involves guaranteeing that all the records use in the research are kept and possibly accessible (Bryman & Bell, 2011, p. 398). The researcher is involves and ensures the trustworthiness of its research. To increase trustworthiness of my research, I have develop an approach of auditing (Bryman & Bell, 2011, p. 398), by keeping all the documentation, records of interviews, transcripts and necessary information use during the research process. The fact that I collected primary data allowed me to be the owner of these data, and therefore, have them in my possession and use them the way I wanted, in agreement with my respondents. And concerning the secondary data, the information I gathered are public. Therefore, every researcher can check them.

9.4 Confirmability

Confirmability is a criteria that assesses the objectivity of the qualitative research (Bryman & Bell, 2011, p. 398). To increase the objectivity of this research, I have used several source of data. During primary data collection, I used open-ended questions during the interviews to limit the impacts of my own opinion on interviewees’ answers. By conducting most of the interviews by phone, I have minimized the possibility of influencing respondents’ answers by comparison with face-to-face interview (Bryman & Bell, 2011, p. 207). Throughout the research work, I have carefully used information, trying to be as objective as possible, avoiding to give personal opinion.

9.5 Authenticity

Authenticity is an important truth criteria for qualitative research. To guarantee fairness, respondents must present various standpoints from distinctive perspectives (Bryman & Bell, 2011, p. 399). As a researcher, I have tried to be as fair as possible, being open to every ideas and knowledge provided by respondents and experts. When I gathered data, I made sure to present all opinions and perspectives shared by respondents and publish all information I found related to my research topic.
REFERENCES


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Womack et al, (1994). The machine that changed the world


Yin, R.K (2014); *Case Study Research: Design and Methods* Yin, R. K. (2010). *Qualitative research from start to finish.* Guilford Press.


APPENDIX

Appendix 1: 3D printed car

(Hoffman, 2014)
Appendix 2: Additive manufacturing process flow

1) From CAD to product

(Cotteleer et al., 2014)

2) Inside the printer

(Voxeljet.de, 2015)

3) Comparison of traditional and additive manufacturing

Traditional

<table>
<thead>
<tr>
<th>Billet</th>
<th>Machining</th>
<th>Part</th>
<th>Scrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Billet Image]</td>
<td>![Machining Image]</td>
<td>![Part Image]</td>
<td>![Scrap Image]</td>
</tr>
</tbody>
</table>

Additive Manufacturing

<table>
<thead>
<tr>
<th>Foil/Powder</th>
<th>AM</th>
<th>Part</th>
<th>Scrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Foil/Powder Image]</td>
<td>![AM Image]</td>
<td>![Part Image]</td>
<td>![Scrap Image]</td>
</tr>
</tbody>
</table>

(3D Scanning, Reverse Engineering & Rapid prototyping, 2015)
Appendix 3: The 7 groups of rapid manufacturing processes and the eight categories of materials used by additive manufacturing process

<table>
<thead>
<tr>
<th>Processes</th>
<th>Modelization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder Jetting</td>
<td>Figure 1: Binder jetting</td>
</tr>
<tr>
<td>Binder Jetting uses a liquid bonding agent</td>
<td>![Binder Jetting](Custompartnet.com, 2015)</td>
</tr>
<tr>
<td>which is deposited with an inkjet-print head</td>
<td></td>
</tr>
<tr>
<td>in order to join powder materials</td>
<td></td>
</tr>
<tr>
<td>Directed Energy Deposition</td>
<td>Figure 2: Directed energy deposition</td>
</tr>
<tr>
<td>Directed Energy Deposition uses thermal</td>
<td>![Directed Energy Deposition](Rpmandassociates.com, 2015)</td>
</tr>
<tr>
<td>energy from a laser to fuse raw materials</td>
<td></td>
</tr>
<tr>
<td>by melting them when they are deposited.</td>
<td></td>
</tr>
<tr>
<td>Material Extrusion</td>
<td>Figure 3: Material extrusion</td>
</tr>
<tr>
<td>This process pushes materials, often a</td>
<td>![Material Extrusion](Custompartnet.com, 2015)</td>
</tr>
<tr>
<td>thermoplastic filament through a nozzle which</td>
<td></td>
</tr>
<tr>
<td>is on a platform and moves in vertical and</td>
<td></td>
</tr>
<tr>
<td>horizontal directions</td>
<td></td>
</tr>
<tr>
<td><strong>Material Jetting</strong></td>
<td>This process injects materials across a build area using a moving inkjet-print head</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Powder Bed Fusion</strong></td>
<td>This process uses thermal energy from an electron beam or laser to selectively fuse powder within a powder bed</td>
</tr>
<tr>
<td><strong>Sheet Lamination</strong></td>
<td>Sheet lamination uses sheets of material bonded in order to form a three-dimensional object.</td>
</tr>
</tbody>
</table>
This process uses light to selectively cure a photopolymer’s liquid in a vat.

In the following table, each process described above lends themselves to certain materials. As I said previously, there is an eight categories of materials defined by Wohlers (2012) that can be used with additive manufacturing technology. The blanks in the table represent material/process combinations which are not currently utilized in industrial processes:

<table>
<thead>
<tr>
<th>Material/Process Combinations</th>
<th>Material jetting</th>
<th>Binder jetting</th>
<th>Vat photopolymerization</th>
<th>Sheet lamination</th>
<th>Powder bed fusion</th>
<th>Directed energy deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers and polymer blends</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Composites</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graded/hybrid metals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Investment casting patterns</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand molds and cores</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 4: Applications of AM in car manufacturing industry (Cotteleer at al., 2014)

Source: Deloitte analysis.

Graphic: Deloitte University Press | DUFpress.com
Appendix 5: Interview guide

BACKGROUND QUESTIONS
1. What position do you have in the company?
2. How long have you been working in this service?

ADDITIVE MANUFACTURING
3. How can you describe additive manufacturing implementation in your company?
4. Why did your company start to use additive manufacturing processes?

IMPACTS ON PRODUCTION WASTE
Do you think additive manufacturing implementation in your company can have an impact (even indirect) on these production waste defined by Toyota production system?

i. Transportation
   - Does additive manufacturing reduce distance between operations? Simplify materials handling systems?

ii. Overproduction
    - Does additive manufacturing reduce batch sizes? Allow your company to base its production on customer demand?

iii. Waiting
    - Does additive manufacturing accelerate the production process?

iv. Motion
    - Does additive manufacturing reduce employees’ necessity to move from a machine to another?

v. Over-processing
    - Does additive manufacturing simplify production processes?

vi. Inventory
    - Can additive manufacturing reduce inventory?

vii. Defects
    - Does additive manufacturing reduce quality errors? Produce less defective products compared to traditional machining?